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Searching behaviour and catch of horse mackerel (*Trachurus murphyi*) by industrial purse-seiners off south-central Chile

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During 11 voyages on two purse-seiners off south central Chile, the size of catch and time spent searching per vessel was related to the behaviour of the jack mackerel (*Trachurus murphyi*) schools. Radar data were used to define groups of fishing vessels. Time spent at sea by purse-seiners was employed either **cruising** or **searching**. Cruising ships travelled in a straight line and cruising was associated with deeper (65 m on average) and larger schools. When schools became more numerous and shallow, skippers began searching, during which they slowed down and changed course frequently. Searching tended to be more persistent outside fishing groups. A search could end or not with a set of the net. The net was set when schools were at a mean of 37 m deep compared with 56 m when no set was made. Abandoned search was more likely outside a fishing group and in groups with few vessels. Setting the net and hauling it again had a high opportunity cost, absorbing on average 1.8 h. During the search period, and before the net was set, the jack mackerel schools tended to coalesce and move deeper in the water column. Some sets failed to catch fish and this usually occurred when the schools were deeper than during a successful set. Unsuccessful sets were also associated with larger groups of fish. Catch per unit search time was highest in the centre of a fishing group where searching was less. The highest amount of time spent searching was in the inner margin of the group. Searching then fell away as vessels moved away from the core of the collection of vessels. The implications are discussed of the grouping behaviour for understanding the relationship between CPUE and fish abundance. The relationships described in the paper are summarised into a set of rules that the fishermen might follow. It is suggested that success in the fishery is mostly a result of information acquisition. To regulate effort it might be effective to put a tax on the technology used to gather information.

Key words: horse mackerel, purse-seiners, fisherman's behaviour, schooling, searching behaviour, catch per unit effort, Chile, effort limitation.

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Introduction

Fishing effort is a function of several different inputs such as vessel size, vessel power, net size, skipper skills, and electronic fish finding equipment. This makes it difficult for managers who want to control effort. Sixteen years ago, Wilen (1979) proposed that managers need to be able to predict the fisher's response to regulation of effort. He formulated his view in three questions. (1) Is it necessarily true that a multiple-input fishery will use too much of all dimensions of effort, or just some? (2) If one component of effort is regulated, how will fishermen combine all other dimensions? Will the industry simply dissipate rents by expanding these other components? And (3) What sorts of policies are likely to be the most effective in regulating fisheries where production techniques are highly flexible? Crucial to answering these questions, argued Wilen (1979), is the nature of the individual fisherman's behaviour. This view alone encourages us to publish the findings of our study which goes some way towards providing better data on the different components of effort and on the behavioural detail of fishermen catching pelagic horse mackerel (*Trachurus murphyi* Jenyns).

A further justification for publication stems from the susceptibility of schooling pelagic fish species to overfishing. Using simple models based on catch per unit effort (CPUE) to manage such species can be misleading (Murphy, 1980; Csirke, 1988). As suggested by Mangel (1982), Mangel and Clark (1983), Hilborn (1985), and Mangel and Beder (1988), both the behaviour of fishermen and the biology of the fish must be considered when trying to understand the catchability and abundance of pelagic shoaling organisms. We investigate the relationship between the details of searching behaviour, variation in effort and the behaviour of fish schools in the highly productive horse mackerel fishery off south-central Chile (1.77–2.0 million tonnes in 1987–1988 (Bailey, 1992)). The properties of fish schools were largely deduced from the grouping behaviour of the purse-seine fleet and the data available from their electronic fish-finding gear.

This paper has two aims. First to describe the spatial distribution of fishing effort and then to examine the way in which skipper actions are correlated with spatial structure. This information will make it easier to understand how catch per unit effort is related to fish abundance and will show in what way effort could be effectively regulated.

Study area and methods

The study site

The study area was located between 39°00′–34°30′S and 72°00′–75°00′W (Fig. 1), and is characterised by strong summer upwelling (December–February) similar to other eastern boundary currents, such as off California and South West Africa. The eastern boundary current flows towards the equator over the shelf whilst the cold Gunther Current, high in nutrients and with oxygen levels as low as 0.2 ml l^{-1}, flows underneath it towards the south (Peterson *et al.*, 1988). The summer–autumn upwelling season is characterised by south to south-west winds with north to north-west winds in winter (Gunther, 1936; Warren, 1970; Smith, 1992). The shelf varies between eight and thirty nautical miles (n.mi) in width and is traversed by canyons, the most conspicuous and deepest of which runs out from the mouth of the Bío Bío River (Fig. 1). (Nautical miles (n.mi) and not kilometres will be used throughout (1 n.mi=1.86 km).) The total area surveyed was estimated to be 16 980 n.mi^2.

The fishing fleet

The local fleet in 1991 operating from Coronel, San Vincente and Talcahuano (Fig. 1) consisted of about 150 purse-seiners belonging to 20 companies and varying in hold capacity between 100–1350 m^3 (1 t of fish occupies approximately 1.0 m^3 of storage space). The holds have no cooling devices so that fish have to be taken back to port within two days if they are to be processed to fish meal (99% of use) and one day or night if destined for canning. Chilled Sea Water (CSW) ships have since been introduced into the fleet. Offloading and maintenance at port takes 3–7 h, which is the time between fishing trips. Sunday is officially a day off, but is not always adhered to.

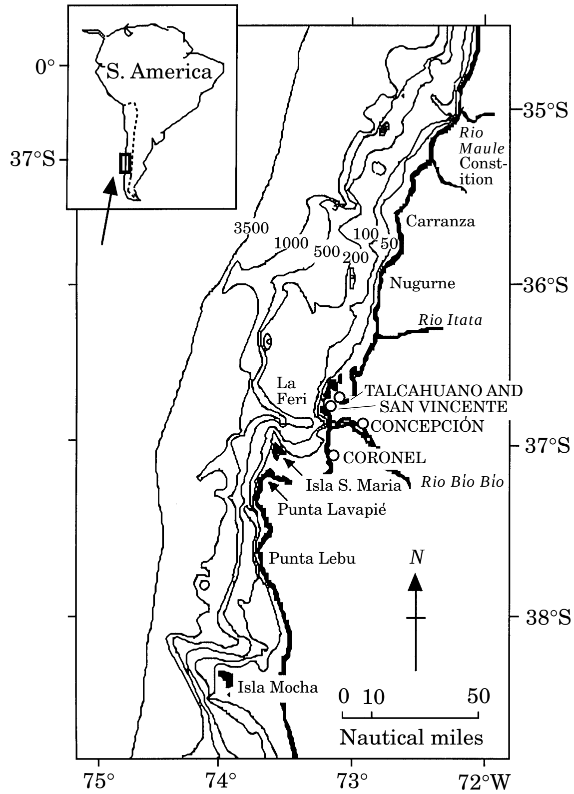

Figure 1. Map showing the location of the study area off south-central Chile with main coastal landmarks. Contour lines were compiled from depths on nautical charts and the numbers on them are depths in metres. The names of cities and ports, indicated by open circles, are in bold type.

