

Use of multi-beam sonar to map seagrass beds in Otsuchi Bay on the Sanriku Coast of Japan

Teruhisa Komatsu ^{a,*}, Chiaki Igarashi ^a, Kenichi Tatsukawa ^a, Sayeeda Sultana ^a,
Yasuaki Matsuoka ^b, Shuichi Harada ^b

^a Ocean Research Institute, The University of Tokyo, 1-15-1, Minamidai, Nakanoku, Tokyo 164-8639, Japan

^b Toyo Corporation, 1-1-6, Yaesu, Chuoku, Tokyo 103-8234, Japan

Accepted 7 April 2003

Abstract

Seagrass beds play an important role in coastal ecosystems as primary producers and providers of habitat and environmental structure. Therefore, mapping seagrass beds is indispensable in the management and conservation of sound littoral ecosystems, and in the development of sustainable fisheries in coastal waters. Multi-beam sonar is often used to map bottom topography. We developed a mapping method to quantify the volume of seagrass using a multi-beam sonar. Seagrass beds were scanned with the multi-beam sonar and quadrat sampled to verify the distribution of seagrasses. We used software to discriminate seagrass signals from echoes to obtain a topographic profile of the bottom without seagrass; this was then subtracted from the topography including the seagrass. We then mapped seagrass distribution, calculated seagrass volume, and estimated biomass using volume and quadrat samples. We applied these methods to map a seagrass bed of *Zostera caulescens* in Otsuchi Bay, on the Sanriku Coast of Japan, during the growing season of 2001. A transducer was attached to a boat (one gross ton) equipped with a differential-GPS, a motion sensor, and a gyrocompass. The vessel completed a grid survey scanning whole seagrass bed with an area of 115 m × 156 m at bottom depths between 2 and 8 m within about 40 min when traveling at a speed of 1.5 m s⁻¹ (3 knots). The multi-beam sonar was able to visualize three-dimensional seagrass distribution without interpolation and easily to estimate area and volume occupied by the seagrass using hydrography software. The results indicated that *Z. caulescens* was distributed at bottom depths of 6–7 m with a surface area of 3 628 m² and a volume of 1 368 m³. The mean biomass of above- and below-ground parts of seagrass were estimated to be 28.6 gDW m⁻² (range 26.6–30.9) and 15.9 gDW m⁻² (range 14.1–17.7). Our study demonstrated that multi-beam sonar is effective for mapping and quantifying the spatial distribution of seagrass beds, and for visualizing the landscape of the seagrass canopy.

© 2003 Éditions scientifiques et médicales Elsevier SAS and Ifremer/IRD/Inra/Cemagref. All rights reserved.

Keywords: Seagrass; Seaweed; Mapping methods; Remote sensing; Multi-beam sonar

1. Introduction

Seagrass beds play an important role in marine coastal ecosystems. They support flora and fauna, including epiphytic organisms, as well as coastal fisheries (Coles et al., 1993), and contribute to the marine environment by stabilizing bottom sediments and maintaining coastal water quality and clarity (Ward et al., 1984; Jeudy de Grissac and Boudouresque, 1985; Komatsu and Nakaoka, 2000; Komatsu and Yamano, 2000). Additional effects of seagrass meadows include those of seaweed forests such as buffering of water flow (Komatsu and Murakami, 1994), pH distribution (Ko-

matsu and Kawai, 1986), and dissolved oxygen distribution (Komatsu, 1989; Komatsu et al., 1990). Many commercially important species spawn in seagrass beds (e.g., sea urchins, balaos, cuttlefish); larvae and juveniles use the beds as nursery grounds (Arasaki and Arasaki, 1978). Thus, seagrass beds support biodiversity and are an important habitat for marine animals.

Increased seafloor reclamation and industrial and agricultural pollution as a result of economic development have decreased the size of large areas of seagrass beds in coastal zones (e.g., Hoshino, 1972; Komatsu 1997). Since seagrass beds are sensitive to pollution and water quality deterioration, they serve as “bio-indicators”. Altered seagrass depth distribution in Chesapeake Bay was used as a bio-indicator when runoff impacted water quality, causing changes in light

* Corresponding author.

E-mail address: komatsu@ori.u-tokyo.ac.jp (T. Komatsu).

penetration and consequently affecting seagrass abundance and distribution patterns (Dennison et al., 1993; Short and Willie-Echeverria, 1996). Monitoring has also been carried out at 24–33 survey sites along the coast of Provence and the French Riviera since 1984, using the lower limit of *Posidonia oceanica* as a bio-indicator (Boudouresque et al., 2000). Mapping of seagrass beds is a very practical method to assess the condition of coastal environments. Recently, it has been stressed that preservation, restoration, and creation of seagrass beds are necessary to recover coastal environments, biodiversity, and bioresources for sound littoral ecosystems and for the sustainable development of fisheries. To preserve or conserve seagrass beds, it is very important to map and monitor them (Lee Long et al., 1996).

The methods of mapping seagrass and seaweed beds can be classified into two categories (Komatsu et al., 2002; 2003); one involves direct observation or measurement, whereas the other involves indirect methods using remote sensing equipment. The former category includes ground surveys (walking, diving, or sampling from the surface). In France, observations from a submarine were used to map the lower limits of seagrass, *P. oceanica*, along the French Riviera (Meinesz and Laurent, 1978). Because they require much time and labor, direct methods are not very efficient. Indirect methods are classified into two groups, based on the type of remote sensing equipment that is used: optical remote sensing or acoustic remote sensing. Aerial photographs and satellite imagery are efficient for mapping areas in which dense seagrass beds can be identified on very coarse scales (Belsher, 1989; Long et al., 1994). However, these methods cannot always be used successfully to map seagrass biomass or to find seagrasses at low densities, and they are not effective in waters that are too turbid or deep for optical remote sensing.

