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Evaluation of a variable angle scanning method to estimate relative abundance and distribution of fish using a single-beam echosounder in shallow lakes

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The validity of a hydroacoustic procedure was assessed using a combination of horizontal and vertical scanning to map the distribution of targets and to estimate target density in a shallow lake. Three distribution patterns were created using 37–50 artificial targets (metal hex nuts) anchored at known positions. Real and acoustic maps were qualitatively similar. Aggregation indices estimated by hydroacoustics were within 15% of the real values. Target density ranged from 1 to 8 targets per 100 m^{-3}. Estimated target densities were within one target of the real values for 88% of our observations. The variable angle approach was used also to monitor daily and seasonal variations in fish distribution and relative abundance outside the littoral zone. Dace *Phoxinus eos* × *P. neogaeus* appeared to use the littoral as a refuge during the day and to migrate to the pelagic zone at dusk. The movements of dace outside the littoral zone were limited to the months of June–August. The variable angle acoustic approach can be useful to estimate fish distribution and relative abundance in shallow lakes.

Key words: hydroacoustics; variable angle scanning; single beam; fish; shallow lake; onshore–offshore migration; distribution pattern; relative abundance; *Phoxinus eos* × *neogaeus*.

INTRODUCTION

Fish abundance has been the focus of many studies because of its potential effect on a suite of biological processes such as fish growth (Backiel & Le Cren, 1967; Weatherley, 1972, 1976), survival (Cushing, 1971, 1974), and predation rates (Murdock & Bence, 1987). Furthermore, fish abundance partly determines the exploitation level that can be tolerated by a population (Hilborn & Walters, 1992).

Fish abundance is highly heterogeneous and the level of heterogeneity depends on the spatial and temporal scales of observation (Harden-Jones, 1968; McKeown, 1984). Adequate description of fish abundance and distribution is complicated further by the frequent use of highly selective gears such as gillnets (Hamley, 1975; Hansson & Rudstam, 1995; Pet *et al.*, 1995). Hydroacoustic systems have been argued to represent a more appropriate approach to describe fish distribution and to be less prone to problems of size selectivity (MacLennan & Simmonds, 1992; Gunderson, 1993). Echosounders are generally used by

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directing the transducer vertically from the surface towards the bottom. The volume sampled by the instrument is associated with the characteristics of the emitting source (beam pattern, frequency, source level) and to the depth of the water column (Foote, 1991). This situation, combined with the narrowness of most beam angles (which depends on the frequency and the size of the transducer), may represent the most important limitation to the use of echosounders in shallow lakes. Several authors have developed a side-scanning strategy which consists of directing the transducer of the echosounder along the horizontal axis. Side-scanning has been used in fisheries as a technique to count and map fish schools (Smith, 1970; Hewitt *et al.*, 1976; Smith, 1977; Gerlotto *et al.*, unpublished; Misund *et al.*, 1995), and to monitor relative fish abundance from a moving boat (Kubecka *et al.*, 1992, 1994) or from a stationary shore-based sonar (Gaudet, 1990; Mesiar *et al.*, 1990). However, in some particular situations, horizontal scanning alone may not give a complete picture of fish distribution patterns. Those situations can be encountered in lakes where fish migrate onshore–offshore and vertically, or when there is vertical segregation in fish depth distribution. One alternative approach may be to combine vertical and horizontal scanning (further referred to as the variable angle approach).

The objectives of the present work were (1) to evaluate the validity of the variable angle approach to estimate the distribution and relative abundance of targets; and (2) to perform a preliminary description of daily and seasonal variations of fish distribution patterns in a shallow lake using that approach.

MATERIALS AND METHODS

DESCRIPTION OF SET-UP

The study was performed in the west arm of Lake Croche (4·2 ha), at the Station de Biologie des Laurentides de l'Université de Montréal in the Lower Laurentian region of Quebec during 1992 and 1993. Lake Croche is an oligotrophic lake with a maximum depth of 11 m. Generally, the lake is covered with ice from November to April. Water temperature reaches a maximum of 20–24° C at the surface in mid-July. Temperature drops to 10–15° C at 4 m from the surface and ranges from 6 to 8° C at the bottom. Generally anoxic conditions are encountered below 4 m from the surface. Fish encountered in that lake include two piscivorous species, the brook charr *Salvelinus fontinalis* Mitchill and the lake trout *S. namaycush* (Walbaum); a bottom dwelling species, the white sucker *Catostomus commersoni* Lacépède; two species of cyprinid, the creek chub *Semotilus atromaculatus* Mitchill and an hybrid between the redbelly and finescale dace *Phoxinus eos* × *neogaeus* Cope; and one species of sunfish, the pumpkinseed sunfish *Lepomis gibbosus* L.