Captains steaming out of port do not start searching immediately. They either head for known fishing grounds or for known groups of other vessels. Information about groups is transmitted over the radio between captains or obtained from daily reports to the Coast Guard. Occasionally, light aeroplanes are used to locate fishing areas. When a vessel arrives at a known fishing ground or joins a group of other boats actively fishing, the captain starts to search using his electronic fish-finding gear. Echo-sounders and side scanning sonar, are used to assess school density and size. The side scanner sonar is used alone in the last few minutes before the net is set to estimate the size and direction of the school more accurately.

There are marked seasonal pattern in fishing (Boré *et al.*, 1988). Fishing occurs during the day in summer and at night in winter. In winter, catches are almost only horse mackerel whereas in summer there are also some catches of whiphake (*Macruronus magellanicus*).

Recording methods used on board

Work on board was carried out during 11 fishing trips, each 1–3 days long, during which ships were engaged in their normal fishing activities. Two purse-seiners were used, one of 900 t capacity in March 1991 and a second of 630 t capacity in April–May 1991. These boats operate for the Compañia Pesquera San Pedro from the port of Coronel. The average cruising speed of these two boats was about 11 knots and their maximum range approximately 200 nautical miles excluding return to port. Nets for the two vessels were about 1000 × 80 m and fishing was consequently limited to areas deeper than 75 m.

Time, ship speed to the nearest knot, and position to the nearest minute from the satellite navigation system were recorded in a log of every fishing trip accompanied. The logging interval was 5, 10, or 15 min, and was chosen at random. The mean interval between observations during search was thus 10 min. The radar location of other boats, weather, cloud coverage, schools, and acoustic information were also logged at the same time. Each individual log of the echo-sounder screen is referred to as a screen observation. Records were made almost continuously during search and/or when within fishing groups (defined later), and every 30–60 min in bouts of a few hours when cruising outside fishing groups. Time spent outside a fishing group was estimated from the log and did not include time spent in waters shallower than 50 m. Bottom depth was recorded from the echo-sounder or estimated from a bathymetric chart together with ships position (to 0.5 miles).

Dawn and dusk were standardised to the middle of the study period, 16 April. As a result, sunrise and sunset were 6 h 25 min on either side of the midpoint of the night and first and last light as 5 h from this midpoint. When referred to, night includes dawn and dusk, and day from sunrise to sunset.

Fleet location

We used radar and visual observation to get information on the characteristics and deployment of ships. The positions of other purse-seiners within 10 nm of the sample ships were recorded from the boats' radar on to specially drawn sheets, noting our own position and bearing, time, range of the radar, and which other boats were fishing. This last was confirmed from visual observation, possible at night because boats with a set net have a flashing light. Radar loggings were done at variable intervals ranging from 15 min and 2 h. It was not possible to follow other individual boats and record their catches.

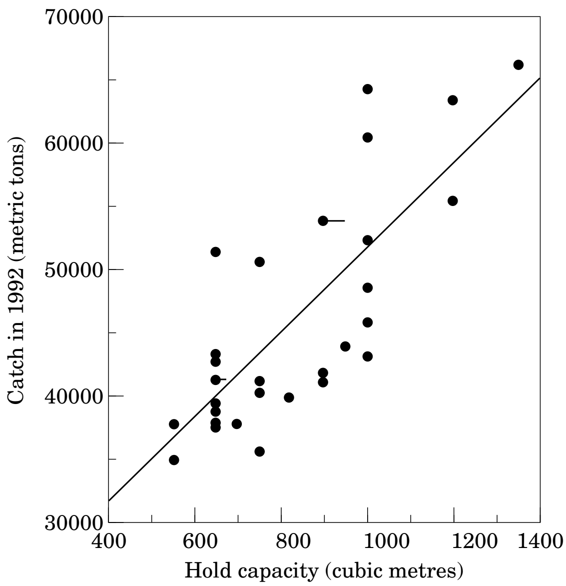

Figure 2. The catch per ship of horse mackerel in tonnes for 1992 plotted against the ship's hold capacity in cubic metres. The sample vessels used for the study reported in this paper are marked by a short horizontal line. One cubic metre of hold space stores approximately one tonne of fish. Catch=18 167+33.314 hold; $r^2=0.605$.

Recording of catch and effort

The tonnage caught by each set of the purse-seine, as estimated by the captain and crew of the two sampling ships have been used and is assumed to have an error of ± 10 t. Sets which resulted in empty nets were recorded as unsuccessful. Net size was similar between the two sampling vessels and captain ability was assumed to be similar (but see Fig. 2 and Abrahams and Healey, 1990, 1993). In 1992, the two vessels recorded landings that were in the top 20 of all Chilean vessels. Both took 59–65.5 t per m^3 of hold capacity. The 1992 catch per vessel as a function of hold capacity is shown in Figure 2. Crews from both boats were largely from the same pool of skilled, union registered fishermen.

Catch composition was estimated visually as the percentage of various species passing through the chutes into the holds. Small percentages of chub mackerel (*Scomber japonicus*) were also present in a few catches as well as whiphake.

Ship behaviour at sea was categorised into **cruising** and **searching**. Cruising was recorded when the vessel maintained a constant speed and showed only slight changes in bearing. Searching was characterised by frequent turns and changes of speed. This difference was obvious from the pilots' and captains' comments as well as from the author's log. Search time was estimated indirectly as the product of the number of screen observations and the average time interval between screen