One acoustic method that has been developed since the 1970s to map seagrass beds in the Mediterranean Sea is the use of scanning sonar, which is more efficient than ground surveying. With this method, swaths of the sea bottom 50–500 m in width are scanned, and individual seagrass beds can be successfully distinguished (Meinesz et al., 1981; Pasqualini et al., 1998; Piazzi et al., 2000). However, the major disadvantages of this system are that it is difficult to apply on a small boat in shallow waters; it is impossible to measure vertical height distributions; and it is difficult to convert horizontal distribution data to mapping data from the position data for the boat. Other acoustic methods use echosounders to detect vertical seagrass distribution (e.g., Hatakeyama and Maniwa, 1978; Komatsu and Tatsukawa, 1998). The disadvantage of echosounders is that only a narrow area can be scanned; since seagrass is often patchily distributed, the narrow strips deform the distribution. Thus, a broader scan width is recommended.

Recently, narrow multi-beam sonar was developed and used to map bottom topography in shallow waters. This narrow multi-beam sonar can scan broad strips, as well as provide vertical topography, making it suitable for mapping

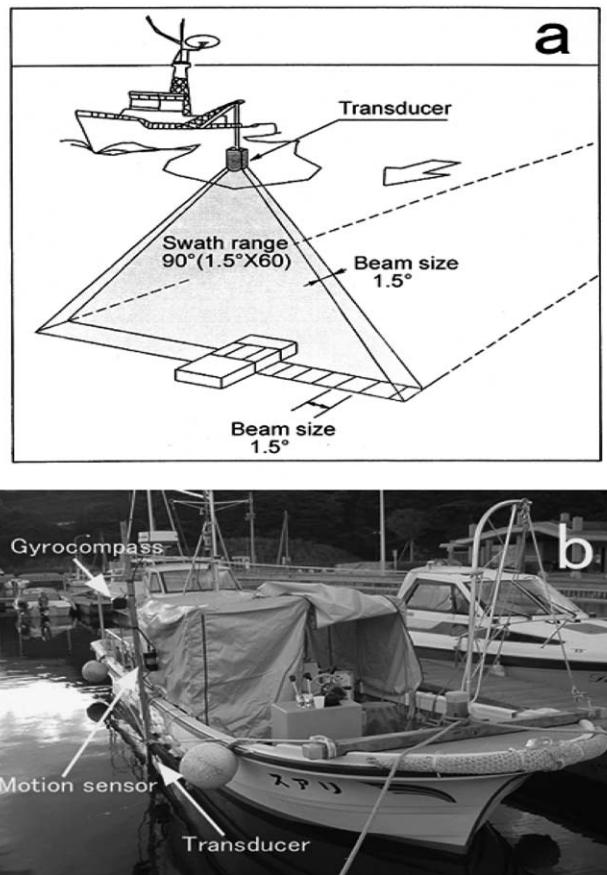


Fig. 1. Schematic view of multi-beam sonar (a) and photography of R/V *Rias* equipped with the multi-beam sonar, gyrocompass and motion sensor utilized for mapping seagrass beds (b). Map of Otsuchi Bay on the Sanriku Coast facing the Northwestern Pacific (left panel) and the study site off Nebama in Otsuchi bay (right panel).

seagrass beds. Therefore, we aimed to develop an efficient method of mapping seagrass beds by using multi-beam sonar to measure their horizontal and vertical distribution.

2. Materials and methods

2.1. Multi-beam sonar

A multi-beam sonar, SeaBat 9001 (RESON Inc.) was used for mapping seagrass beds. The SeaBat 9001 multi-beam echosounder measures 60 soundings in a single pass from a lightweight and portable transducer head. The operating frequency of the ultrasound is 455 kHz. Sixty sonar beams within each swath (combined to form a 90°-wide by 1.5°-long geometrically correct cross-section) provide simultaneous sonar coverage equivalent to about two times the measured depth (Fig. 1a). Because of its small size, the SeaBat 9001 was installed on a small vessel (one gross ton), the R/V *Rias* of the Otsuchi Marine Research Center, Ocean Research Institute, The University of Tokyo (Fig. 1b).

A motion sensor (Model DMS2-10, TSS Ltd.) and a gyrocompass (Model ADGC, KVH Inc.) were combined with SeaBat 9001 to compensate for the motion and direction of

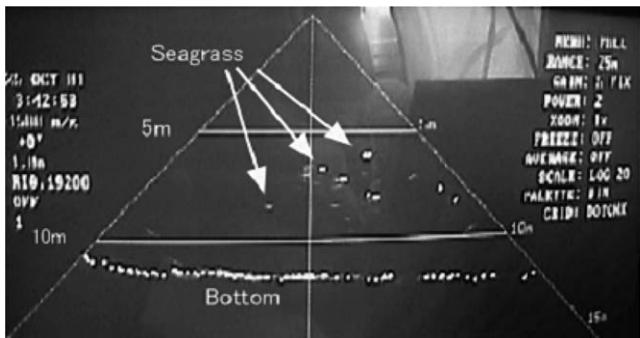


Fig. 2. Echoes of multi-beam sonar reflecting from seagrass and sand bottom.

the vessel (Fig. 1b). The position of the boat and the transducer were localized using differential-GPS (Model AgGPS 132, Trimble). The transducer was fixed vertically on the side of the boat to scan the bottom topography. The data were stored in a notebook computer and analyzed with hydrography software (Hypack Max, Coastal Oceanography Inc.).

2.2. Estimation of seagrass volume and biomass

Most seagrasses, including *Zostera caulescens* Miki, grow on sandy beds. If the seagrass canopy is much higher than the sand bed, we can distinguish the seagrass from the bottom (Fig. 2) by the multi-beam sonar.