The variable angle approach was evaluated by comparing known distribution patterns and relative abundances of artificial targets to values obtained using hydroacoustics. Targets were detected using a single beam echosounder with a 200-kHz transducer (SIMRAD EY-200P). The transducer was installed at the extremity of a mobile pole and set at a depth of 0·8 m. This pole was positioned on a pair of axles: one to pivot the transducer in the horizontal plane and another to tilt the transducer in the vertical plane. The direction of the transducer's axis in the horizontal and vertical planes was determined using marks and protractors located on the axles. Hydroacoustic sampling was performed from a floating platform anchored at 50–60 m from shore (depending on the horizontal direction taken as reference) in a small bay (surface area: 3800 m^2, maximum depth: 9·5 m).

CALIBRATION

Calibration consisted of finding the settings that should be used to position the targets adequately and to estimate the volume sampled by the acoustic beam.

The settings recommended for vertical scanning are a pulse duration of 1·0 ms, a receiver gain of 3 (52 dB) and a time varied gain (TVG) function of 40 log*r* starting at 1·5 m (T. Lindem, Department of Physics, University of Oslo, pers. comm.). Using this arrangement, the hydroacoustic system could detect a target strength of −60 dB, and hence fish as small as *c.* 2 cm in length. The validity of these settings was evaluated for horizontal scanning by comparing the distance of targets as detected by the echosounder to real values (10, 20, 30, and 40 m from the transducer). Two types of targets were used: a standard copper sphere (target strength, TS = −44·1 dB) and live fish (the hybrid of redbelly and finescale dace; 60 mm total length). The theoretical determination of the target strength of those fish was −52 dB (TS = 20 log*L* − 68; Lindem & Sandlund, 1984; Bjerkeng *et al*., 1991). These targets were suspended at 0·8 m from the surface of the lake to maximize the probability of positioning the targets in the middle of the transducer's axis. The original settings were valid for both vertical and horizontal scanning, except that the TVG start was set higher (4·0 m) to minimize noise saturation, since the system received more interference from the surface when scanning horizontally.

The volume sampled by the transducer was estimated using the geometric equation for a cone. This equation requires values of the beam angle and of the maximum distance at which a target could be recorded. Although the theoretical beam angle was provided by the manufacturer (−3 dB half-beam angle of 3·5°), the effective beam angle was estimated in the field. During horizontal scanning, the calibration sphere was hauled perpendicularly to the axis of the beam at a depth of 0·8 m and at distances of 10, 20, 30 and 40 m from the transducer. The angular position of the calibration sphere as it entered and exited the beam was noted using a protractor installed on the platform on which the transducer was located. The effective beam angle determined using this approach was 11° (± 0·5°). This value did not vary within the range of distances used from the transducer. The procedure was repeated with the use of a wired live fish and gave the same result, within the range of distances adopted (10–40 m). The maximum distance from the transducer at which a target could be discriminated from the background (bottom of lake or shore) ranged from 35 to 50 m during horizontal scanning and from 7 (directing the transducer downward) to 35 m during transversal scanning.

VALIDATION

The validity of the variable angle approach to position targets adequately, was evaluated using three combinations of abundance and distribution patterns. The three distribution patterns represented different degrees of regularity (from clumpiness to uniformity). Each pattern was created by installing 37–50 targets at known positions in the bay. The position of each target was defined using polar co-ordinates (distance, and vertical and horizontal angles relative to the transducer installed on the platform). The targets consisted of metal hex nuts of approximately −48 dB (25 mm diameter, 3·5 times the acoustic wavelength) submerged at 0·5–3·5 m below the surface. Each target was attached to a monofilament line (0·5 mm diameter) anchored at the bottom of the lake and supported by floating rubber balloons on the surface. The monofilaments and the floats were not detected by the echosounder.

Hydroacoustic sampling was performed using nine horizontal sectors of 11° originating at the transducer on the platform and directed towards the shore. Each sector was separated by 1° to minimize statistical dependence among observations made in adjacent sectors. The total horizontal coverage was consequently of 107° (9 × 11°) + (8 × 1°). The sectors were scanned vertically also to sample three depth layers (0, 20, and 40° relative to the surface). This sampling strategy resulted in the observation of a total of 27 acoustic cones (nine sectors × three vertical directions). Sounding was made between 1300 and 1700 hours when several clues (hydroacoustics, pelagic seine hauls, diving observations) indicated the absence of fish in the study area.