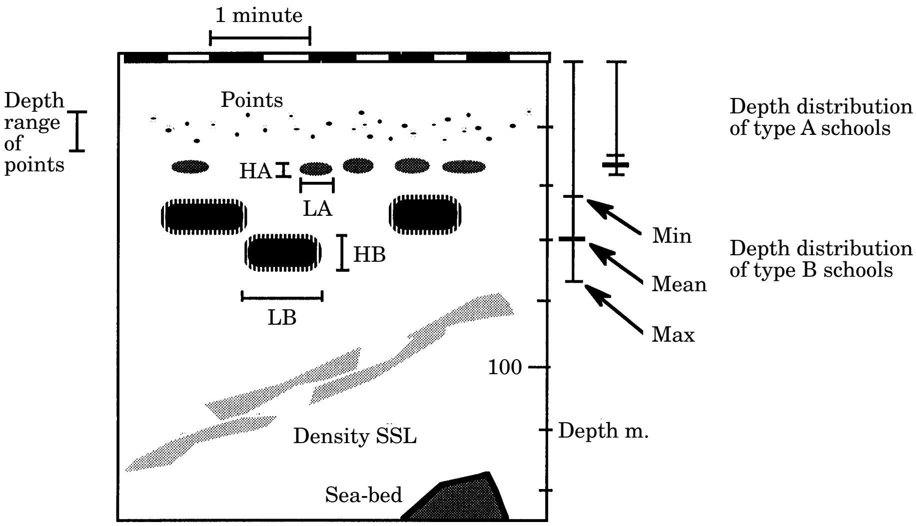

Figure 3. A stylised representation of the echo-sounder screen to show the different phenomena that were observed and recorded. For details see the text. HA and LA are the height and length of school Type A, whilst HB and LB repesent the same for Type B schools. SSL=Sound Scattering Layer.

observations (10 min). Search time was divided further into **abandoned search time**, which ended without setting the net, and **search with set** when a search period was followed by the net being set. A set can be described as an **attack** on a fish school which could either succeed or fail to capture anything. It is possible that time spent by skippers in conversation with others on the radio formed an element of search. We have no information on this, so our search time could underestimate true search time. The approximate time spent hauling nets was recorded directly from the log.

Data on fish schools from echo-sounders

Furuno echo-sounders were used to record data on fish schools with gain held constant and operating at 50 kH. The depth range of 150–200 m and the speed across the screen were rarely changed.

The type of data gathered from the echo-sounder is shown in Figure 3. The schools were consistently well defined though it has to be stressed that the term “school” is used as an expression of fish aggregation as shown by the echo-sounders and does not imply anything about the structure within schools (see Pitcher, 1983). The number of schools was quantified as the number of schools per screen observation.

A screen observation was standardised to $1700 \times 150\ m^2$, which was the distance traversed in five minutes (1700 m), multiplied by the mean depth range on the screen (150 m). The area of individual schools was calculated as a product of height and length (m^2), so making the fewest assumptions about beam width. The total area of schools, which was taken as an index of biomass, was found by multiplying the number of schools by the area of each school (m^2) per screen observation for each type of school. Analyses on individual school area were done separately on caught and uncaught schools when they occurred on the same screen. However, for most analyses, school types were combined to produce the total number and the total area of schools per screen observation.

Schools on the echo-sounder screen could be divided into three broad categories (Fig. 3). At low abundance fish appeared as individual dots. On some screen observations fish were aggregated into small schools perhaps with several of these appearing on one screen observation. These were classed as Type A schools in Fig. 3. On other occasions, fish were aggregated into one large mass and these have been called Type B (Fig. 3).

Results

The definition of fishing groups

Areas where boats grouped nearly always consisted of boats searching or cruising amongst boats with set nets. We will use the partitioning of fishing time of the two sample vessels to characterise how boats without set nets use their time around boats with set nets. We also use data gathered on the vessels to explore aspects of fish behaviour.

Radar observations were used to estimate the mean nearest neighbour distance (NND) between all ships with set net within a radius of 10 n.mi from the observer’s vessel (Fig. 4). The groups of boats with set nets were usually discrete, although one case showed a

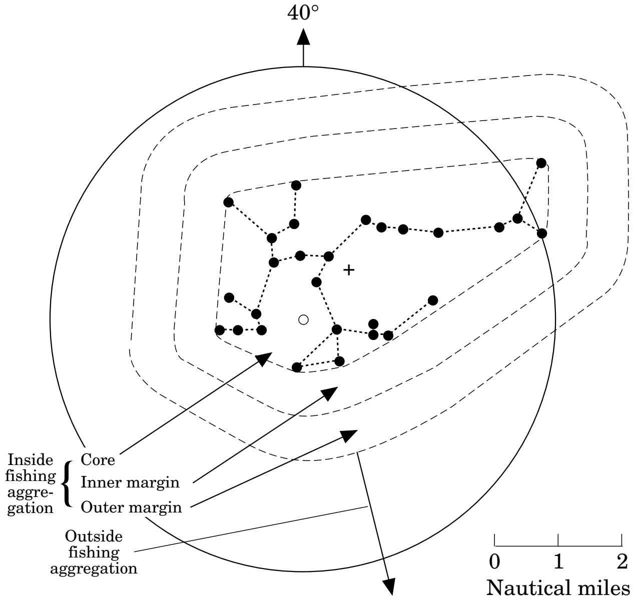

Figure 4. An example of the radar recording of boats with set nets, represented by the filled points, taken at 0350 on 9 May 1991 at 36°23′S and 74°38′W. The large circle has a diameter of 8 nautical miles (n.mi). The small filled arrow shows the bearing of the searching boat (40°), the position of which is marked by a small open circle at the centre. Finely dotted lines show distances to the nearest boat with a set net, never replicating a distance between boats and linking up all boats. The mean nearest neighbour distance (NND) and standard deviation for this group of boats is 0.57 ± 0.27 n.mi, and this was used to calculate the 95% upper confidence limit for the NND of 0.67 n.mi. This 95% upper confidence limit was in turn used to delimit the areas within the fishing group, shown by the heavily dashed lines. The inner and outer margin are each one 95% upper confidence limit wide. The midpoint of the fishing group was found by eye and is shown by a cross. Boats without set nets have been omitted for clarity.

division into more than one sub-group. Outlying boats were rare. The area outlined by the boats with set nets and the 95% upper confidence limit of the NND for each group were used to define the **core**, **inner** and **outer margins** of the fishing groups (see Fig. 4). The term "group" is applied when there were two or more boats with set nets. When only two boats were present the distance between the two boats was used to estimate NND. The area of a fishing group with only two boats present was arbitrarily defined as the distance between them multiplied by 0.5 miles, the approximate horizontal diameter of a net which has been set but not yet hauled in. It is important to realise that there were nearly always other boats searching within and around the vessels of a fishing group even if only two boats had set nets.