We estimated the volume occupied by the seagrass using the difference in depth between the above-ground part of the seagrass and the sand bed. The procedure for this estimation was as follows: (1) a seagrass bed was mapped; (2) data of bottom depth distribution were stored in the computer; (3) using the hydrography software, the seagrass data were removed from the bottom depth data to obtain the bottom distribution of only the sand bed (Fig. 3); (4) the bottom depth distribution of the sand bed was subtracted from the data including the seagrass to obtain the volume occupied by the seagrass. In Fig. 3a, we can observe seagrass signals sticking out upward from the base lines on the hydrography software (Hypack Max). These signals were echo reflecting from the leaves or stems of seagrass on the bottom of which substratum was only sand in this area. Therefore we obtained a topographic profile of the bottom without seagrass (Fig. 3b) by processing seagrass signals as noise on the software. We estimated volume occupied by seagrass subtracting the topographic profile of the bottom without seagrass from that with seagrass (canopy depth) on the software for dredging canals and ports that can calculate the volume between two layers with different bottom depths in an identical area.

Seagrass biomass is estimated by the following steps. In July and October, *Z. caulescens* grew two kinds of shoots in Funakoshi Bay, which neighbors Otsuchi Bay (Sultana and Komatsu, 2002, 2003): flowering and vegetative shoots. The former were >80 cm and the latter were ≤ 80 cm. Since the vegetative shoots are positioned below the flowering shoots, their biomass depends on the aerial cover of seagrass on the bottom.

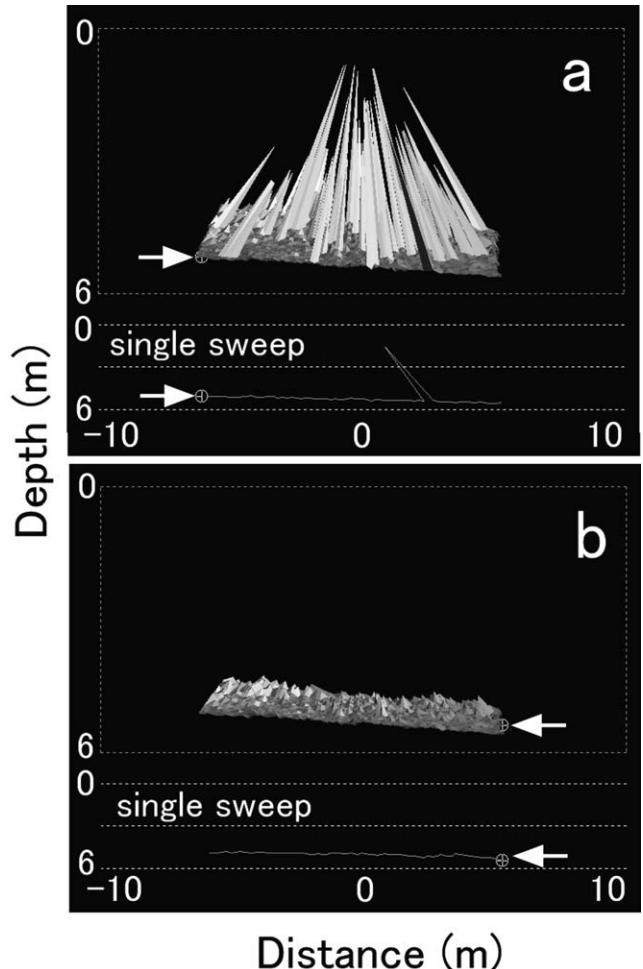


Fig. 3. Bottom depth distributions including sand bottom and seagrass sticking from the sand bed (a) and those of only the sand bed without the seagrass data removed from the bottom depth data by using the hydrography software. Bottom depth data were set along the vessel course. Single sweep shows the bottom depth distribution with a solid line connecting data obtained by one sweep of multi-beam sonar. The corresponding bottom distributions are represented by the white arrows in each panel.

We can estimate vegetative shoot biomass by multiplying the area covered by seagrass and the vegetative shoot biomass per unit area obtained by quadrat sampling. If we assume that the volume occupied by flowering shoots between the bottom and 80 cm above the bottom is vertically constant, the volume can be obtained by multiplying the height of 80 cm and the area occupied by the seagrass at the level of 80 cm above the bottom. Total volume occupied by the flowering shoots is calculated from the sum of that from the bottom to 80 cm above the bottom and that from 80 cm above the bottom to the canopy of seagrass above 80 cm. We can estimate flowering shoot biomass by multiplying the volume occupied by flowering shoots and the flowering shoot biomass per unit volume obtained by quadrat sampling.

The definition of the shoot length is from the base of stem to the tip of maximum leave attaching to the top of stem. However, leaves attaching to the top of flowering shoot stem trail downward in situ. Since the canopy heights of *Z. caulescens* greater than 80 cm are proportional to stem length,

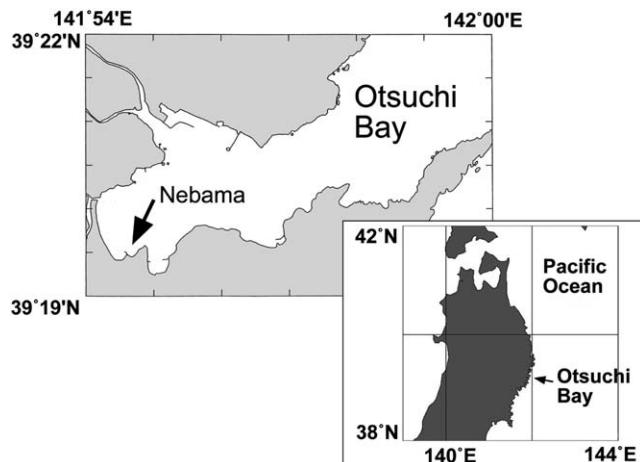


Fig. 4. Map of Otsuchi Bay on the Sanriku Coast facing the Northwestern Pacific (right panel) and the study site off Nebama in Otsuchi bay (left panel).

flowering shoot biomass per unit volume was calculated dividing above-ground biomass of flowering shoots by mean stem length based on the quadrat sampling of seagrass.

