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A cost-effective alternative for assessing the size of deep-water fish aggregations

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Abstract

Acoustic methodologies are important tools for monitoring deep-water fish and have the potential to provide high precision estimates of aggregation size. However, they can be costly to design and implement for monitoring fish. Data from two years of scientific surveys of the spawning aggregations of orange roughy (*Hoplostethus atlanticus*) on the Cascade Plateau, Tasmania, collected using commercial fishing vessels and echosounders, were used to develop a cost-effective approach for estimating the size of deep-water aggregations. Criteria were developed to standardise the identification of orange roughy echo-traces from acoustic data from 23 surveys in 2001 and 19 in 2005. The spawning condition of the fish was monitored simultaneously with the acoustics in each year (n = 29 trawls each year). The volumes of the aggregations were estimated throughout the survey period. Although the precision of the estimated aggregation size is low, large amounts of data can be collected over extended periods using this approach and the equipment on standard commercial fishing echosounders. Aggregation volumes varied markedly during each spawning season and changes in volume appear to be linked to the spawning biology. Monitoring the spawning biology therefore provides crucial complementary information for interpreting estimates of aggregation size from acoustic surveys.

Additional keywords:

Orange roughy, *Hoplostethus atlanticus*, bathypelagic, deep-water, spawning biology

Running head:

Assessing the size of deep-water fish aggregations

Introduction

With the depletion of many traditional shallow water fisheries, considerable fishing effort has shifted towards harvesting fish in deeper waters (> 500 m deep) (Morato *et al.* 2006). While some deep-water fisheries have existed for over a century (e.g. the Portuguese line fishery for black scabbardfish (*Aphanopus carbo*) (Gordon 2001a)) most new deep-water fisheries developed during the 1960s and 1970s (Roberts 2002). Advances in technology and equipment, as well as financial incentives from governments, encouraged these developments, and today over 40% of trawl grounds are in waters deeper than the continental shelf (Roberts 2002). Examples of species targeted in deep-water commercial fisheries are roundnose grenadier (*Coryphaenoides rupestris*) in the North Atlantic (Lorance *et al.* 2001), Pacific grenadier (*C. acrolepis*) (Merrett and Haedrich 1997) in the North Pacific, and blue grenadier (*Macruronus novaezelandiae*) and orange roughy (*Hoplostethus atlanticus*) in New Zealand and Australia (Koslow *et al.* 2000).

In general, many deep-water fisheries exhibit a typical ‘boom-bust’ cycle (Gordon 2001b; Haedrich *et al.* 2001) and are difficult to manage. Because many deep-water species are typically long-lived and slow-growing, with low fecundity, they are especially vulnerable to over-exploitation (Clarke *et al.* 2003). In addition, cost-effectively assessing the size and status of deep-sea stocks is difficult as this environment introduces challenges not faced in the shallower waters of continental shelf fisheries. For example, deep-sea fisheries often target large aggregations which violate the assumptions of constant catchability and random distribution of fish and complicate the use of commonly used abundance indices such as catch-per-unit-effort (Punt 2003). Furthermore, trawl and acoustic survey methodologies have additional problems in deep waters compared to those < 500 m deep, and this adds to the challenge of assessing deep-water stocks in a cost-effective way.

In this paper, we investigate the use of acoustic and biological data, collected from commercial fishing vessels in surveys of the winter spawning aggregations of orange roughy (*Hoplostethus atlanticus*) on the Cascade Plateau, south-eastern Australia, as a cost-effective technique to assess the size of deep-water aggregations for monitoring changes in stock size over time. The Cascade Plateau is a rocky seamount located approximately 230 km east-south-east of Hobart, Tasmania (Figure 1). Australian vessels began regularly fishing the Cascade Plateau in 1996, at a time when tighter management controls on more easily accessible orange roughy aggregations around Tasmania encouraged fishers to venture further offshore. Annual scientific surveys were conducted using commercial fishing vessels to collect acoustic and biological data on the winter spawning aggregations of orange roughy from 1999 until 2008. This study uses acoustic and biological data from the 2001 and 2005 surveys of the spawning aggregations of orange roughy on the Cascade Plateau. Both these years were thought to be years when large shoals of spawning fish were present.

The orange roughy is a slow-growing, long-lived species, and is one of the best known examples of a deep-water commercially valuable fish. Orange roughy are commonly found along the mid-slope depths of 450-1 800 m in the temperate regions of the Atlantic, Pacific, and Indian oceans (Branch 2001). In the southern hemisphere, orange roughy form large spawning aggregations in mid-winter (Bell *et al.* 1992). These aggregations are predictable in time and space and thus easily targeted by commercial trawlers, making them highly vulnerable to overfishing (Branch 2001). Orange roughy also form large non-spawning aggregations and some evidence suggests that feeding rates increase during the formation of these non-spawning aggregations (Bulman and Koslow 1992). This species is well known for its extreme longevity (> 100 years) (Andrews *et al.* 2009) and late age-at-maturity (20-30 years) (Bell *et al.* 1992; Horn *et al.* 1998) and has supported large commercial fisheries in several countries including Australia, Chile, Namibia, and New Zealand (Branch 2001). The extreme longevity and slow growth of orange roughy means that length and age frequency distributions show little variation between years and cannot be used easily in assessment models (Branch 2001).

Several different techniques have been used to estimate the size of orange roughy spawning shoals. These include egg surveys (Zeldis 1993; Koslow *et al.* 1995b), trawl surveys (Clark 1996) and acoustic surveys (Kloser *et al.* 1996). Acoustic surveys appear to be the most efficient and cost-effective method for estimating the size of orange roughy spawning aggregations. Orange roughy have a low acoustic reflectivity due to the lack of an air-filled swim bladder, which, coupled with the depth of the aggregations, introduces significant challenges for using acoustics to accurately detect and measure the size of these aggregations (Kloser *et al.* 1997). The estimation of biomass from acoustic surveys depends upon a reliable estimate of the backscattering cross-section of orange roughy, a notoriously difficult parameter to estimate (Kloser *et al.* 1997), and a clear acoustic definition of orange roughy to distinguish it from that of surrounding highly reflective species (McClatchie and Coombs 2005).

Over the last decade, considerable technological advances have been made in acoustic methods, including the introduction of multi-frequency systems and towed bodies, to produce reliable estimates of the biomass of orange roughy spawning aggregations (e.g. Kloser 1996; Kloser *et al.* 2002; Ryan *et al.* 2009). However, these techniques are costly and require sophisticated equipment and expertise; they are not fitted as standard equipment on commercial vessels and the costs to industry and management may be prohibitive for monitoring fish stocks over larger geographic areas and extended periods of time such as throughout the spawning season.