In the study area, only one or rarely two fishing groups were ever present at any one time during night or day. No fishing group was continuous through both day and night although groups would reform at night after the boats had rested during the day. Fishing groups were classified into four different types according to whether they were in the night or day and for how long they lasted. Short lived daytime fishing groups (**ephemeral day groups**) were seen from early in the mornings and rarely lasted beyond midday. Four of these fishing groups were encountered over the continental shelf and near the shelf break, all in March and April. Night-time fishing was more variable and, in four cases, lasted up to 2–3 consecutive nights and included all those that were found far offshore. The assumed permanence of these fishing groups was supported by the observation that the captains often returned to an area where they had been fishing the night before. Ships following these long-lasting groups were dispersed during daytime and stopped fishing. Such groups were encountered primarily in April and May. The data from each night of these groups was treated separately and labelled accordingly. The first night of a group lasting over two nights was called a **persistent night** group. The last night of such groups, or night groups lasting only one night but still all the way till dawn were called **night** groups. Nine of these were encountered. Three night-time fishing groups did not last till dawn and were called **ephemeral night** groups. These were associated mostly with the shelf break and were also only encountered in March and April. They were not associated with longer lasting night fishing groups occurring during the night before or the night after.

Within groups the overall mean ± s.d. of 346 distances between boats with set nets was 0.748 ± 0.394 n.mi. Mean NND between boats showed no significant correlation with the area covered by the fishing group or the distance offshore. However, mean NND was related to

Table 1. Mean areas and mean number of boats in different types of fishing groups encountered by the two sample vessels during the study period. For definitions of fishing groups and core of fishing group see text. 95% confidence interval in parentheses.

	Type of fishing group			
	Persistant night	Night	Ephemeral night	Ephemeral day
No. of radar observations of fishing groups:	11	16	5	8
Mean no. of boats with set nets in area:	13.6 (8.9, 20.8)	7.9 (5.5, 11.4)	4.0 (1.8, 8.9)	3.3 (2.3, 4.8)
Mean area of centre of fishing groups (n.mi^2):	4.5 (2.5, 8.1)	3.6 (2.6, 6.6)	1.1 (0.1, 11.0)	0.4 (0.2, 1.1)
Core as % of whole fishing group:	17	15	11	5

the number of boats in fishing groups. In those with more than 15 boats with set nets the mean NND was 0.60 ± 0.15 nautical miles, compared to 0.98 ± 0.46 when fewer boats were present (t=2.635, df=38, p=0.012). Despite a significant difference in the number of boats present for each type of fishing group (see Table 1, $F_{(3,36)}=8.889$, p=0.0001), there was no difference in mean NND for the type of fishing group.

Pooling all core sizes of fishing groups and analysing the log transformed data an average of 2.2 (1.4, 3.6: 95% CL) n.mi^2 (n=40) was obtained while the inner margin area surrounding it was 9.6 (7.3, 12.7) n.mi^2 in the original scale and the outer margin 17.0 (12.9, 22.5) n.mi^2. Table 1 shows that the proportion of the area taken up by the core was greater in the fishing groups with large core areas.

The size of the fishing groups was related to their persistence (Table 1). Short day fishing groups were significantly smaller in area than persistent night and night fishing groups, but were not significantly smaller than ephemeral night fishing groups (using log-transformed values: $F_{(3,36)}=7.575$, p=0.0005). The size of the fishing groups was more clearly related to distance from shore, especially when closer than 30 n.mi. Ephemeral day and ephemeral night fishing groups were closest to the shore (mean 11 and 17 n.mi out), and persistent night fishing groups and night fishing groups were generally found to be independent of distance from shore though never very close (mean 36 n.mi).

The correlation between the properties of fish schools and the behaviour of fishers

The ships' activities were classified into three categories; cruising, searching, and attacking schools. Searching was subdivided into a search which ended in the net being set and searches that broke off without the net being launched. The attack of a school could end with the school being caught successfully or with it being missed. The relationship between these categories and their subdivisions with the abundance, area and, depth of schools is shown in Figure 5.

When the ships were cruising, schools were at a mean depth of 65 m. Schools were at an average depth of 56 m when a search was abandoned before the net was set. Setting the net at the end of a search was associated with an average school depth of 37 m. These depths were significantly different from each other ($F_{(2,185)}=17.04$, p=0.0002). When cruising, there were significantly fewer schools per screen observed than when the ships were either successfully or unsuccessfully searching (Kruskall–Wallis H=16.22, df=2, $p<0.001$) (Fig. 5a). The schools associated with cruising had a larger mean area than those observed when ships were searching but this difference was not significant ($F_{(2,184)}=2.769$, p=0.065).

When the ship was searching there were more schools but with a lower mean area than when the schools had been attacked and either caught or missed (Fig. 5a). During a search there could be two to three schools under the ship (Type A, Fig. 3) whereas there was usually just one large school when the net was launched (Type B, Fig. 3). The mean area of schools encountered during a search was just under 400 m^2, but this rose to just over 2000 m^2 for the schools attacked, a difference which was statistically significant (t=6.68, df=95, p=0.0001). The difference in mean area between attacked schools that were caught and those that were missed was not significant. Missed schools were, on average, 24 m deeper than those that were caught and this difference was significant (t=4.228, df=32, p=0.0002, Fig. 5b).

Are the different types of fishing group a response to different school properties?

In this section we look at the correlation between the mean number of schools per screen, the school area, and the school depth in relation to the type of fishing group and the ships location in it (Fig. 6a,b). Ship position was classified as being in the core of the group, in the inner margin, the outer margin, or outside the group. If outside, we look at the school properties for ships that are cruising or searching.

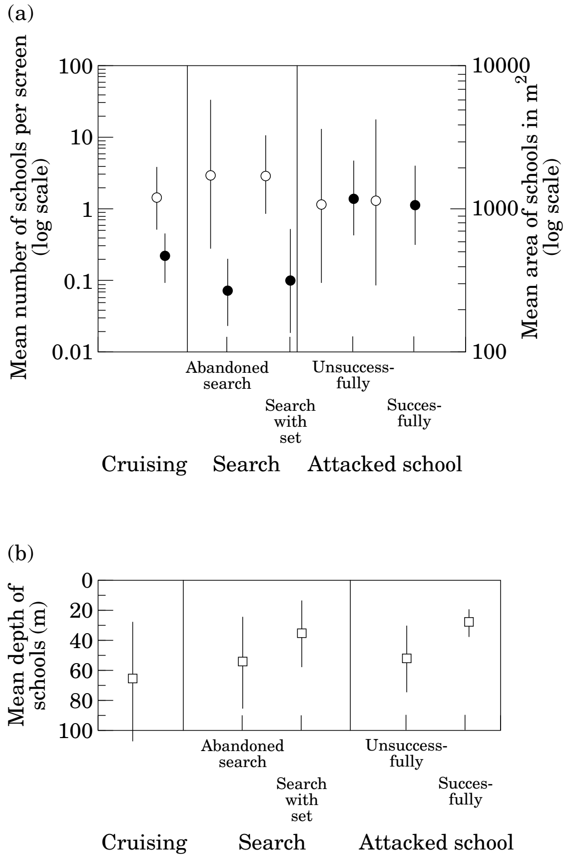

Figure 5. (a) The mean combined number of schools per screen (○, left axis) and the mean area in square metres of individual schools (●, right axis) plotted against one of three different actions of the ship. Points are means and the bars represent the 95% confidence limits on the mean. (b) The mean depth of schools. Points are means and bars show standard errors on the mean. "Attacked" schools were observed before the net had been set.