DESCRIPTION OF FISH MIGRATION PATTERNS

Fish migration patterns were monitored using the same method as detailed for the validation except that only four sectors of 11° oriented from the pelagic zone towards the shore were used, each sector separated by 5°, and a fourth depth layer (at 80° relative to the surface) was scanned also. Therefore fish migration patterns were estimated by observing targets in 16 acoustic cones (four sectors × four vertical directions). Echosounding was performed on 11 occasions: in 1992: 28–29 August, and 24 October; in 1993: 20 March through a hole made in the ice; 29 April; 6 and 20 May; 8 June; 1 and 6 July; and 18 September. On each date, individual acoustic cones were sampled for 3 min at 4-h intervals over 24 h starting at 0900 hours. Fish moving outside the littoral zone were sampled from June to August at weekly to fortnightly intervals using a pelagic seine (50 × 3 m; mesh-size = 5 mm). Seine hauls were made from 1400 to 0300 hours on days when there was no hydroacoustic sampling, to avoid interference. The largest pelagic invertebrates found in Lake Croche were holopediums, which reached their peak density in September and were particularly abundant at night (110 inds l^{-1}; B. Pinel-Alloul, Département de sciences biologiques, Université de Montréal, unpublished data). Since no echoes were recorded during hydroacoustic samplings at night in September, it was assumed that the echoes recorded were produced only by fish.

COMPUTATIONS

The targets (hex nuts or fish) perceived by the echosounder were represented by marks on the printout of the hydroacoustic system. Each mark was associated with a specific cone (horizontal and vertical angular position from the platform) and with its distance from the transducer (read directly on the print-out). Analytical tools for recognizing multiple echoes (within half pulse length) were not available and so the echoes were interpreted as single targets.

Estimation of target distribution

The maps of the targets developed from hydroacoustic observations (angular positions and distances from transducer) were compared with real maps using an aggregation index *r* based on the nearest neighbour method (Clark & Evans, 1954). The aggregation index can range from 0 to 2·2 and has been described to represent clumped ($0<r<0{\cdot}9$), random ($0{\cdot}9<r<1{\cdot}25$) and uniform ($1{\cdot}25<r<2{\cdot}2$) distributions (Morrison, 1970). For each map, the aggregation index was calculated as:

$$r=\frac{\bar{d}_A}{\bar{d}_E} \tag{1}$$

where $\bar{d}_A$ is the mean distance to the nearest neighbour and $\bar{d}_E$ is the expected distance to the nearest neighbour assuming a uniform distribution. $\bar{d}_A$ was calculated as:

$$\bar{d}_A=\frac{\Sigma d_i}{n} \tag{2}$$

where d_i is the distance to the nearest neighbour for target ‘ *i* ’ as estimated using the maps (real or produced using hydroacoustics) and *n* is the number of targets in the study area. Distances estimated using the maps developed with hydroacoustics were calculated under the assumption that a target detected at a given distance from the transducer was situated on the axis of the beam $\bar{d}_E$ was calculated as:

$$\bar{d}_E=\frac{1}{2\sqrt{\rho}} \tag{3}$$

where ρ is the density of targets (number of targets in the study area/surface of the study area).

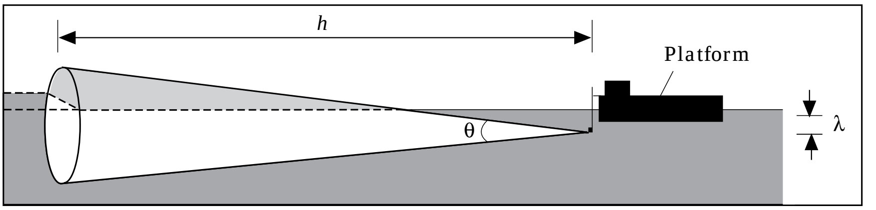

FIG. 1. Schematic view of a horizontal beam projection with the variables used to estimate the theoretical volume of the hyperbolic section. θ, beam angle; λ, depth of the transducer; h, length of the projection.