Fish do not position themselves randomly within schools (Partridge *et al.* 1980) and a relationship between the volume and biomass of a fish school has been established for a number of pelagic species, including sardines (*Sardinops sagax*) (Coetzee 2000), pollock (*Pollachius virens*) (Pitcher and Partridge 1979), herring (*Clupea harengus*) (Pitcher and Partridge 1979; Misund *et al.* 1992), sprat (*Sprattus sprattus*) (Misund *et al.* 1992), and the demersal cod (*Gadus morhua*) (Pitcher and Partridge 1979). The aim of the current study was to use the data from acoustic and biological surveys of the spawning aggregations of orange roughy on the Cascade Plateau to investigate cost-effective alternatives for estimating and monitoring the relative size of deep-water aggregations. We hypothesised that during spawning individuals in the orange roughy school position themselves to maintain a packing density that is optimal for the successful mixing of gametes, as has been hypothesised for the spawning dynamics of other species (Johannes 1981; Johannes *et al.* 1999). Changes in the shape (particularly volume) of the schools approaching, during, and after spawning were hypothesised to be driven primarily by the imperative to achieve optimal packing density for spawning, and should therefore be consistent between years, relative to the time in the spawning cycle of the aggregation.

Although other fish species are found in orange roughy schools, trawl catches typically consist of over 90% orange roughy by number and weight (Kloser *et al.* 1996). The impact of a high number of small high reflective species can have a significant impact on any estimate of biomass produced by echo-integration techniques (Kloser *et al.* 1996). However, we assumed that the volume and shape of the typical orange roughy echo-traces is largely determined by the biomass of orange roughy and not influenced by the presence of other species. The terms ‘aggregation’ or ‘spawning aggregation’ are used throughout this paper to refer to the large schools of orange roughy, observed as distinct echo-traces on the echosounders (Figure 2).

Methods

Survey design

Two commercial fishing vessels were used to survey the Cascade Plateau orange roughy aggregations in both 2001 and 2005, although the actual vessels used in the surveys differed between years. The timing of the surveys was established from prior experience with sampling the spawning aggregations of orange roughy on the Cascade Plateau. The 2001 surveys commenced on 18 June and continued until June 30. Surveying ceased on 21 June because of severe weather and could not be recommenced until June 28. In 2005, the surveys commenced on 21 June and progressed until July 3. In both years, commercial fishing of the Cascade Plateau was closed under voluntary agreement during the surveys, and the operation of the each survey vessel was under the direction of two onboard scientists. The fishing industry and Australian Fisheries Management Authority (AFMA) allocated a scientific quota of 100 tonnes for the surveys, survey vessels sold their catch and the proceeds were used to cover both vessel operating and scientific costs.

The surveys used an adaptive search method; knowledge of the aggregations' characteristics was used to focus the searching on areas where the spawning aggregations were likely to be located – a small ridge which runs along the 700-m depth contour of the western flank of the seamount (Figure 1). The echo-traces of the orange roughy aggregations are distinct and easily identifiable on the commercial echosounders (Figure 2). After locating an orange roughy aggregation, a series of tight east-west transects were traversed repeatedly over the length of the aggregation running north to south. The duration and distance between transects varied between surveys, with most surveys taking between one and three hours. The movement of the aggregation during a survey would result in a bias; either underestimating or overestimating aggregation size, depending on which direction the fish are moving relative to the survey (Misund 1997). When the echo-traces of the orange roughy were no longer observed on the echogram of the east-west transects, the vessel returned over the previously surveyed ground in a north-south direction to determine if the aggregation was relatively stationary during the survey (Figure 1). The survey was considered completed when the north-south transect, referred to as the tie-line, was concluded. If possible, and depending on the research plan, a trawl shot was directed at the surveyed aggregation, immediately after the acoustic survey (average duration 1 to 2 hours). Only surveys where the tie-line indicated that the aggregation was relatively sedentary were included in the analysis. On some occasions, the aggregation was very mobile and it was not possible to find the aggregation on the second transect. In these instances, the survey was aborted, and the vessel returned to searching the plateau for a stable aggregation.

Collection of biological data

When possible, a sample of 100-200 orange roughy was randomly taken from each survey trawl shot, to record sex and macroscopic gonad stage. Gonads were staged according to a protocol developed by the New Zealand National Institute of Water and Atmospheric Research (NIWA), based on Pankhurst *et al.* (1987). The sex ratio and proportion of female fish at each spawning stage were determined for each day of the survey. Twenty-nine successful trawl shots were completed in each year (Tables 1 and 2).

Collection of acoustic data

Initially, the surveys aimed to map the location and extent of the orange roughy aggregations on the plateau, using the industry standard 28-kHz Furuno echosounders on commercial fishing vessels. In 2003, the commercial vessels were upgraded to the new industry standard 38-kHz Simrad ES60 echosounders, capable of logging acoustic data of sufficient quality for echo-integration, with the aim of estimating the biomass of the orange roughy. In 2001, the acoustic data were logged using EchoListener units, installed in parallel to the vessels' echosounders, which were not calibrated. Therefore, the data collected in 2001 can be used to investigate changes in estimated size of the aggregations during the spawning season but not compared with estimates of aggregation size in other years. The Simrad ES60 echosounders used in 2005 were capable of directly logging onto hard drives and were calibrated prior to the survey (Foote *et al.* 1987).

Pre-processing of acoustic data

The acoustic data were processed in Echoview V4.70 (Myriax 2009). The minimum display and processing threshold for the uncalibrated data in 2001 were determined empirically, to display an echogram which both fishers and scientists identified as echo-traces of orange roughy. The empirically determined minimum display and processing thresholds for the 2001 vessels were -49.00 and -40.00 dB respectively, with a 36.00 dB display range. The minimum display and processing thresholds for 2005 were both -65.00 dB, with a 36.00 dB colour display range. An automatic seafloor line detection algorithm was applied to all echograms, and manually corrected as necessary. To avoid the potential inclusion of the seafloor in any analysis, a fixed offset line of 4 m was applied to the auto-detected bottom line. An upper exclusion line was applied to all echograms, offset 200 m above the bottom offset line. Only parts of the echograms within the boundaries of these two lines were analysed. Some parts of the echograms were affected by poor weather and marked as 'bad data'. However, none of the 'bad data' sections included echo-traces of orange roughy.