2.3. Study area and ground-truthing survey

We selected a seagrass bed off Nebama Otsuchi Bay on the Sanriku Coast of Japan, facing the Northwestern Pacific (Fig. 4). Otsuchi Bay is a *rias*-type bay neighboring Funakoshi Bay, where the longest seagrass on record, *Z. caulescens*, is distributed (Aioi et al., 1996, 1998). The boat, equipped with the multi-beam sonar, scanned the bottom at a speed of 3 knots (about 1.5 m s⁻¹) from 10:22 to 11:03 on 23 October 2001.

To verify the seagrass distribution, a diver made in situ observations and sampled two quadrats (0.5 m × 0.5 m) of seagrass in the area where the acoustic survey was performed at bottom depths of 5.1 and 6.1 m. Samples of seagrass were preserved in plastic bags with 10% formalin seawater. Since seagrass, *Z. caulescens*, is classified as a threatened species by Division of Wildlife, the Ministry of Environment of Japan (2000), it was necessary to limit number of quadrat sampling that destroyed the seagrass beds of *Z. caulescens* (Orth et al., 1984).

To estimate the error of depth detection by the multi-beam system, we compared differences of bottom depth at a quadrat of 20 cm × 20 cm on the sand bed, which is roughly equivalent to the foot print of each sound beam at the study area, sounded at three times. Since surveyed area was 2 m × 2 m, we obtained 100 samples of the difference in the bottom depth.

2.4. Seagrass biomass

Plant material was rinsed in freshwater and cleaned off sand and shells in the laboratory. Shoot density (i.e., density of only the above-ground foliar portions of a plant) and shoot length (i.e., length from the bottom end of a shoot to the top

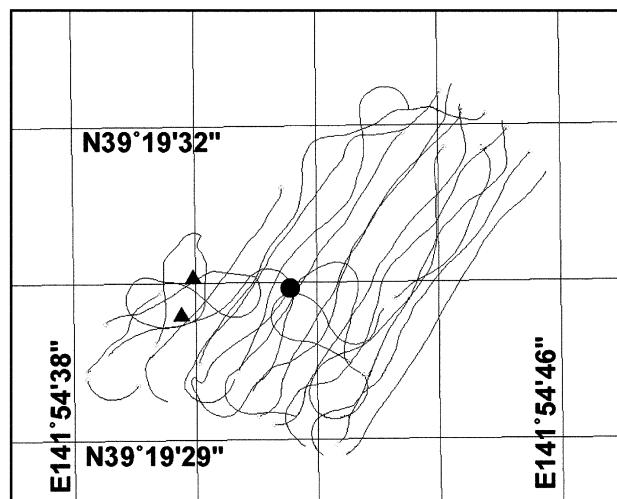


Fig. 5. Map of traces made by the R/V *Rias*, which was equipped with a multi-beam sonar for mapping a seagrass bed of *Z. caulescens* in Otsuchi Bay. Triangles show quadrat-sampling stations. Circle represents the area (2 m × 2 m) to estimate the error of depth detection by the multi-beam sonar system where three courses of bottom measurements were crossing..

of the longest blade) were measured. Samples were also sorted into above- and below-ground parts. Epiphytic plants and animals were removed from leaves by dipping the plants into 5% acetic acid water. Wet weights were taken prior to drying the seagrass in a hot-air oven (DX300, Yamato Scientific Co. Ltd) at 60 °C for 48 h. Dry weights of the samples were then obtained and used to calculate above- and below-ground biomass. Biomass was expressed as dry weight (g) per unit area (i.e., gDW m⁻²), which is the most widely used expression for biomass.

3. Results

Boat traces with the multi-beam sonar are shown in Fig. 5. Bottom topographic profiles with and without seagrass were mapped with the triangulated irregular network (TIN) model using the hydrography software (Fig. 6), and we found that *Z. caulescens* formed a band-like distribution.

To estimate the error of depth detection, the differences of bottom depth at a quadrat of 20 cm × 20 cm on the sand bed sounded at three times in an area of 2 m × 2 m were classified into 5 cm intervals (Fig. 7). Mean of differences of the bottom depth was 11.4 cm (S.D. = 5.4 cm). Therefore, the bottom depth measured by the multi-beam system had an error of ±16.8 cm.

Longer, flowering shoots of *Z. caulescens* were distributed on the western part of the scanned area, where the bottom depth was greater (Fig. 8). The northwestern part of the scanned area was occupied by rafts used in aquaculture, whereas the southeastern part was occupied by buoys. The blank areas on the top and bottom of Fig. 9 correspond to these rafts and buoys. The horizontal distribution of *Z. caulescens* suggests that it was mainly limited to a maximum bottom depth of about 6.5 m (Fig. 9). Dense patches of