Estimation of target density

The validity of the variable angle approach to estimate relative target abundance was assessed by comparing real to estimated target densities (number of targets per unit volume). Each acoustic cone was divided into sections of 100 m^3, correcting when necessary the volume calculated for that part of the beam situated theoretically above the water surface during horizontal scanning (Fig. 1). This aerial part of the beam was estimated using an equation of a hyperboloid defined by the effective beam angle (θ), the depth at which the transducer was set (λ) and the distance of the sampling projection (h). Each acoustic cone could be divided in one to three sections of 100 m^3 (depending on the orientation of the cone) for a total of 35 independent sections. For each section insonified, the difference was calculated between the number of targets counted using hydroacoustic and real values. Finally, the percentage was estimated of sections for which the hydroacoustic method predicted target density accurately.

Fish relative abundance and magnitude of migration

The maximum distance from the transducer at which a target could be discriminated from the background during horizontal scanning (35–50 m) corresponded approximately to the intersection between the bottom of the lake and the euphotic zone (3-m isobath in Lake Croche; *c*. 15 m from shore). Consequently, the targets were interpreted as fish located outside the littoral zone of the bay surveyed.

Fish relative abundance outside the littoral zone (A_R: number of targets per 100 m^3) at a given time of day was estimated for each acoustic cone as:

$$A_R = 100\, n_t\, V^{-1} \tag{4}$$

where n_t is the number of targets recorded during 3 min and V is the total volume insonified.

The position of the fish front relative to the littoral zone was determined for each acoustic cone as the maximum distance from the littoral zone at which a target was observed.

Fish density

Fish density (D: number of fish 100 m^{-3}) was estimated as:

$$D = 100\, N\, V_S^{-1} \tag{5}$$

where N is the number of fish captured per haul and V_S is the volume sampled by the pelagic seine. The volume sampled by the pelagic seine ($V_S = 200$ m^3) was assumed to be represented adequately by a cylinder having a radius of 8 m and a height of 3 m. Because fish may have escaped by diving below the depth covered by the seine and since the seine was closed rarely in a perfectly symmetrical fashion, the estimates of fish density probably underestimated the real values.

STATISTICAL ANALYSIS

Real and estimated target densities were compared using a model II regression (major axis). The slope of the relationship between real and estimated target densities was calculated for each distribution pattern and was tested against an expected value of 1. The 95% confidence intervals (CI) of the slopes were calculated following the method of Jolicoeur (1968).

Within- and among-date variations were tested in fish relative abundance and in magnitude of migration with a two-way analysis of variance (ANOVA). Fish were recorded only in the horizontal sectors and only from June to August. Consequently, for the ANOVA, the two factors consisted of three classes of time of day (0500–0900, 1300–1700 and 2100–0100 hours) and five dates. Furthermore, different sectors sampled for a given combination of times and dates were used as replicates.

RESULTS

ESTIMATION OF TARGET DISTRIBUTION

Real distribution patterns of artificial targets had aggregation indices ranging from 0·66 to 1·36 (Fig. 2). Maps of the targets produced with signals recorded using hydroacoustics were qualitatively similar to the real distributions. The differences between the aggregation indices estimated using real target positions and those obtained using hydroacoustics corresponded to 4·5 and 2·6% of the real values for the clumped and random distribution patterns respectively. This difference was 15·4% for the uniform distribution pattern (Fig. 2). The magnitude of the discrepancy between real and estimated aggregation indices was not related to the number of targets present in the study area nor to the size of the area over which the targets were distributed (230 m^2 for the clumped distribution, 770 m^2 for the random distribution, and 510 m^2 for the uniform distribution).

ESTIMATION OF TARGET DENSITY

Real target density ranged from 0 to 8 targets 100 m^{-3}. There was no artificial target in 22 of the 35 sections for the clumped and uniform distributions. There were only eight empty sections for the random pattern. Target densities determined using hydroacoustics ranged from 0 to 7 targets 100 m^{-3}. The number of empty sections estimated by hydroacoustics was 21 for the clumped and the uniform distributions and 10 for the random distribution. There were significant and linear relationships between estimated and real number of targets per 100 m^3 ($0{\cdot}57<r^2<0{\cdot}90$; Fig. 3). The slopes of the relationships for the clumped, random, and uniform distributions were, respectively, 0·72, 0·94, and 1·25. The 95% confidence intervals of these slopes included the expected value of 1 only for the random distribution (95% CI: 0·68–1·28). Hydroacoustics tended to underestimate the relative abundance of targets for the clumped distribution (95% CI of the slope: 0·62–0·82) and to overestimate this value for the uniform distribution (95% CI of the slope: 1·11–1·40).