School detection and echo-trace classification

The Echoview school detection algorithm was used to detect and define the echo-traces for both years. To be considered as a valid candidate for orange roughy, Echoview was set to detect only echo-traces that exceeded a minimum total school length and height of 80 and 10 m respectively, a minimum candidate length and height of 10 and 2 m respectively (candidate length is the length of a single echo-trace considered part of the school), and a maximum vertical and horizontal linking distance of 25 m. The resulting echo-trace candidates were evaluated against the following criteria: 1) located in waters between 700 – 750 m in depth (in general, echo-traces in waters shallower than 680 m were not accepted as orange roughy), 2) on or closely associated with the seafloor, with an average volume backscattering strength (S_v) of between -61 and -57 dB in 2005 (not applicable to 2001), 3) ‘typical school shape’ as determined by fishers and researchers, and 4) if possible, verified by trawl samples of the aggregation. Echo-traces that fulfilled these criteria were accepted as orange roughy (see Figure 2)

Validation of criteria

The Cascade Plateau catch records from 1999-2003 were examined to validate the criteria used to classify the echo-traces as orange roughy. The commercial fishers who contributed their knowledge to developing the visual criteria used on the Cascade Plateau had an extensive knowledge of orange roughy fishing, developed over many years of fishing other orange roughy aggregations in southern Australian. During the developmental years of the Cascade fishery (1996-1998), before the spawning aggregation was discovered, fishing took place throughout the year and virtually all echo-traces of fish schools were trawled in an effort to catch orange roughy. With this experience, skippers refined their fishing practices, discovered the aggregation of orange roughy during the winter months and were able to narrow the criteria for identifying a ‘typical’ echo-trace of spawning orange roughy from commercial hull-mounted echosounders at the Cascade Plateau. These criteria were developed to provide a conservative, reliable, indicator of spawning biomass, accepting that a mix of other species will be present around the main area of the orange roughy aggregations. These criteria were developed to exclude ambiguous echo-traces that were likely to contain at some time a dispersion of orange roughy mixed with other species. When validating the criteria with survey shots, we expected to find catches of between hundreds and thousands of kg of orange roughy (usually > 90% by weight) from echo-traces conforming to our criteria. If trawl shots were directed at ambiguous echo-traces, the catches often consisted entirely of other species, with occasionally a small proportion of orange roughy (e.g. <10%). Extensive verification sampling in the early years of the spawning surveys and examination of the commercial catch records indicated that echo-traces against the bottom, but above the 680-m depth contour very rarely contained large quantities of orange roughy. Therefore, echo-traces in water shallower than this depth were not accepted as orange roughy.

Estimation of aggregation size

A survey was defined as a set of contiguous transects, with echo-traces accepted as orange roughy, completed by a tie-line joining the two bounds of the survey where echo-traces of roughy were last found. Twenty-three surveys were completed of the orange roughy spawning aggregation in 2001 and 19 in 2005 (Tables 1 and 2). The cross-sectional area of the orange roughy echo-trace in each transect was calculated in Echoview, which automatically corrects for the distortion due to beam geometry (see Diner 2001). The mean and standard area of the cross-sectional area of each survey was calculated. The length of the aggregation was defined as the north-south extent of the aggregation, and was estimated as the great circle distance (i.e. the shortest distance between two points on the sphere approximating the size of Earth) between the mid-point of the first and final transects (Figure 1).

The volume of each survey was calculated as the mean cross-sectional area multiplied by the aggregation length. Data on the number of transects, duration of survey, aggregation length, mean volume backscattering strength (S_v), mean area of the echo-traces and the mean depth of the centre of the echo-trace were exported from Echoview and tabulated in a database. A Student's t-test was used to test for significant differences between these variables between 2001 and 2005.

Results

Spawning biology

Female fish with ripe (stage 4) and running ripe gonads (stage 5) comprised over 70% of the orange roughy from the trawl survey samples in 2001 and 2005 (Figure 3). Few female fish were identified with maturing or spent gonads (< 10%). The sex ratio varied considerably both within and between years. For example, in 2005, the proportion of females ranged from >90% on 24 June to <5% on June 28 (Figure 4a).

Approximately 40% of female fish had ripe gonads, and almost 30% were running ripe on June 18 2001, indicating that spawning had commenced before the start of the 2001 survey (Figure 4b). On June 28 2001, the proportion of females with running ripe gonads had increased to approximately 70%, with <20% of females having ripe gonads (Figure 4b). The sex ratio had decreased considerably at this time, with females accounting for 11-30% of the fish (Figure 4a).

Biological samples from each day of the 2005 survey show a clear progression of gonadal development, with a high prevalence of female fish with ripe gonads early in the season, and an increase in the proportion of female fish with gonads at the running ripe stage as the season progressed (Figure 4c). The proportion of females with running ripe gonads was <12% before 26 June 2005, peaked at 80% on 30 June and remained above 65% until the end of sampling on 3 July 2005 (Figure 4c). Females comprised 35-80% of the sampled catch between 29 June and 3 July 2005 (Figure 4a). In 2001, >25% of female fish were observed with running ripe gonads on June 18 (Figure 4b). Spawning appeared to commence later in 2005, with the proportion of females with running ripe gonads first exceeding 25% on June 27 (Figure 4c).

Acoustic surveys

The orange roughy spawning aggregations were located in the same general region on the Cascade Plateau in 2001 and 2005, predominantly along the 700-m contour on the western edge of the seamount (Figure 1). The mean depth of the shoals did not differ significantly between 2001 and 2005 ($t_{40} =$ -0.77, P = 0.22), however the mean length of the 2001 surveys was significantly longer in 2001 than in 2005 (t_{32} = -3.3, P= 0.001, Tables 1 and 2). The mean duration and mean distance between transects of the acoustic surveys did not differ significantly between years (t_{36} = -1.4, P=0.09, and t_{40} = -1.4, P=0.08 respectively), although there was significantly more transects of the aggregation for each survey in 2001 than 2005 (t_{30} = -3.2, P= 0.001, Tables 1 and 2). The mean area of the echo-traces and the mean estimated volume of the shoals did not differ significantly between vessels in either 2001 (t_{19} = 0.8, P= 0.2, t_{21} = 0.07, P= 0.5 for area and volume respectively) or 2005 (t_5 = -0.01 P= 0.5, t_{17}, = 0.8, P= 0.2 for area and volume respectively).

The estimates of area and volume from the 2001 survey are only useful as relative measures to detect high and low abundance echo-traces because the echosounders were not calibrated before this survey. While aggregation length did not vary greatly during the season, the relative volume of the shoals and the mean area of the echo-traces appeared to decline as the survey progressed (Table 1). The mean volume and area from the last three days of sampling (28-30 June) were >40% of the mean values from the first four days of sampling (18-21 June, Table 1).