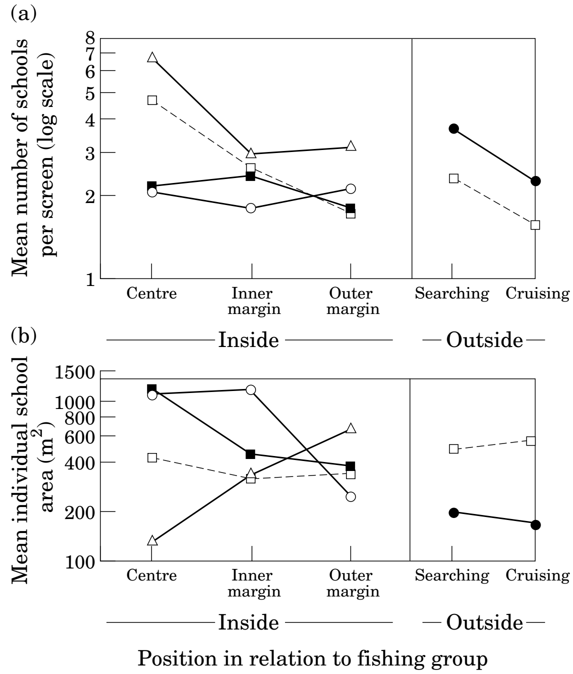

Figure 6. (a) The numbers of schools per screen observation, excluding screens with no schools. (b) The size of schools expressed as area for different positions within and outside fishing groups during the day (□) and night (●). Types of night groups are distinguished as; ephemeral night groups (△), night groups (○) and persistent night groups (■).

Within a fishing group, the proportion of observed echo-sounder screens that showed schools was 65% and this did not vary from one night to the next. Outside fishing groups the proportion of screens showing evidence of schools was 65% at night and 29% during the day, a difference that proved to be significant ($\chi^2=13.23$, df=1, p=0.0003).

In general, the mean number of schools per screen declined from the fishing group centre out towards its edge (Fig. 6a). The decline shown for day samples was not significant, possibly because sample sizes were small. Persistent night groups and night groups had a closely similar number of schools from the group centre-outwards. Ephemeral night groups were the only ones to show a strong decline in numbers. This result would support the conclusion that fishing groups that lasted for one or more nights were sited over high densities of fish spread over a wide area.

This conclusion is supported by the data on mean school areas. In the centres of night and persistent night groups, schools had large mean areas (1100 m^2) which decreased out towards the outer margin (290 m^2, Fig. 6b), a decline which is significant ($F_{(2,79)}=4.708$, p=0.011). This trend was echoed weakly by day groups. The opposite trend was shown for the ephemeral night groups in which mean school area was lowest in the fishing group centre (130 m^2) and highest in the outer margin (650 m^2, Fig. 6b).

Schools observed at night between last and first light from ships within fishing groups were closer to the surface when ships were in the centre of the group than at the margin ($F_{(2,55)}=5.60$, p=0.0061). The mean depth of schools at the centre of a night group varied with the type, so that schools were only 24 m deep on average when ships were in ephemeral night groups and as deep as 38 m on average when ships were in persistent night groups. This difference was significant ($F_{(2,53)}=8.382$, p=0.0007). The deepest schools were found in the margins of the persistent night groups at 47 m. The day groups did not show any relationship between depth and position of the observer ship in the fishing group.

During the day, there were fewer schools per screen when the ships were cruising than when they were

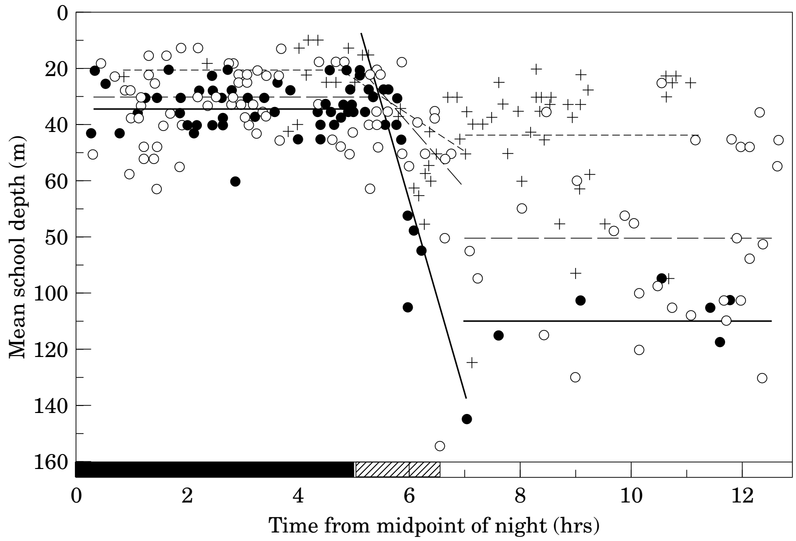

Figure 7. The mean depth of all schools observed during the study period against the time from the midpoint of the night, adjusted so that sun-up and sun-down are the same for all days. The bar on the horizontal axis is black for night, hatched for dawn and dusk and open for daylight hours. Horizontal lines show mean depths during day and night at the different distances offshore. Crosses and short dashed lines denote observations closer than 10 nautical miles offshore, open circles and long dashed lines between 10 and 30 nautical miles offshore. Filled circles and solid lines denote observations further than 30 nautical miles offshore. Diagonal lines between 5 and 7 h from the midpoint of the night are regression lines of depth versus time for that period (see text for the equations).

searching (Fig. 6a). These schools were more dispersed and covered a larger area under cruising ships than under those that were searching (Fig. 6b). At night the mean number of schools per screen followed the same pattern as during the day, higher under searching than under cruising vessels. For both states, the means at night were higher than those during the day (Fig. 6a). At night, fish appeared to be more concentrated in that schools areas were lower both under cruising and searching ships (Fig. 6b) although the difference was slight.