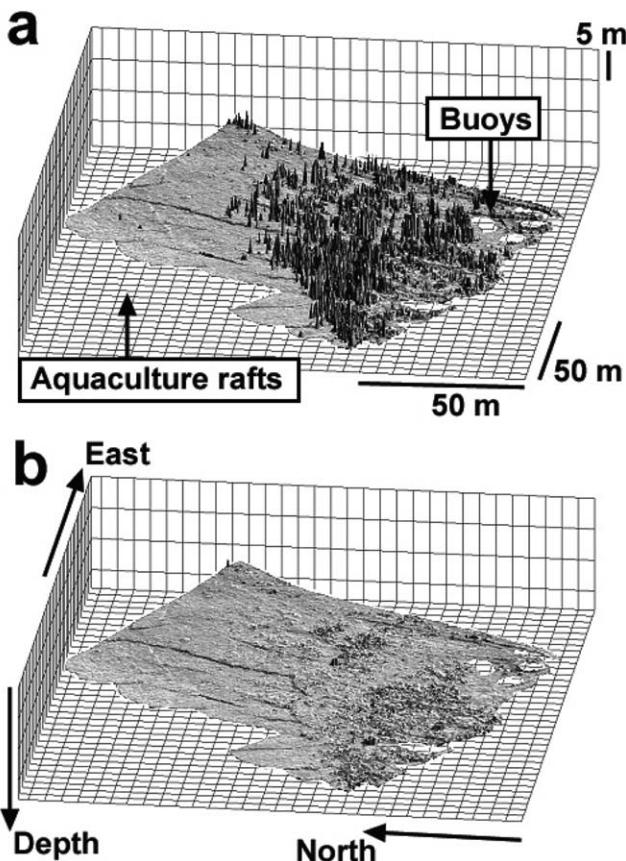


Fig. 6. Three-dimensional distributions of *Z. caulescens* on the bottom (a) and bottom profile without seagrass (b) in Otsuchi Bay using the TIN model. Intervals of grid lines on the East-West, North-South and depth axis are 5 m. Seagrass were observed at bottom depths between 6 and 4.5 m.

Using the software (Hypack Max), we calculated that the areas occupied by seagrass at 1 and 80 cm above the bottom were 3628 and 543 m², respectively. The reason for cutting

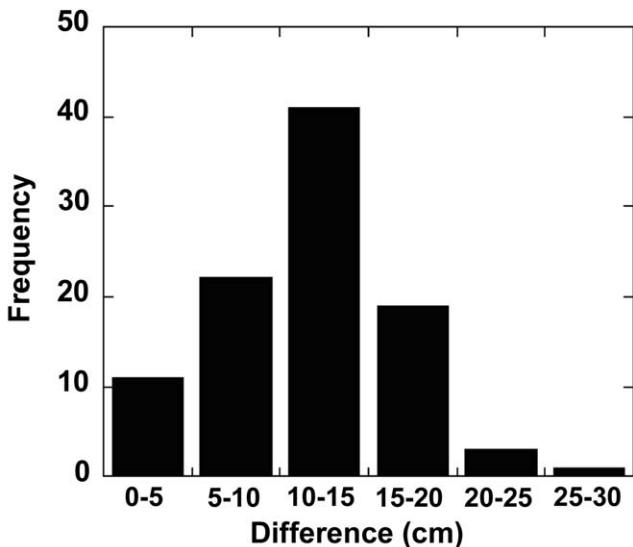


Fig. 7. Frequency distribution of differences between maximum and minimum bottom depths at a quadrat of 20 cm × 20 cm on the sand bed sounded at three times in an area of 2 m × 2 m.

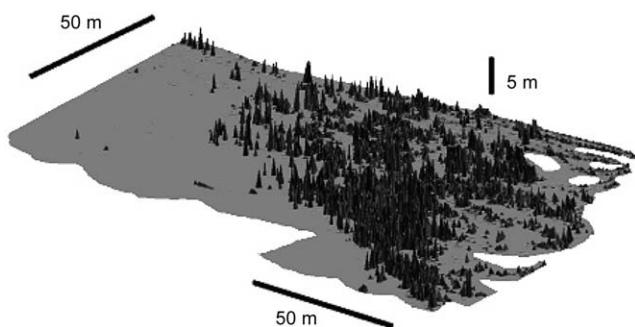


Fig. 8. Three-dimensional distribution of *Z. caulescens* in Otsuchi Bay using the TIN model after subtracting the bottom with the seagrass from the bottom topography including the seagrass.

seagrass at 1 cm above the bottom is to separate seagrass from the bottom. Since three-dimensional distribution of seagrass was extracted from the bare bottom, the aerial cover of the sand bed was 10,205 m². The volumes occupied by the seagrass greater than 1 and 80 cm above the bottom were 1354 m³ (± 610 m³) and 342 m³ (± 91 m³). Therefore, volume occupied by the seagrass was 1368 m³. The mean height of seagrass greater than 1 cm was 19.7 cm when we excluded the area covered by shoots greater than 80 cm from the volume and area estimates. The mean height of shoots above 80 cm was 143.1 cm (± 16.8 cm).

Shoot lengths determined by quadrat sampling were divided into two categories: groups of shoots below and above 80 cm (Fig. 10). We pooled samples at depths of 5 and 6 m to calculate the mean lengths and total weights of the two groups of shoots. The mean lengths of shoots below and above 80 cm were 21.7 cm (± 50.3 cm) and 311.4 cm (± 96.5 cm). The mean stem length of flowering shoots was 263.4 cm (± 103.0 cm). The total dry weights of vegetative and flowering shoots per unit area were 24.3 gDW m⁻² (range 23.4–25.3) and 52.7 gDW m⁻² (range 33.6–71.7). The dry

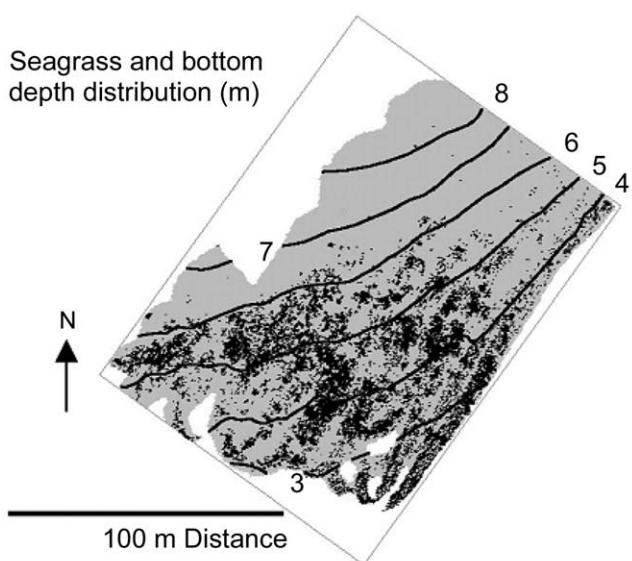


Fig. 9. Horizontal distribution of the area occupied by *Z. caulescens*, as well as bottom depth.