In 2005, the maximum estimated daily mean volume of the orange roughy aggregation was 8.30 million m^3 ± 6.85 (= 1 SE) on June 26 with the peak volume (22 million m^3) measured between 08:04 and 09:23 (Figure 5, Table 2). However, the volume of the aggregation varied greatly on this day (coefficient of variation = 143%, range of volume estimates = 1.42 – 22 million m^3). At 05:00 and 22:00 the estimated volumes were only 6% of the peak morning volume, with greater variation in the mean area of the echo-traces than in the length of the aggregation (Table 2, Figure 5). The estimated aggregation volume appeared to be most stable on 27 and 28 June 2005, with a mean volume of 6.78 million m^3 ± 0.58 (CV =17%, Figure 5). This period of relative stability coincided with an increase in the proportion of running ripe fish in the trawl samples (Figure 4c). The volume of the aggregation decreased on the last two days of sampling, with the smallest volume of 0.35 million m^3 measured on June 29 and a mean volume of 1.17 million m^3 ± 0.38 (CV =56%, Table 2, Figure 5) on June 30.

Discussion

The methodology developed in this study attempts to provide an estimate of aggregation metrics (volume and mean echo-trace area) that can be measured readily in future years and match these metrics with the spawning condition of the aggregation. It does not attempt to measure all orange roughy present on the seamount nor does it aim to provide an absolute estimate of the volume or biomass of the orange roughy population on the Cascade Plateau. The variation in size of the aggregations, both in volume (Figure 5), and presumably also biomass, demonstrates that it is crucial that any comparison of aggregation size between years must take into account the intra-seasonal variation in spawning condition of the aggregation. The exact relationship between the volume and the biomass of an orange roughy aggregation is not known and changes in packing density of the fish in the aggregation will affect the volume of an aggregation while leaving the biomass unchanged. If the packing density of an aggregation is related to its biological behaviour (i.e. in this case, the spawning condition and behaviour of orange roughy), estimates of aggregation size must be interpreted within the context of the spawning biology of the fish.

Spawning dynamics of orange roughy on the Cascade Plateau

In 2005, the maximum volumes occurred on the afternoon of June 25 and the early hours of June 26, when most females were ripe and <10% of females were running ripe. The sex ratio of the aggregation appeared to be highly skewed at this time, with female fish comprising 80% of the catch. However, at this time, the size of the orange roughy shoals was very dynamic and fluctuated greatly in cross-sectional area and volume over a 24-hour period (Figure 5). The volume of the orange roughy shoal was relatively stable when proportionally more fish were running ripe and the proportion of ripe females had decreased (Figures 4 and 5). In 2001, the greatest volumes of the aggregations were measured when the proportion of running ripe fish were >30% (Figure 4). In 2001, the estimated volume of the orange roughy aggregations appeared to decrease as the spawning season progressed (Table 1). Towards the end of the season, following six days when poor weather conditions prevented surveying, the volumes and cross-sectional area of the echo-traces were much lower than those at the start of the surveys. The large changes in the prevalence of actively spawning female fish and the decline in percentage of female fish in the shoal after June 27 indicate that some major change in the characteristics of the aggregation had taken place in the previous six days (Figure 4b). Furthermore, the low number of spent fish in the trawl samples from both years suggests that fish leave the aggregation immediately after spawning.

Sources of bias

The technique presented in this paper relies on a number of critical assumptions and has other sources of bias that cannot be quantified readily. This methodology assumes that the position of the aggregation is stable in time and place during each survey and, as a consequence, is best applied to slow-moving large schools. The results of this study suggest that the aggregations of orange roughy on the Cascade Plateau can vary greatly in area and volume during the spawning season and that the spawning biology appears to be the underlying driver behind these changes in behaviour. The results highlight the need to interpret the estimates of aggregation size in the context of the spawning biology, particularly the stage of gonad development and sex ratio of the aggregation.

Acoustic data collected from periods when the orange roughy aggregations are very dynamic (i.e. the aggregations are moving too much to complete a survey (1-2 hours)), cannot be used in the estimation of aggregation volume by this method. While we were able to estimate the variability in the area of the echo-traces by the repeated transects across the aggregation, we were not able to estimate the variability in the length of the shoals. The measurement of variability in the cross-sectional area of the echo-traces is related to the number of transects across the aggregation and the distance between consecutive transects. Increasing the number of cross-aggregation transects and decreasing the distance between these transects increases the time that the survey will take, and hence the possibility that the aggregation has changed in position or shape. The results of this study suggest that it is possible to effectively survey the orange roughy aggregations on the Cascade Plateau within 1-2 hours with a distance between transects of 300 to 400 m. However, the optimal distance between transects is a matter for further research.

Acoustic surveys of species associated with the seabed are confronted with the issue of the acoustic dead zone, a region where fish cannot be detected because of interactions between the acoustic signals of the fish and the seafloor (Ona and Mitson 1996). The area and influence of the acoustic dead zone is affected by topography and is greater on steep seafloors, with the strong acoustic signal from the steep sides effectively shadowing the signal from fish close to the seabed. The effect of the acoustic dead zone can be reduced by using very narrow beam-width echosounders or deep-towed transducers (Kloser 1996). However, neither of these methods can be used on commercial vessels equipped with only commercial fishing echosounders. In this study, we have assumed that the proportion of orange roughy shadowed by the dead zone is likely to be consistent between surveys because the aggregations are found in the same general area and in similar depths (i.e. along the 700 m contour on the western bank of the plateau (Figure 1)).

Cost-effective alternative method to estimating size of deep-water shoals

The various sources of bias in this method are likely to affect the precision of any estimate of volume of the aggregations. However, we argue that the methodology described in this paper provides a technique to rapidly and cost-effectively estimate the relative size of deep-water aggregations of orange roughy. It also engages industry in the collection of data that will be used in the stock assessment. Recently developed techniques, such as multi-beam, deep-towed echosounders, have the potential to considerably increase the precision of estimates of biomass of orange roughy aggregations (Kloser 1996; Ryan *et al.* 2009). However, these techniques present other challenges, and require expensive and sophisticated equipment and expertise. For example, orange roughy show avoidance behaviour to deep-towed instruments (Koslow *et al.* 1995a) and, in response to a towed instrument, 200-m high plumes of fish have been observed to compact to a much smaller mark, about 25 m high (McClatchie *et al.* 2000). Furthermore, the duration of sampling is often restricted in time and spatial extent due to the cost and resources required to deploy this more sophisticated acoustic equipment. The results from this study indicate that the behaviour of the orange roughy spawning aggregation on the Cascade Plateau varies between years. Clearly, the ability to sample throughout the entire spawning season provides much beneficial information for any monitoring of the size and spatial location of the spawning aggregation. The technique outlined in this paper allows large amounts of biological and acoustic data to be collected that provide good spatial-temporal coverage of aggregations, with little additional costs to those of normal commercial fishing operations.