The depth distribution of schools with distance from the shore

A two-way analysis of variance on the mean depth of the schools with distance from shore and with time of day (night, dusk & dawn, day) showed that both factors and their interaction were highly significant (all $p<0.0001$, Fig. 7). Schools was closer to the surface during the night (mean depth=32 m) compared to the day (58 m). Both day and night schools were significantly shallower on average towards the coast. The rate of descent and ascent of schools observed during dawn and dusk was lower towards the coast. Dawn or dusk was designated to occur 5–7 h either side of midnight, allowing for changes in light when the sun is just above the horizon. Rate of vertical displacement was 13 m h^{-1} (correlation of depth with time, $r=0.462$, $p=0.04$) within 10 nm from shore, 27 m h^{-1} ($r=0.531$, $p=0.008$) between 10 and 30 nm offshore and 65 m h^{-1} ($r=0.919$, $p=0.0001$) beyond 30 nm from shore. Day depths were sometimes deeper than recorded on the screen.

How effort and catch varied inside and outside fishing groups

Aspects of schooling behaviour of the fish have been considered in the previous three sections in relation to the behaviour of the fishing boats. The interaction between these factors is likely to influence the catch per unit effort and it is to this that we now turn.

Thirty-nine sets of the net were observed, of which 33 were successful and six unsuccessful. The tonnages of successful sets were lognormally distributed and have therefore been presented as the geometric mean with 95% confidence intervals in the original scale. The mean of all catches was 66.3 (45.1, 97.5) t, with a minimum of 5 t and a maximum of 630 t which filled the hold of the smaller of the two sample ships.

A net set in the outer margin and outside the fishing groups was less likely to be successful (Fisher's exact test: $p=0.014$, Fig. 8). An analysis of variance of successful catch tonnages showed no significant differences in catch with position in the fishing group ($F_{(3,24)}=0.94$, $p=0.4366$), though mean catch per successful set

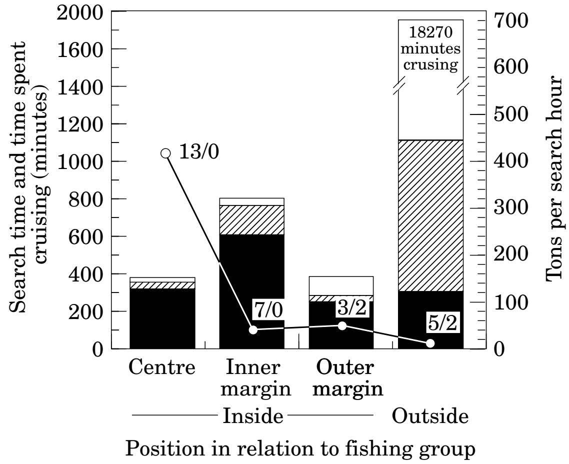

Figure 8. The histograms show the time spent searching with set (■), searching with no set of the net (▨) and cruising (□) plotted for each position within and without fishing groups. Search time was obtained from the number of successful/unsuccessful sets. For exact definitions see methods. The open circles and line show the tonnes of fish caught per search hour. The two numbers next to each point separated by a slash give first the number of hauls observed in that category followed by the number that yielded no fish.

decreased from the core of the fishing groups (91 t) to the outside (33 t).

There was no significant difference in the tonnes caught between the different types of night fishing groups (Table 2a, $F_{(2,20)}=1.204$, $p>0.05$), though the catch from the ephemeral night groups was small. There was no significant difference in catch weight between day and night catches outside the fishing groups. Because of a few very large catches in night groups their total catch was comparatively high (Table 2a). Similarly, the catches were small in the few ephemeral night groups and their total catch was consequently low.

Search time has been partitioned by its spatial location in the fishing group (Fig. 8). Time spent hauling nets and repairing gear is excluded from this analysis. Some basic assumptions have been made in the following analysis; for example that the captains' decision to start searching did not depend on the time of day and that the captains switched from cruising to searching as soon as they encountered suitable conditions unless the boat was full. Data for full boats have been omitted from the search analysis. Mean time for searches which ended in a set was 45 min, the shortest being 10 min and the longest uninterrupted search, 3.5 h. Only the sets for which there were accompanying search data have been used in the analysis.

Within a fishing group, 90% of the time was spent searching. Ninety-four per cent of the time outside the group was spent cruising in to port or to fishing areas. This obvious difference cannot be tested for significance since data on cruising outside and inside fishing groups were collected differently. The ratio of searches that were abandoned to those that ended with a catch was much greater outside than inside fishing groups ($\chi^2=80.75$, df=3, $p=0.0001$). Within fishing groups, the proportion of time spent cruising increased towards the outer margin but the amount of time spent searching stayed the same whether it resulted in a set of the net or not (Fig. 8, $\chi^2=12.99$, df=4, $p=0.011$).

Did the number of sets made and the amount of search time vary with average size of the three zones of a fishing group? Significantly more sets were made in the core and fewer in the outer margin than expected from area size. Only 24% of available time within fishing groups was spent in the outer margin which accounted for 58% of the area (Fig. 8, $\chi^2=75.01$, df=2, $p<0.001$). Time spent in the core and inner margin was in proportion to their areas ($\chi^2=1.944$, df=1, $p=0.16$). The amount of time spent cruising within the three group zones appeared to be proportional to the size of each zone, though samples were too small to test this statistically.

Tables 2a–c show the data from Figure 8 divided further by the type of fishing group and by day and night when ships were outside a group. The total time spent at sea was 16.5 days, an equal amount taken up by night and day taking into account that nights were on average 13 h long. Only 6.5 h of this time was within groups occurring during the day, compared to 72 h in groups occurring at night.

Outside fishing groups day time searches were more likely to be cut short than were night searches (Table 2b, $\chi^2=8.034$, df=1, $p=0.005$). Time spent searching outside fishing groups varied with distance from the shore. Searching outside and inside groups during the day occurred at the same frequency and was within 30 n.mi of the shore 97% of the time. At night, ships outside groups spent 86% of their time within 30 n.mi of the shore but ships in groups spent only 51% of their time this close, a difference that was significant ($\chi^2=24.374$, df=2, $p=0.0001$). Time spent searching within groups during the day was more often in groups close to shore than it was at night ($\chi^2=7.76$, df=2, $p=0.021$). This was clearest within 10 n.mi from the shore where 61% of daytime searching was spent compared to 34% at night.