Differences between estimated and real counts of target per section ranged from −3 (underestimation) to +2 (overestimation). Hydroacoustic sampling provided the exact number of targets for 74% of the sections with the clumped

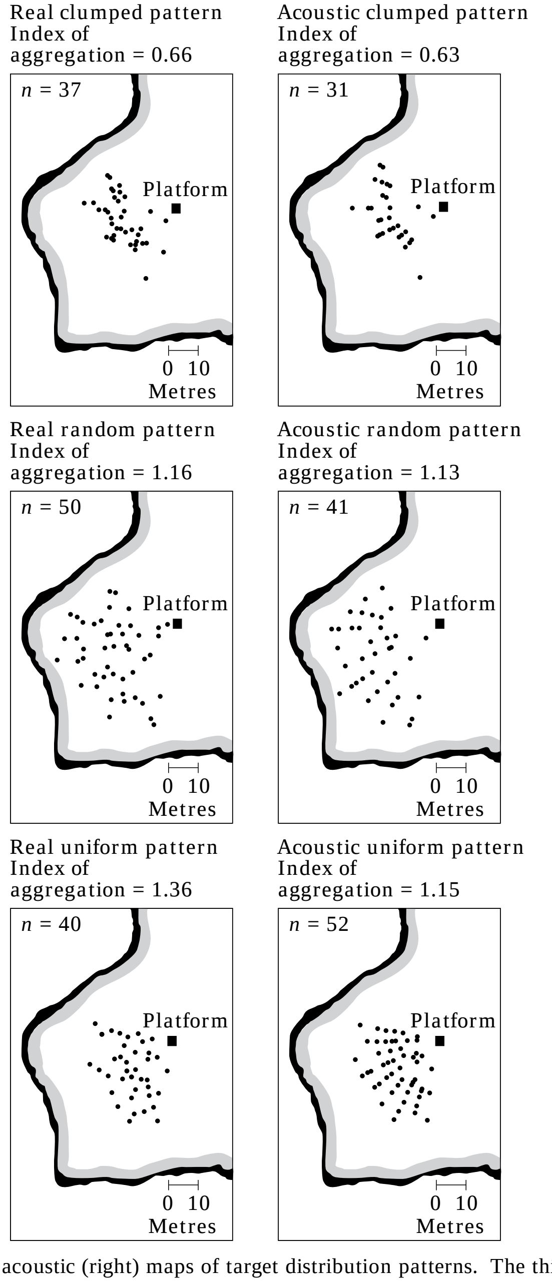

FIG. 2. Real (left) and acoustic (right) maps of target distribution patterns. The thick line represents the shore.

and uniform distributions, and 60% with the random distribution (Fig. 3). Counts determined by hydroacoustics were within ± 1 target for 88–95% of the sections depending on the distribution patterns. For sections containing >3 targets $100\,m^{-3}$ target densities estimated using hydroacoustics were always within $\pm 30\%$ of real values.