The winter spawning aggregations of orange roughy on the Cascade Plateau were acoustically surveyed and only fished under research permit from the time of their discovery in 1999 until 2008. This is the only known time series in the world of long-term data for spawning aggregations of orange roughy. In addition to having the potential to investigate interannual variation in aggregation volume, these data allow the aggregation volume and spawning dynamics to be investigated in each spawning season. A number of potential indices of abundance could be used to compare aggregation sizes between years. For example, the mean volume of the aggregation over a number of surveys, selected by standardising by spawning biology, could be monitored between years. Alternatively, the size of the aggregation at initiation of spawning could be a useful index of abundance. The full extent to which this technique can be applied to monitoring the size of deep-water orange roughy aggregations will not be apparent until this methodology is applied to a number of consecutive years of data. Nonetheless, the results from these two years suggest that this methodology could be applied to both past and future surveys of the orange roughy aggregations on the Cascade Plateau.

The technique demonstrated in this paper provides a large amount of data on the dynamics of a spawning aggregation, uses relatively simply techniques and is low in cost. However, the trade-off for the ability to collect large amounts of data is the probability that these data will have low precision. The value of a large, low-precision data set, opposed to a small dataset with high precision for any given fishery depends on a number of factors, including economic value of the fishery and the financial cost of other techniques. While this method is not limited to deep-water species, it is particularly applicable to deep-water highly aggregating species like orange roughy because these species are typically difficult to assess, especially in a cost-effective way (Clark 1996). The concurrent collection of data on the spawning condition of the fish is an essential part of this method as the acoustic data can only be compared between years when they have been standardised to the same time in the spawning cycle of the fish.