Time spent hauling in the net and pumping fish into the holds (handling time) was positively related to the size of the catch ([handling time in h]=0.003[t]+1.554, $r^2=0.294$, df=41, $p<0.001$). The mean time spent doing this per set was 1.80 ± 0.6 h. The mean time hauling nets did not differ between types of fishing groups ($F_{(2,21)}=0.122$, $p=0.886$). Time not taken up searching or cruising within fishing groups (overall 66%) was time spent hauling in the nets and, on a few occasions, doing minor repairs. Thus, differences between types of fishing groups in the time spent in activities other than

Table 2. (a) Catches, (b) the partitioning of time, and (c) search effort per set and various estimates of catch per unit effort (CPUE) for the different types of fishing groups and outside them separated out for day and night. Values for ratios and yields have been calculated using untransformed values. Dashes denote values that were inapplicable. Numbers in parentheses for search time ratios are number of screen observations (see Methods).

	Inside fishing groups				Outside fishing groups	
	Persistant night	Night	Ephemeral night	Ephemeral day	Night	Day
(a)						
Catch						
Total no. of successful sets/unsuccessful sets:	7/1	14/0	2/1	0/0	3/0	2/2
Mean catch in tons per successful set: (95% confidence intervals)	94 (53.0, 166.8)	84 (41.0, 172.3)	25 (0.6, 1138.0)	—	41 (4.5, 367.6)	54 (6.6, 445.0)
Total catch (tons):	770	2155	70	0	100	120
(b)						
Time in areas (minutes)						
Index of search time	400	540	190	330	740	350
Abandoned search as % of all search time	0	10	25	42	80	46
Ratio of search time in inner margin to core	3.1	1.9	0.4	4.0	—	
Ratio expected from areas	1.5	2.8	5.2	7.2	—	
Total time spent in zone	1140	2700	480	390	8940	10 080
Mean time spent in group (h)	4.8	5.0	2.7	1.6	—	—
(c)						
Search time per set and CPUE						
Search time per set, excluding abandoned search	50	34	50	—	50	40
Catch per time spent searching (tons per hour)	115.0	239.4	22.1	0.0	8.1	20.6
Catch per total time spent in area (tons per hour)	40.5	47.9	8.8	0.0	0.7	0.7

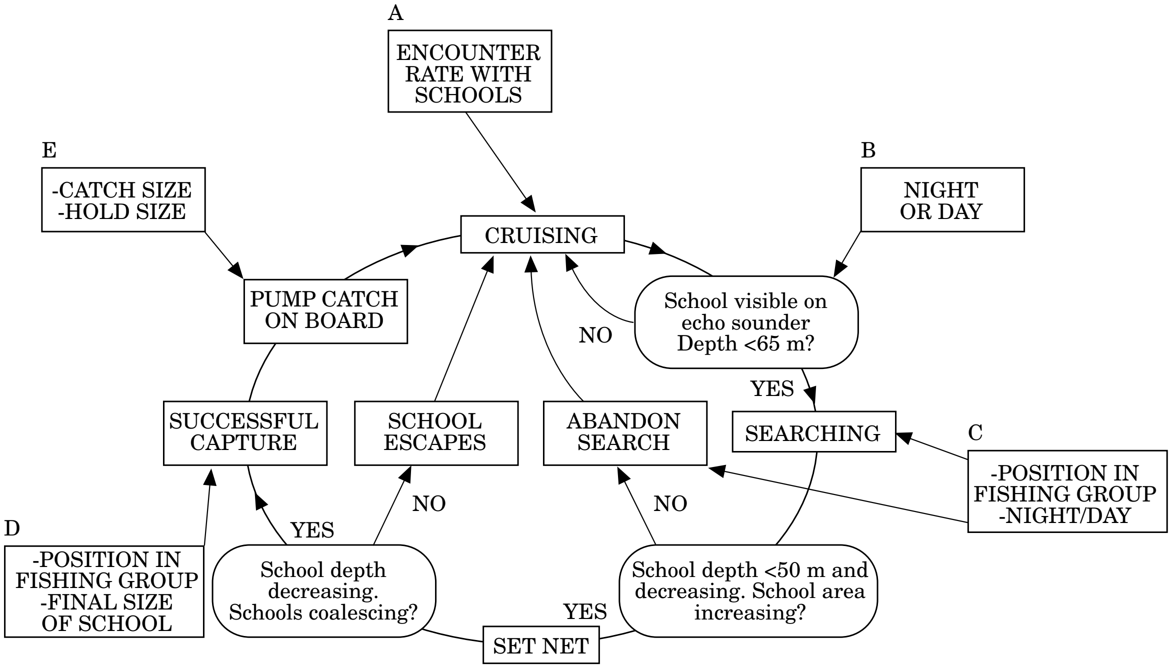

Figure 9. The cycle of decisions and activities during purse-seining with an indication of the factors that alter the decisions that skippers make. The values of factors such as school depth have been derived from this study and are discussed further in the text. The boxes labelled A–E give factors that have been shown by this study to have an effect on the process or decision indicated by the arrow.

searching or cruising can be partly ascribed to the number of sets which had to be hauled in.

Time spent searching before each set of the net was lowest in the core of the fishing group (25 min), highest in the inner margin (87 min) and roughly the same in both the outer margin and outside the group (50 and 45 min, respectively, $\chi^2=38.42$, df=3, p=0.001). There was no overall difference in search time per set within and outside fishing groups.

Time spent searching for each net set was not significantly different between the types of night-time fishing groups though it was lowest in night groups (Table 2c, $\chi^2=3.951$, df=2, p=0.139), nor was there any difference between night or day search and sets outside fishing groups ($\chi^2=0.385$, df=2, p=0.535). There were no sets within ephemeral day fishing groups although search occurred within them which lead subsequently to a set outside the group.

An estimate of catch per unit of time spent searching was obtained by dividing total catch by the sum of search times (Fig. 8). This shows a very large catch per unit of search time in the core of the fishing group of 417 t h^{-1} compared to 40–50 t h^{-1} in the margins and 14 t h^{-1} outside the fishing group.

Discussion

This paper establishes that purse-seiners off south central Chile fish mostly in groups. We have provided data on three aspects of these groups; the structure of the groups (Fig. 4), the behaviour of skippers inside and outside of these groups (Fig. 5), and the characteristics of the fish schools under the groups (Figs 5, 6 and 7). We have also suggested how the ships respond to the behaviour of the fish schools (summarised in Fig. 9).