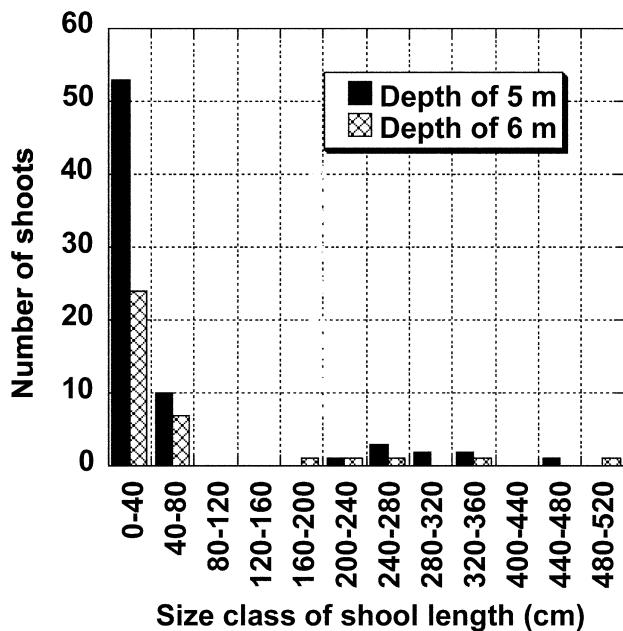


Fig. 10. Distribution of shoot lengths of *Z. caulescens* sampled at bottom depths of 5.1 and 6.1 m in Otsuchi Bay in October during the growing season.

weight of flowering shoot per unit volume was 20.8 gDW m^{-3} (range 15.1–26.4). Roots attaching to vegetative and flowering shoots were classified into two categories of roots: roots of vegetative shoots and flowering shoots. Biomass of the former and the latter were 15.3 gDW m^{-2} (range 13.8–16.8) and 3.5 gDW m^{-2} (range 1.4–5.5).

Biomass of vegetative and flowering shoots were estimated to be 88 kg (range 85–92) and 16 kg (range 12–20). Root biomass of vegetative and flowering shoots were 56 kg (range 50–61) and 2 kg (range 1–3). Biomass of above- and below-ground parts were 104 kg (range 97–112) and 58 kg (range 51–64). Biomass of above- and below-ground parts averaged in total seagrass area were 28.6 gDW m^{-2} (range 26.6–30.9) and 15.9 gDW m^{-2} (range 14.1–17.7), respectively. Consequently, mean seagrass biomass including above- and below-ground parts was 44.5 gDW m^{-2} (range 40.7–48.6).

4. Discussion

Many studies that have mapped seagrass beds using side-scan sonar were unable to show three-dimensional images of the seagrass beds, and provided only horizontal images. On the other hand, mapping studies that relied on echosounders produced only vertical images of seagrass beds. Our study demonstrated that multi-beam sonar could detect seagrass meadows precisely and visualize three-dimensional structure on a computer display. Three-dimensional images of seagrass beds can be used to analyze the formation of seagrass beds, including considerations of gap regeneration, horizontal and vertical development of seagrass patches, and landscape ecology. By quadrat-sampling of seagrass beds, Sul-

tana and Komatsu (2002; 2003) reported that blade length was proportional to bottom depth. We observed a similar phenomenon when we mapped the landscape of the seagrass canopy (Fig. 8).

Colantoni et al. (1982) attempted to use a low-frequency echosounder (3.5 kHz), which proved to be rather ineffective in distinguishing the acoustic characters of *P. oceanica* beds from those of the bottom. Although high-resolution continuous seismic reflection (3.5 kHz) can distinguish *P. oceanica* beds from others (Rey and Diaz del Rio, 1989), the long wavelengths of ultrasound result in worse vertical precision of the echosounder. Echosounders with an ultrasonic wave of 200 kHz are more appropriate for detecting seagrass beds (Komatsu and Tatsukawa, 1998). The multi-beam sonar (SeaBat 9001) used 455 kHz and was reflected by the seagrass. Beam frequencies above 200 kHz are necessary to detect seagrass beds.

Hatakeyama and Maniwa (1978) used echosounding to map a *Zostera* bed, but they calculated only an index of biomass, i.e., the sum of canopy heights per unit sector along a transect scanned by the echosounder. Since it is necessary to estimate seagrass biomass for a quantitative understanding of the seagrass ecosystem, Komatsu and Tatsukawa (1998) proposed a simple method using echosounder and global positioning system to convert the shading grades of seagrass on echograms to above-ground biomass based on quadrat samplings. However, they did not estimate the volume occupied by the seagrass. Multi-beam sonar measurement of seagrass beds and subsequent software processing of data allowed us to estimate the area and volume occupied by seagrass. Incorporating these data with quadrat sampling, we could then estimate the biomass of the seagrass beds.

Sabol et al. (2002) presented a technique for rapid detection of submersed aquatic vegetation (SAV) using a high-frequency, high-resolution digital echosounder linked with global positioning system equipment. The acoustic reflectivity of SAV allows for detection and explicit measurement of canopy geometry using a digital signal processing algorithm. However, it is difficult for this system to map three-dimensional shape of seagrass patches because the echosounder detects only narrow area along survey course of the vessel equipped with the echosounder. The single beam needs interpolation and geostatistics of data between survey courses. Patch distribution of shoots prevents the reconstruction of seagrass canopy by using only one single beam. Thus the multi-beam sonar is more precise than the single beam for detection and explicit measurement of canopy geometry, and estimation of the volume occupied by the seagrass.