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Figures

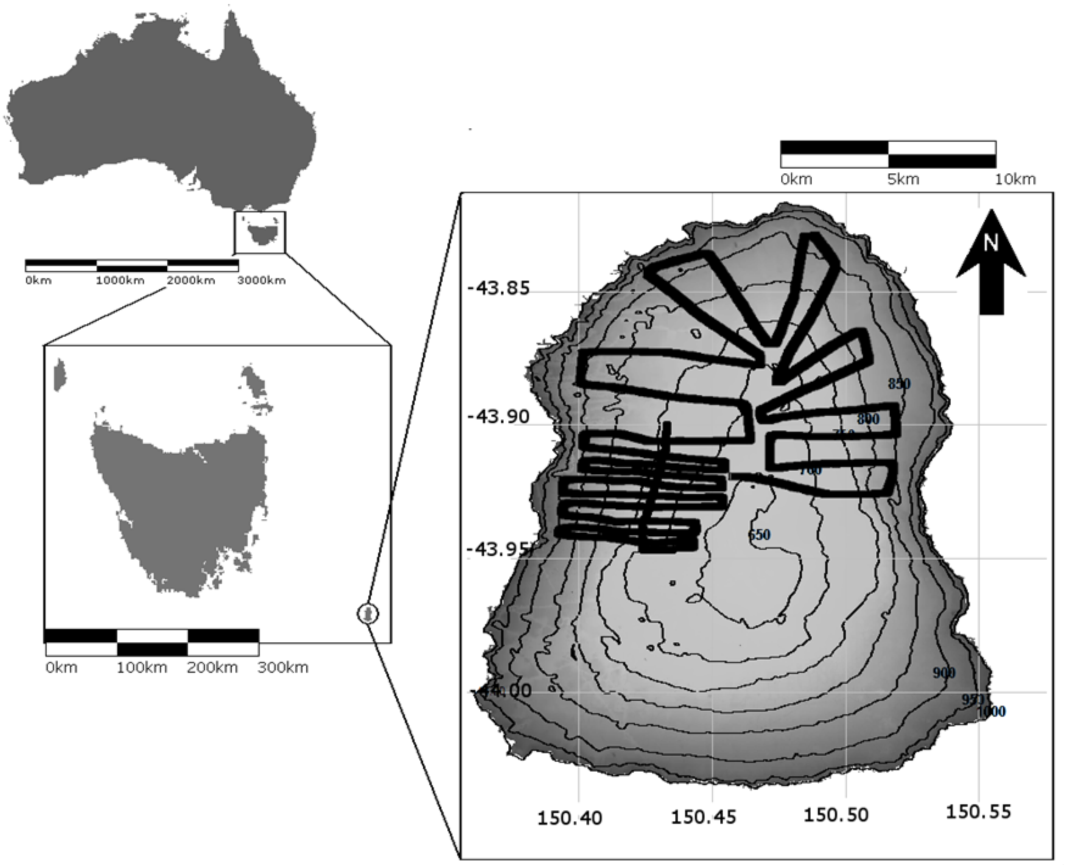

Figure 1

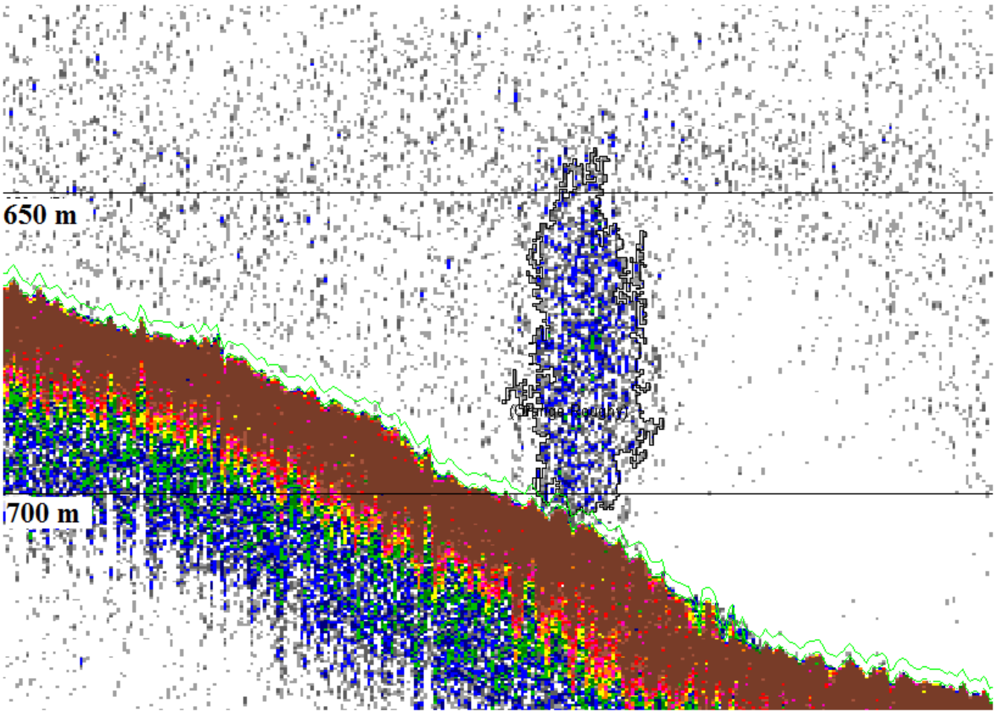

Figure 2

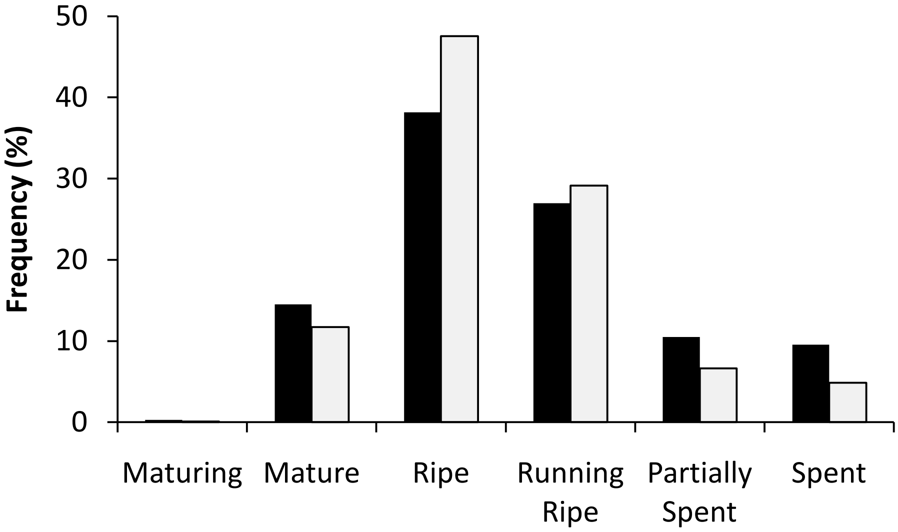

Figure 3

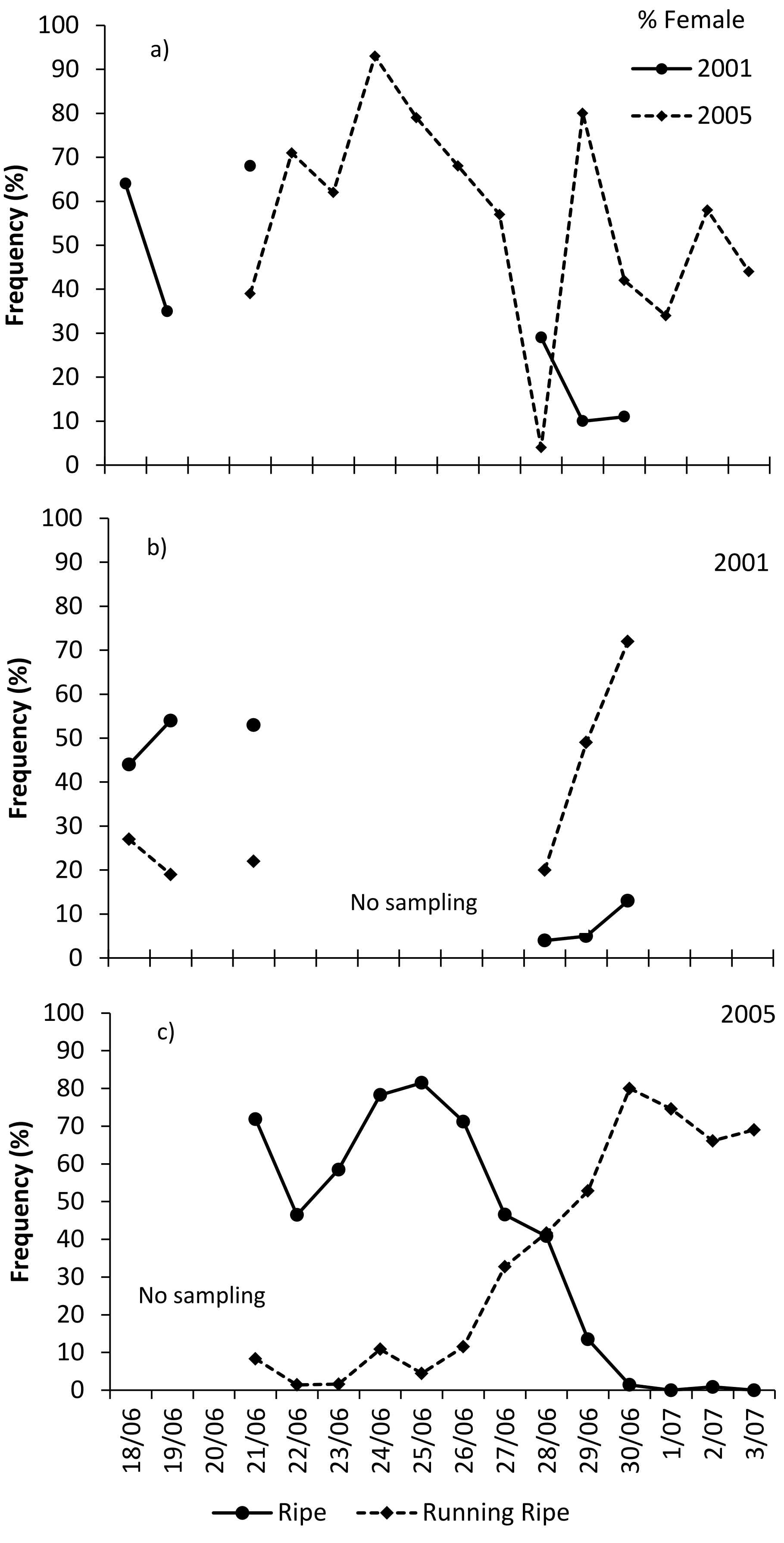
a)
% Female
2001
2005
b)
2001
No sampling
c)
2005
No sampling
Frequency (%)
0
10
20
30
40
50
60
70
80
90
100
18/06
19/06
20/06
21/06
22/06
23/06
24/06
25/06
26/06
27/06
28/06
29/06
30/06
1/07
2/07
3/07
Ripe
Running Ripe