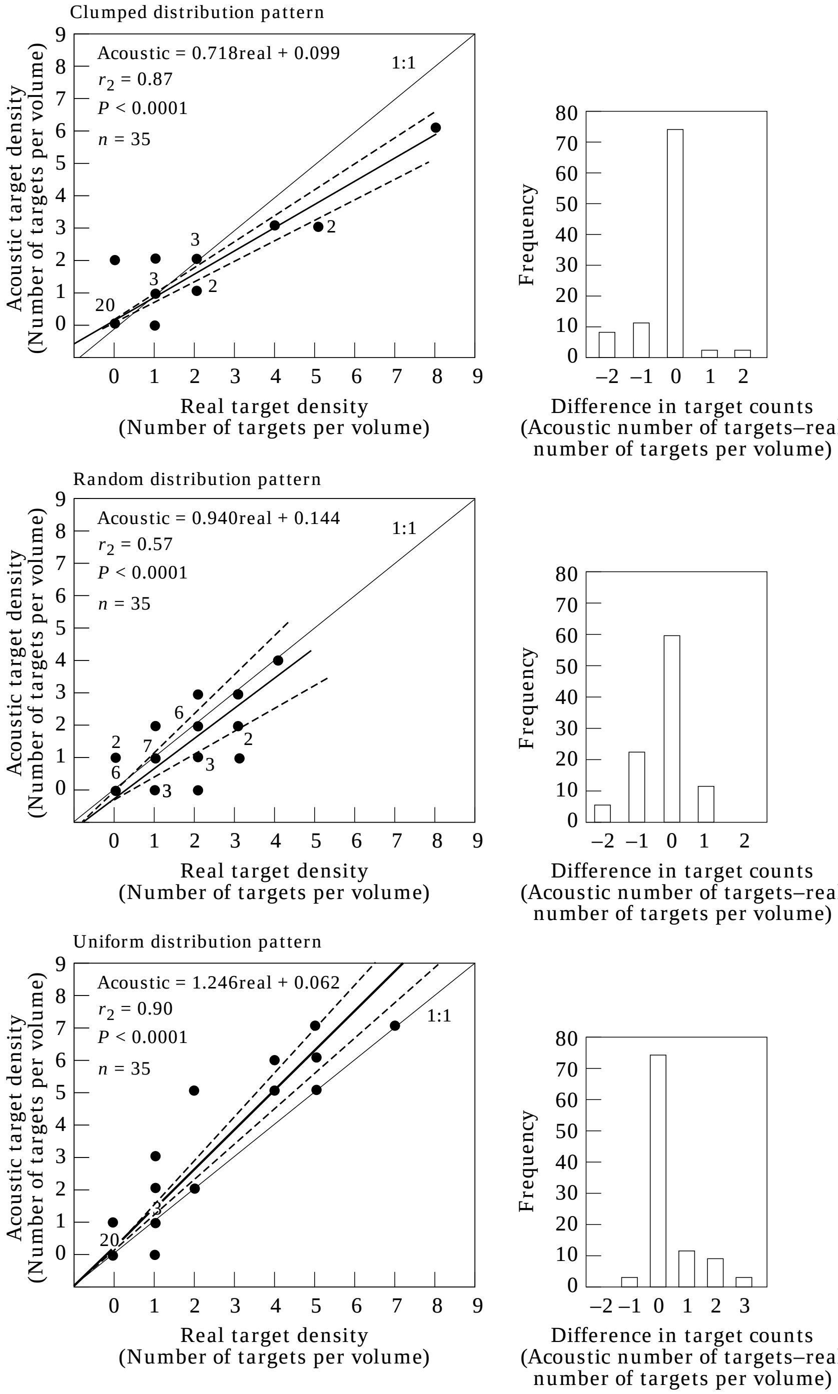

FIG. 3. Relationship between real and acoustic target densities for each distribution pattern (——=regression line; ——=1 : 1 ratio; · · ·=95% CI of the slopes). The per cent difference between real and acoustic target densities is also presented.

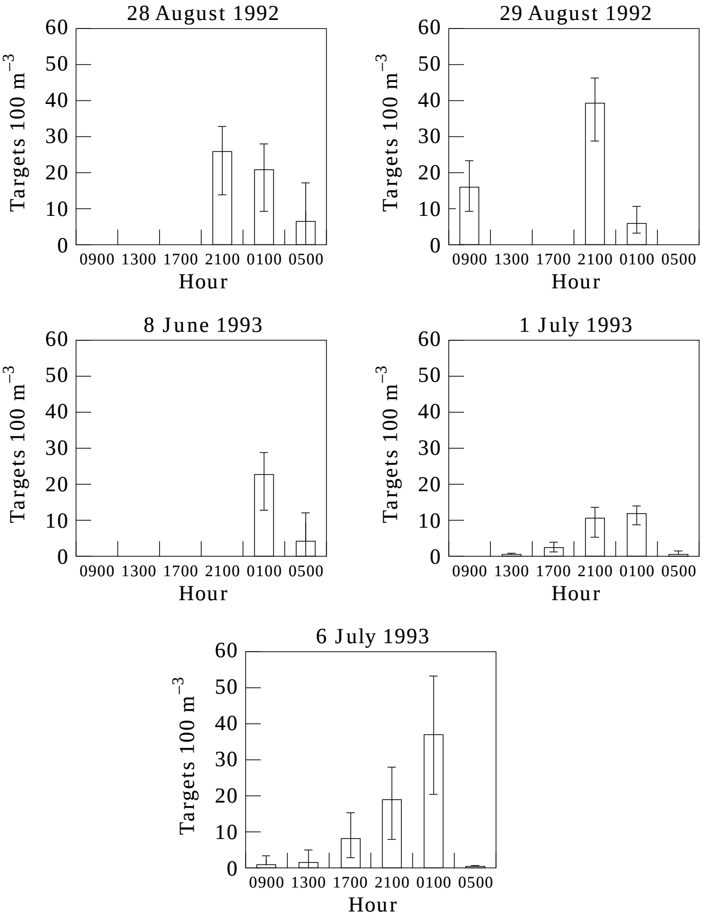

FIG. 4. Geometric mean of fish relative abundance for each combination of dates and time of day. Vertical bars represents the range of values. Days when no fish were recorded are not shown.