The lower depth limit of seagrass beds is related to the light extinction coefficient, which affects the minimum degree of light required for seagrass growth (Duarte, 1991). Thus, it can be used as an indicator of water quality. In France, the lower depth limit of *P. oceanica* was monitored by placing concrete markers (Meinesz, 1977). In this case, the results were very precise, but the area of observation was limited. In contrast, multi-beam sonar can be used to define

the vertical distribution and the lower depth limits of seagrass beds by correcting depths measured by the echosounder to mean sea level. Therefore, monitoring the lower depths with multi-beam sonar is useful for detecting the lower limits of seagrass beds precisely over a wide area.

Multi-beam sonar can scan a seagrass bed with an area of 115 m × 156 m at bottom depths between 2 and 8 m within about 40 min when traveling at about 1.5 m s⁻¹ (3 knots). The survey produces bottom distributions in the entire scanned area, except in places that the boat cannot approach. It is therefore possible to investigate about 500 m × 800 m per day at bottom depths of 6 m with 60 s per turn of a boat at the end of survey line, and under a condition of 25% overlap of width scanned along two neighboring lines when a boat with an echosounder travels at 1.5 m s⁻¹ for 10 h. In this way, multi-beam sonar is a very useful apparatus for mapping seagrass beds and visualizing the underwater landscape.

5. Conclusion

Mapping with multi-beam sonar is a simple, labor-saving, and efficient method to assess the three-dimensional distribution of seagrass canopies. It can be used to estimate the volume and area occupied by seagrass, and, in conjunction with quadrat sampling, the biomass of seagrass beds can also be estimated. The results of such a three-dimensional investigation can then be used to study seagrass ecology from a landscape approach.

Acknowledgements

We thank Mr. Koichi Morita and other staff of the Otsuchi Center for Marine Science, and Mrs. Hiroko Aoyama, University of Tokyo, for their help during our field survey and research. We are also grateful to Prof. Yoshinobu Miyazaki of the University of Tokyo and Mr. Toshio Oyagi and Kazuhiro Hantani of Toyo Corporation for their encouragement. This study was supported in part by a grant from the Ministry of Education, Culture, Sports, Science, and Technology and by a grant from the Ministry of Agriculture, Forestry, and Fisheries.

References

- Aioi, K., Komatsu, T., Morita, K., 1996. Giant seagrass, *Zostera caulescens*, discovered in Funakoshi Bay, Iwate Prefecture. Bull. Japan. Soc. Fish. Oceanogr. 60, 7–10 (in Japanese with English Abstract).
- Aioi, K., Komatsu, T., Morita, K., 1998. The world's longest seagrass, *Zostera caulescens* from northeastern Japan. Aquat. Bot. 61, 87–93.
- Arasaki, M., Arasaki, T., 1978. Compilation of Stories on Algae. Tokai University Press, Tokyo (in Japanese).
- Belsher, T., 1989. Apports du satellite SPOT à la cartographie des végétaux marins. La Mer 27, 144–145.
- Boudouresque, C.-F., Charbonel, E., Meinesz, A., Pergent, G., Pergent-Martini, C., Cadiou, G., Bertrand, M.C., Foret, P., Ragazzi, M., Rico-Raimondino, V.A., 2000. Monitoring network based on the seagrass *Posidonia oceanica* in the northwestern Mediterranean Sea. Biol. Mar. Medit. 7, 328–331.
- Colantoni, P., Gallignani, P., Fresi, E., Cinelli, F., 1982. Patterns of *Posidonia oceanica* (L.) Delile beds around the Island of Ischia (Gulf of Naples) and in adjacent waters. P.S.Z.N. Mar. Ecol. 3, 53–74.
- Coles, R.G., Lee Long, W.J., Watson, R.A., Derbyshire, K.J., 1993. Distribution of seagrasses, and their fish and penaeid prawn communities, in Cairns Harbour, a tropical estuary, northern Queensland, Australia. Aust. J. Mar. Freshw. Res. 44, 193–210.
- Dennison, W.C., Orth, R.J., Moore, K.A., Stevenson, J.C., Carter, V., Kollar, S., Bergstrom, P.W., Batiuk, R.A., 1993. Assessing water quality with submerged aquatic vegetation: Habitat requirements as barometers of Chesapeake Bay health. Bioscience 43, 86–94.
- Division of Wildlife, the Ministry of Environment of Japan, 2000. Threatened Wildlife of Japan: Vascular Plants: Red Data Book. second ed. Japan Wildlife Research Center, Tokyo (in Japanese).
- Duarte, C.M., 1991. Seagrass depth limits. Aquat. Bot. 40, 363–377.
- Hatakeyama, Y., Maniwa, Y., 1978. On the investigation of seaweed distribution by utilizing a fish finder. Tech. Rep. Fishing Boat 73, 155–168 (in Japanese).
- Hoshino, Y., 1972. Pollution in the Seto Inland Sea. Iwanami, Tokyo (in Japanese).
- Jeudy de Grissac, A., Boudouresque, C.-F., 1985. Rôle des herbiers de Phanérogames marines dans les mouvements des sédiments côtiers : les herbiers à *Posidonia oceanica*. In: Ceccaldi, H.J., Champalbert, G. (Eds.), Acte du Colloque Pluridisciplinaire Franco-Japonais d'Océanographie. Soc.Franco-Japonaise Océanogr. vol. 1, Marseille, pp. 143–151.
- Komatsu, T., 1989. Day-night reversion in the horizontal distributions of dissolved oxygen content and pH in a *Sargassum* forest. J. Oceanogr. Soc. Japan 45, 106–115.
- Komatsu, T., 1997. Long-term changes in *Zostera* bed area in the Seto Inland Sea (Japan), especially along the coast of Okayama Prefecture. Oceanol. Acta 20, 209–216.
- Komatsu, T., Igarashi, C., Tatsukawa, K., Nakaoka, M., Hiraishi, T., Taira, A., 2002. Mapping of seagrass and seaweed beds using hydro-acoustic methods. Fish. Sci. 68 (Suppl. 1), 580–583.
- Komatsu, T., Kawai, H., 1986. Diurnal changes of pH distributions and the cascading of shore water in a *Sargassum* forest. J. Oceanogr. Soc. Japan 42, 447–458.
- Komatsu, T., Kawai, H., Sakamoto, W., 1990. Influences of *Sargassum* forest on marine environments. Bull. Coast. Oceanogr. 27, 115–126 (in Japanese with English abstract).
- Komatsu, T., Mikami, A., Sultana, S., Ishida, K., Hiraishi, T., Tatsukawa, K., 2003. Hydro-acoustic methods as a practical tool for cartography of seagrass beds. Otsuchi Mar. Sci. 28, 72–79.
- Komatsu, T., Murakami, S., 1994. Influence of a *Sargassum* forest on the spatial distribution of water flow. Fish. Oceanogr. 3, 256–266.
- Komatsu, T., Nakaoka, M., 2000. Water flow and sedimentation rate in seagrass beds off Khao Bae Na in Trang Province, Thailand. Biol. Mar. Medit. 7, 240–242.
- Komatsu, T., Tatsukawa, K., 1998. Mapping of *Zostera marina* L. beds in Ajino Bay, Seto Inland Sea, Japan, by using echosounder and global positioning systems. J. Rech. Océanogr. 23, 39–46.
- Komatsu, T., Yamano, H., 2000. Influence of seagrass vegetation on bottom topography and sediment distribution on a small spatial scale in the Dravuni Island Lagoon, Fiji. Biol. Mar. Medit. 7, 243–246.
- Lee Long, W.J., Mckenzie, L.J., Rasheed, M.A., Coles, R.G., 1996. Monitoring seagrasses in tropical ports and harbours. In: Kuo, J., Phillips, R.C., Walker, D.I., Kirkman, H. (Eds.), Seagrass Biology: Proceedings of an International Workshop, Rottnest Island, Western Australia, 25–29 January 1996. Faculty of Science, The University of Western Australia, Nedlands, pp. 345–350.