Figure 4

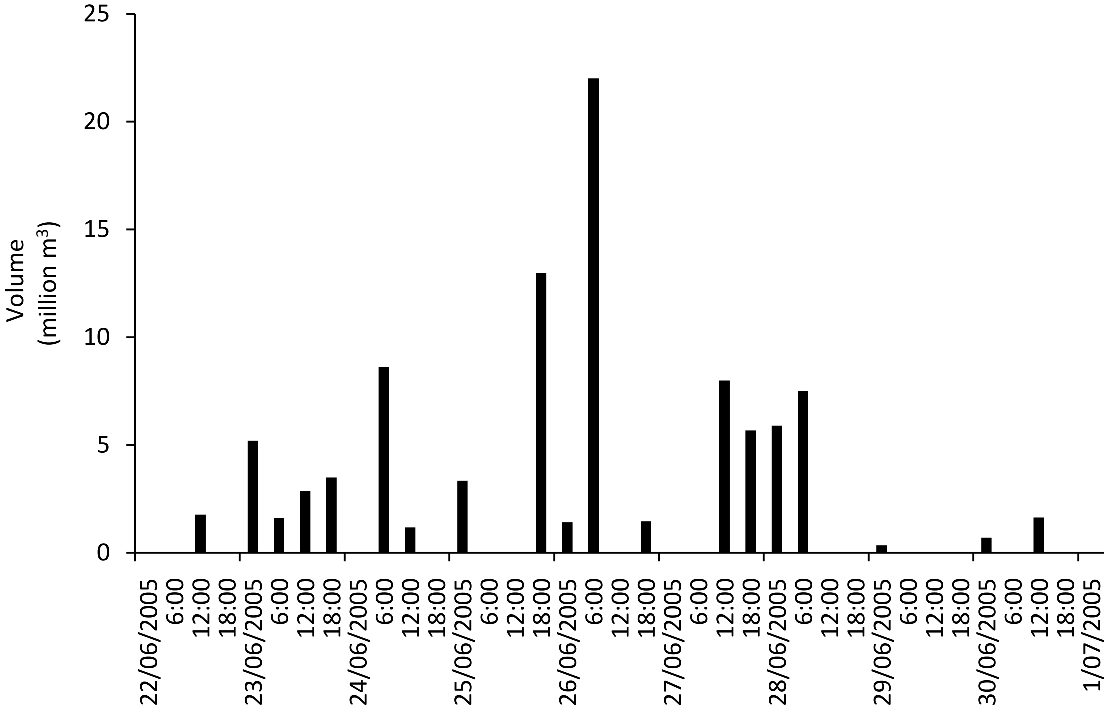

Figure 5

Figure captions

Figure 1 A typical search pattern (solid black line) for the orange roughy aggregation on the Cascade Plateau, Australia (depth in metres). The aggregation was located on the mid-western side of the seamount, as indicated by the close transects. The ‘tie-line’ extends northwards through the previously surveyed aggregation.

Figure 2 Typical echo-trace of a transect across a spawning aggregation of orange roughy on the Cascade Plateau, south-eastern Australia. The aggregation is touching the seafloor in 705-m depth, and extends about 60-m above the seabed. The 4-m bottom offset line is visible as a thin green line.

Figure 3 Frequency of gonadal development stages from female fish sampled at the Cascade Plateau in 2001 and 2005.

Figure 4 The a) ratio of female fish in sample catches of orange roughy at the Cascade Plateau in 2001 (solid line) and 2005 (dashed line), and proportion of female fish with gonads at ripe (solid) and running ripe (dashed) for the b) 2001 and c) 2005 surveys of the Cascade Plateau. There was no sampling from 22-27 June 2001 due to extreme weather. Arrows indicate the time of maximum aggregation volume.

Figure 5 Volume (million m^3) of the orange roughy spawning aggregation at the Cascade Plateau in 2005. The x-axis is divided into 6-hour segments.

Table captions

Table 1 Characteristics of individual acoustic surveys for each day of the survey of the orange roughy spawning aggregation on the Cascade Plateau, south-eastern Australia, during 2001. Mean transect distance is the mean distance (in metres) between transects for each survey. Mean S_v is the mean of the volume backscattering strength from each transect. Actual distance presented when only two transects completed. Length is the north-south extent of the aggregation. Mean depth is the mean depth of the centre of the echo-traces for each survey.

Table 2 Characteristics of individual acoustic surveys for each day of the survey of the orange roughy spawning aggregation on the Cascade Plateau, south-eastern Tasmania, during 2005. Mean transect distance, S_v, actual distance, length and mean depth defined in Table 1.

Tables

Table 1

Date and vessel	Time	Duration (mins)	# transects	Mean transect distance (± SE)	Mean S_v (dB ± SE)	Length (m)	Mean depth (m ±SE)	Mean area (m^2 ± SE)	Volume (million m^3)
18 June									
I	1409	124	8	481 (37)	-34.58 (0.43)	1823	691 (12)	13723 (3352)	25.02
I	2226	126	5	540 (52)	-35.54 (0.39)	1462	685 (6)	19617 (2799)	28.69
Mean 18th (± SE)		125 (1)	6.5 (1.5)	510 (29)	-	1642 (180)	688 (3)	16670 (2946)	26.86 (1.83)
19 June									
I	0900	70	6	618 (84)	-35.75 (0.21)	2441	707 (5)	4113 (904)	10.04
II	1314	96	7	587 (155)	-43.77 (0.18)	3256	713 (5)	11096 (2792)	36.13
I	1605	119	11	321 (60)	-37.89 (0.52)	2926	699 (5)	11668 (3279)	34.15
II	2032	98	9	273 (50)	-43.41 (0.22)	1725	679 (3)	17781 (3338)	30.69
Mean 19th (± SE)		95 (10)	8.3 (1.1)	449 (88)	-	2587 (332)	700 (7)	11164 (2795)	27.78 (6.01)
20 June									
I	0638	82	4	501 (80)	-36.90 (1.14)	774	671 (7)	36494 (8065)	28.27
II	1007	84	10	344 (40)	-42.77 (0.52)	1347	697 (3)	18723 (4733)	25.22
I	1459	63	5	448 (51)	-35.67 (0.19)	1444	694 (7)	11411 (5799)	16.48
II	1555	73	8	341 (80)	-41.57 (0.72)	1312	692 (4)	13381 (5573)	17.56
I	2101	72	5	356 (107)	-37.75 (0.61)	1346	684 (6)	23475 (8891)	31.59
Mean 20th (± SE)		74 (3)	6.4 (1.1)	398 (32)	-	1244 (119)	687 (4)	20696 (4477)	23.82 (2.96)
21 June									
I	0325	45	3	352 (36)	-38.58 (0.65)	649	667 (4)	21699 (12798)	14.07
I	0623	69	6	415 (27)	-37.51 (0.57)	1866	663 (4)	14737 (4368)	27.50
I	1151	410	10	317 (120)	-35.62 (0.23)	1358	693 (3)	6587 (888)	8.94
II	2356	48	5	467 (116)	-41.87 (0.49)	1842	688 (4)	10973 (3137)	20.22
Mean 21st (± SE)		143 (89)	6 (1.5)	387 (33)	-	1428 (285)	677 (7)	13499 (3200)	17.68 (4.00)
28 June 2001									
I	1354	319	20	486 (73)	-36.91 (0.47)	5891	696 (5)	3116 (671)	18.36
II	1714	50	7	566 (206)	-47.16 (0.61)	3291	698 (6)	3404 (880)	11.20
I	2149	191	7	449 (119)	-37.95 (0.49)	2074	705 (8)	8451 (1546)	17.52
Mean 28th (± SE)		186 (77)	11.3 (4.3)	500 (34)	-	3751 (1125)	699 (3)	4990 (1732)	15.70 (2.26)