FISH RELATIVE ABUNDANCE AND MAGNITUDE OF MIGRATION

Fish relative abundance (A_R) ranged from 0 to 55·8 targets 100 m^{-3}. Those targets could represent anything from minnows to large piscivorous trout. In preliminary sampling (using six gillnets of 50 × 2 m; mesh-size: 3–10 cm^2), the abundance of piscivorous trout was low in Lake Croche (four individuals captured after 12 h of sampling). The targets recorded were probably mostly minnows. Analysis of variance indicated that A_R varied significantly within ($F_{2,87}$ = 49·0; P < 0·0001) and among dates ($F_{4,87}$ = 3·49; P < 0·01). The interaction term was also significant ($F_{8,87}$ = 2·28; P < 0·03). A_R was generally low during the day (1300–1700 hours), tended to increase towards dusk, and to peak at night (Fig. 4). Maximum average A_R recorded during the night was 41 targets 100 m^{-3}. The rate at which A_R increased toward the night was not constant among dates.

The distance from the littoral zone at which fish were recorded (D_L) followed a pattern similar to that displayed by relative abundance (Fig. 5). The maximum D_L was 24 m. The two-way ANOVA suggested that D_L varied significantly

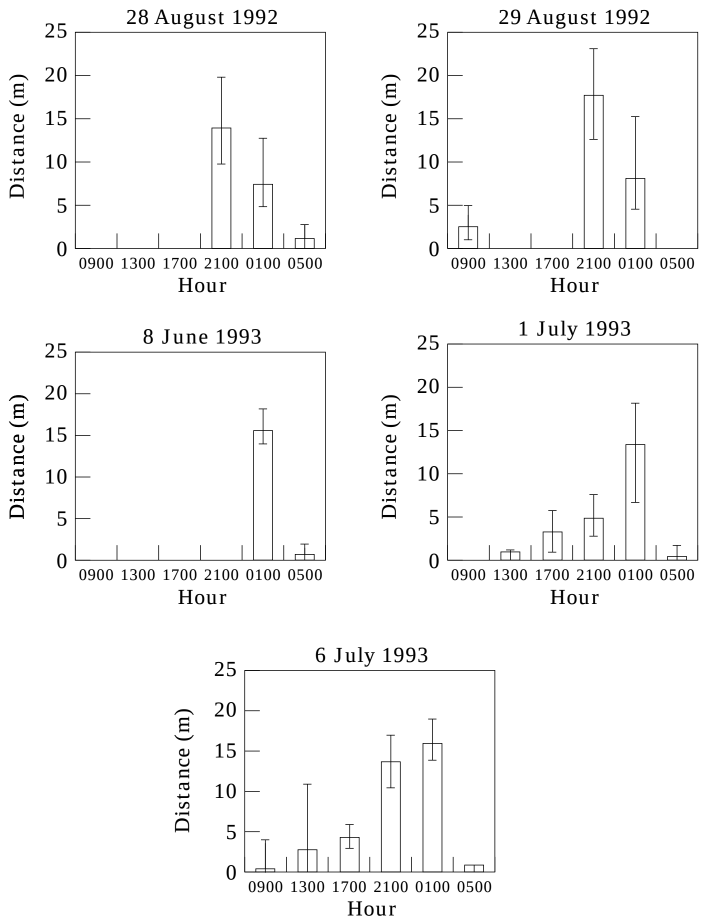

FIG. 5. Mean of the maximum distance from the littoral zone at which fish were observed for each combination of dates and time of day. Vertical bars represents the range of values. Days when no fish were recorded are not shown.

within ($F_{2,87}=80{\cdot}6$; $P<0{\cdot}0001$) and among dates ($F_{4,87}=2{\cdot}91$; $P<0{\cdot}03$). The interaction term was not significant ($F_{8,87}=1{\cdot}23$; $P>0{\cdot}03$).

From pelagic seine sampling, the only fish moving outside the littoral zone were the hybrid dace (Legendre, 1970). These fish are mainly zooplanktivorous (Gauthier & Boisclair, 1997). Fish were captured only during the night between 2100–0300 hours, and ranged from two to 16 fish per seine haul, representing 1–8 fish 100 m^{-3}. The length of the minnows captured was 4·5–6·5 cm.