- Long, B.G., Skews, I.D., Pointer, I.R., 1994. An efficient method for estimating seagrass biomass. *Aquat. Bot.* 47, 277–292.
- Meinesz, A., 1977. Balisage de la limite inférieure de l'herbier de *Posidonia oceanica* en rade de Villefranche-sur-Mer (Alpes-Maritimes, France) – Rapp. P.V. Réunion Comm. Int. Explor. Sci. Medit. 24, 143–144.
- Meinesz, A., Laurent, R., 1978. Cartographie et état de la limite inférieure de l'herbier de *Posidonia oceanica* dans les Alpes-Maritimes (France) – Campagne Poseidon 1976. *Bot. Mar.* 21, 513–526.
- Meinesz, A., Cuvelier, M., Laurent, R., 1981. Méthode récentes de cartographie et de surveillance des herbiers de Phanérogames marines. *Vie Milieu* 31, 27–34.
- Orth, R.J., Heck, K.L.J., Van Monfrans, J., 1984. Faunal communities in seagrass beds. A review of the influence of plant structure and prey characteristics on predator-prey relationships. *Estuaries* 7, 339–350.
- Pasqualini, V., Pergent-Martini, C., Clabaut, P., Pergent, G., 1998. Mapping of *Posidonia oceanica* using aerial photographs and side scan sonar: Application off the Island of Corsica. *Estuar. Coast. Shelf Sci.* 47, 359–367 (France).
- Piazzesi, L., Acunto, S., Cinelli, F., 2000. Mapping of *Posidonia oceanica* beds around Elba Island (western Mediterranean) with integration of direct and indirect methods. *Oceanol. Acta* 23, 339–346.
- Rey, J., Diaz del Rio, V., 1989. Cartographia de los fondos marinos de la Bachia de Palma (Baleares, Espana): Distribución de las praderas vegetales y sedimentos superficiales. In: Boudouresque, C.-F., Meinesz, A., Fresi, E., Gravez, V. (Eds.), International Workshop on Posidonia Beds 2. GIS Posidone Press, Marseille, pp. 29–41.
- Sabol, B.M., Melton, R.E., Chamberlain, R., Doering, P., Haunert, K., 2002. Evaluation of a digital echo sounder for detection of submersed aquatic vegetation. *Estuaries* 25, 133–141.
- Short, F., Willie-Echeverria, S., 1996. Natural and human-induced disturbance of seagrasses. *Environ. Conserv.* 23, 17–27.
- Sultana, S., Komatsu, T., 2002. Preliminary study on shoot density and biomass of seagrass, *Zostera caulescens*, in Funakoshi Bay off the Sanriku Coast, Japan. *Otsuchi Mar. Sci.* 27, 23–27.
- Tatsukawa, K., Komatsu, T., Aioi, K., Morita, K., 1996. Distribution of seagrasses off Kirikiri in Funakoshi Bay, Iwate Prefecture, Japan. *Otsuchi Mar. Res. Cent. Rep.* 21, 489–494 (in Japanese).
- Ward, L.G., Kemp, W.M., Boyton, W.R., 1984. The influence of waves and seagrass communities on suspended particulates in an estuarine embayment. *Mar. Geol.* 59, 85–103.