Table 1 continued

Date and vessel	Time	Duration (mins)	# transects	Mean transect distance (± SE)	Mean S_v (dB ± SE)	Length (m)	Mean depth (m ±SE)	Mean area (m^2 ± SE)	Volume (million m^3)
29 June 2001									
I	0934	9	2	275	-35.90 (0.80)	276	696 (3)	4679 (1216)	1.29
II	1045	63	6	556 (244)	-43.63 (0.84)	2605	706 (5)	2186 (478)	5.69
I	1949	145	7	730 (228)	-37.43 (0.31)	4162	708 (8)	1762 (382)	7.33
II	2211	27	4	118 (40)	-44.65 (0.33)	248	708 (9)	2139 (517)	0.53
Mean 29th (± SE)		61 (30)	4.8 (1.1)	419 (137)	-	1822 (955)	704 (3)	2691 (669)	3.71 (1.66)
30 June 2001									
I	0100	88	4	593 (258)	-38.35 (0.51)	1164	695 (9)	10444 (4032)	12.16
Overall Mean (±SE)		107 (19)	7 (0.8)	440 (29)	-	1969 (270)	693 (3)	11811 (1771)	18.64 (2.19)

Table 2

Date and vessel	Time	Duration (mins)	# transects	Mean transect distance (± SE)	Mean S_v (dB ± SE)	Length (m)	Mean depth (m ±SE)	Mean area (m^2 ± SE)	Volume (million m^3)
22 June									
I	1701	47	3	1039 (422)	-60.02 (2.26)	2079	700 (11)	855 (182)	1.77
23 June									
I	0031	152	6	392 (94)	-60.60 (0.38)	1409	703 (8)	3695 (1128)	5.21
II	0119	12	2	594	-59.12 (0.15)	594	682 (19)	2726 (1192)	1.62
II	1156	33	4	526 (160)	-59.54 (0.55)	1044	686 (8)	2751 (755)	2.87
II	2121	55	4	510 (151)	-58.65 (0.17)	1519	724 (4)	2302 (869)	3.50
Mean (± SE)		63 (31)	3.8 (0.9)	505 (42)	-59.48 (0.42)	1141 (209)	698 (10)	2868 (294)	3.30 (0.75)
24 June 2005									
II	1051	64	5	474 (96)	-60.03 (0.65)	1803	690 (8)	4780 (1245)	8.62
II	1316	57	3	168 (41)	-57.63 (1.58)	262	693 (2)	4487 (522)	1.18
Mean (± SE)		60 (3)	4 (1)	321 (153)	-58.83 (1.20)	1032 (770)	691 (2)	4633 (147)	4.90 (3.72)
25 June 2005									
II	0340	67	4	291 (34)	-58.37 (0.08)	808	696 (11)	4135 (995)	3.34
I	2019	88	6	391 (49)	-60.52 (0.37)	1737	682 (6)	7479 (2014)	13.00
Mean (± SE)		77 (10)	5 (1)	341 (50)	-59.44 (1.08)	1272 (464)	688 (7)	5807 (1672)	8.17 (4.82)
26 June 2005									
II	0443	48	3	386 (50)	-59.16 (0.93)	771	698 (9)	2026 (732)	1.42
II	0907	79	5	362 (49)	-59.81 (0.62)	1333	663 (3)	16504 (4202)	22.00
II	2142	19	3	273 (81)	-60.87 (0.48)	457	685 (1)	3204 (1165)	1.47
Mean (± SE)		48 (17)	3.7 (0.7)	340 (34)	-59.94 (0.50)	853 (256)	681 (10)	7244 (4642)	8.30 (6.85)
27 June 2005									
II	1410	63	6	298 (60)	-57.82 (0.79)	1242	683 (2)	6442 (1652)	8.00
II	1733	36	3	318 (21)	-59.61 (0.24)	631	675 (3)	9015 (2492)	5.69
Mean (± SE)		49 (13)	4.5 (1.5)	308 (10)	-58.72 (0.90)	936 (305)	678 (4)	7728 (1286)	9.84 (1.16)

Table 2 continued

Date and vessel	Time	Duration (mins)	# transects	Mean transect distance (± SE)	Mean S_v (dB ± SE)	Length (m)	Mean depth (m ±SE)	Mean area (m^2 ± SE)	Volume (million m^3)
28 June 2005									
II	0108	189	7	222 (22)	-58.35 (0.44)	1234	685 (4)	4788 (1803)	5.91
I	0809	180	5	262 (81)	-59.76 (0.57)	907	686 (6)	8297 (1965)	7.52
Mean (± SE)		184 (4)	6 (1)	242 (20)	-59.05 (0.71)	1070 (163)	685 (0.4)	6542 (1754)	6.72 (0.81)
29 June 2005									
II	0128	144	5	83 (20)	-57.02 (0.86)	237	695 (3)	1460 (315)	0.35
30 June 2005									
II	0457	51	2	220	-59.57 (1.17)	221	690 (5)	3204 (399)	0.71
II	1332	60	5	86 (16)	-58.00 (0.28)	187	693 (2)	8766 (740)	1.64
Mean (± SE)		55 (5)	3.5 (1.5)	153 (67)	-58.79 (0.78)	203 (17)	691 (2)	5985 (2780)	1.17 (0.47)
Overall Mean (±SE)		76 (12)	4.2 (0.3)	362 (49)	-59.18 (0.25)	972 (140)	690 (3)	5101 (849)	5.04 (1.22)