DISCUSSION

The variable angle approach can be useful to describe and quantify distribution patterns and relative abundance of the artificial targets, but its precision differed with the variable examined. The hydroacoustic maps were qualitatively similar to real target distributions. Furthermore, aggregation indices estimated using hydroacoustics were always within 15% of real values. Most of the difference between real and acoustic aggregation indices was attributed to the inability of the single beam echosounder to position the targets adequately within the cones ensonified. This shortcoming may have biased the estimated distances between nearest neighbours, and hence, the aggregation indices calculated using hydroacoustics. This source of error can be expected to be eliminated largely by using split or dual beam echosounders.

Target relative densities determined using hydroacoustics were within one target of real values for at least 88% of the sections. However, the 95% CI of the slope of the relationship between acoustic and real target densities included the expected value of one for only the random distribution pattern. This result implies that the hydroacoustic surveys tended to under- or overestimate real target density systematically. Two alternative hypotheses can be proposed to explain the different directions of this bias. First, overestimation of target density may have been produced by movements of the platform due to the wind. Echosounding was not performed in very windy conditions (>15 km h^{-1}), since entrapped air bubbles and small surface waves produced considerable interfering noise. However, the floating platform could have moved even in low windy conditions (the anchoring system of the platform can rotate freely by *c.* 5°). Those movements may increase the effective volume sampled by the system above the expected 11°. One potential outcome of this situation was that a single target located in one specific section (particularly on the margin) might be recorded by more than one acoustic cone. Consequently, under windy conditions such as those experienced during the sampling of the uniform pattern, the total number of targets recorded using hydroacoustics (52 targets) could be larger than the total number of targets present in the study area (40 targets). Secondly, underestimation of target density might be associated to the difficulty with discriminating multiple targets. This difficulty could explain the underestimation observed in the clumped distribution. The minimum distance along the beam axis that must separate targets to allow their discrimination corresponded to half the pulse length of the signals produced by the hydroacoustic system. The pulse length can be calculated as the product of the pulse duration and of the speed of sound in water (Tucker & Gazey, 1966). If we assume a speed of sound of 1480 m s^{-1} in fresh water, the half pulse length of the system was 0·74 m. The numbers of targets separated by $<0{\cdot}74$ m for the uniform, random, and clumped distributions were four, eight, and 15 respectively. These values support the hypothesis that target density was underestimated particularly for the clumped pattern.

Determination of fish distribution and variations of fish relative abundance outside the littoral zone on a daily and a seasonal basis was complicated by the discrimination of multiple targets. In addition, two other biases were associated with recording fish from a stationary platform. First, densities may have been overestimated by the recurrent entering and exiting the beam by a single fish. Secondly, abundance may have been overestimated by repetitive changes in the orientation of small fish such that their target strength may have become momentarily too low to be recorded by the sounder. For instance, Kubecka (1994) has shown a difference of 10–15 dB around average target strength by yawning and pitching a rudd *Scardinius erythrophthalmus* (L.) (190 mm) during horizontal scanning. Similarly, the relationships between target strength and fish incidence aspect in vertical scanning have been discussed widely (Nakken &

Olsen, 1977; Goddard & Welsby, 1985; Foote, 1980, 1985, 1986; MacLennan *et al*., 1989; Ona, 1990). Since it may be difficult to assess the orientation of free-swimming fish during horizontal scanning, interpretation of target strength measurements are impractical and of relative usefulness. Furthermore, most algorithms used to estimate fish target strength in a single beam echosounder are based on a probability density function of insonified volumes corresponding to steps of decreasing intensity (Craig & Forbes, 1969; Rudstam *et al*., unpublished). The Hydro Acoustic Data Analysis System (HADAS) developed by T. Lindem uses this approach (Lindem, 1983). Since, during the present study, part of the acoustic beam was scattered by the surface, the volumes and hence the algorithm equation of target strength obtained using this procedure should be revised. In addition to the potential errors described above, the horizontal use of hydroacoustics near the surface may give rise also to specific problems such as surface reflections and interference with direct-path echo returns. This phenomenon may produce noise difficult to interpret. Despite the problems listed above, the results suggest that the variable angle approach may be a useful tool to provide information on temporal and spatial distribution and on relative abundance of fish in the pelagic zone of deep and shallow lakes.

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