The structure of fishing groups

Fishing groups have been defined as being collections of ships close together (about 0.6–0.9 n.mi apart) with their nets in the water. Such groups consisted of from 3–14 boats and covered an area of from 0.4–4.5 n.mi^2 (Table 1). Other boats would be found moving within the group. The presence of a group is correlated with higher densities of horse mackerel schools (Fig. 6). The number of schools under the core of a fishing group could be as high as seven schools along a 1500 m transect as opposed to two–four outside the group (Fig. 6). Fishing boats did not stay in the groups more than one night, but very often groups would reform the next night over what appeared to be the same aggregation of fish. Evidence not presented in this paper showed that aggregations of fish steadily move offshore and reformed groups of ships do the same over a two to three day period.

Fish under persistent night and night groups are usually found beyond 30 n.mi from the coast. They contain fish split into about two schools each with a large area (Fig. 6b). The number and area of schools decline only slightly towards the edge of the fishing group. At the centre of the group the schools are, on average, 38 m below the surface but they are deeper at the group margins. In contrast, ephemeral night and day groups have a higher number of smaller schools and these are concentrated into the centre of the fishing group and are closer to the surface, at about 24 m (Fig. 6).

During the winter period studied the fishery was mostly at night. Fish depth varied with time of day so that at night, fish were closer to the surface (Fig. 7). Daytime depths were less, closer to the shore and this may explain why daytime groups were more frequent near the coast.

The aggregations of fish schools being exploited by fishing groups appear to be discrete and well isolated from each other. There were rarely more than two fishing groups in the area studied at any one time and this implies that aggregations are hard to find. It is easier for skippers to find fish by first finding other fishing boats than it is to make an independent search for new aggregations. The low incidence of fish under cruising ships outside groups is support for the hypothesis that fish aggregations contain a much higher concentration of fish than the surrounding water and that the aggregations are far apart. There is no easy technological advance that could improve the large scale search capacity of the individual ships themselves.

Behaviour within the fishing group

Within a group, the schools caught are shallower and smaller than those missed (Fig. 5). These results indicate that there might be preferred positions within the fishing group. If so, there must be competition within a group for access to the schools. One skipper reported that, in his experience, schools are most abundant and closest to the surface at the leading (seaward) edge of the fishing group (O. Guzman, pers. comm.). Skippers move to the leading edge to set their nets and are then overtaken by the rest of the group as the catch is pumped aboard. Further studies should examine the dynamics of ships within fishing groups.

Anecdotal information (P. Campos, O. Guzman, pers. comm.) also indicates that skippers of different skill employ different tactics. The best are less worried by failure and will search on their own when necessary. Skippers of medium skill often hunt together and such groups may also contain a high proportion of related individuals. Groups of individuals that know each other will exchange information about the location of fish which they would not pass to strangers.

Catch per unit effort as a measure of stock abundance

Being in the core of a group gives a vessel a much higher catch per unit effort (CPUE) than being in the margin (Fig. 8). A higher catch and CPUE is also achieved by vessels in groups than those fishing outside (Table 2). The persistent night and night groups give the highest catch rates and searches in them are most likely to end in the net being set. The benefits of being in a group presumably explain why the vessels aggregate.

Catch per unit effort, where effort is measured as search time within a fishing group, is not a good measure of stock abundance for the horse mackerel fishery. The grouping behaviour of the fishermen meant that the effort to find aggregations of fish was not distributed evenly over the area the fish inhabit. CPUE is only a measure of abundance within the area occupied by the fishing group. Over the period covered by the study, fishing groups occurred over the whole of the 16 980 $n.mi^2$ exploited by the fleet. The CPUE at each point sampled in the area will be maintained by the aggregations at an artificially high level. This will be true until the last aggregation of fish is exploited.

To estimate stock density adequately it is necessary to know the relationship between CPUE and the number of fish in an aggregation. In addition, one would need a relationship between search effort (outside fishing groups) and the number of fish aggregations. A further complicating factor is that the aggregations of fish only occur at points of upwelling, although this has not been properly established in this paper. If this is true, then random searching over the whole area would bias the relationship between search time and the number of aggregations. What is required to refine the analysis is improved information on the area where upwelling is likely.

Rules for successful skippers?

To be successful, a skipper needs to complete the cycle in Figure 9 quickly and with a high catch. Our results can be used to deduce a set of provisional rules that would give the skipper the greatest chance of completing the cycle. These rules would be:

1. Be in the core of the fishing group;
2. Be in an ephemeral night group as this would have the
   – shallowest schools
   – the highest number of schools
   – the smallest school areas, particularly in the core;
3. Be close to the shore.

Our data on catches in the different types of fishing group show that the ephemeral night groups did not lead to the highest catches. These came from the persistent night and night groups. This discrepancy needs explaining. Fishing in any particular type of group will involve a trade-off. Ephemeral night groups have a high probability of a catch but yield a low tonnage which must be set against fishing in a persistent night group where the probability of success might be lower, but tonnages caught will be higher. Although conditions for catching fish seemed better close to the shore, there must have been advantages in following schools offshore as this happened quite frequently during the study period.

Technological and biological factors, which we have not quantified, will contribute to the variance of catch size. Some of these might be oceanographic conditions, net size, net condition, the captain's skill at setting the net and, to a lesser extent, the net hauling abilities of the crew. Further human factors, independent of the presence of other fishing boats, that may change search effort and catch success are behaviours such as the captain's awareness of the approaching dawn. This may force him to find a suitable school before it becomes light even though the option chosen is less than optimal.

In a purse-seine fishery of this nature, the amount of time to set and haul the net can be large. An unsuccessful set of the net can incur a high opportunity cost, as the time spent hauling the net and pumping fish on board is generally far greater that the time spent searching per set. The decision to set the net is a considerable one and very much dependent on what the captain observes on his sonar equipment and what he sees other captains doing in the group.

How could effort be limited most effectively?

Following Wilen's (1979) plan we have obtained data on some of the factors that determine the level of effort that can be applied to the horse mackerel stock. Does this information make it any easier to predict the outcome of limitations of effort that might be imposed? Conventional restrictions that would limit effort might be putting a maximum on vessel length, limiting trips to less than two days, limiting net length and depth, setting individual transferable quotas (ITQs), or imposing company quotas. Only the last two might have a chance of working. The remaining measures would encourage vessel operators to invest in equipment that would reduce the time taken to find a suitable school, increase the probability with which it could be caught and reduce the time taken to load the catch onboard.

The least intrusive way to limit effort would be to manipulate the cost/benefit equation made by the skipper as he chooses a course of action, so that he decides of his own volition to apply lower effort. This study has concentrated on elucidating the costs represented by search and capture behaviour. As is typical of most fisheries, these costs have been reduced by technological innovation. Search times are reduced by more and more effective information gained through sophisticated sonar and echo-sounding equipment. For example the Furuno CSH-22F sonar can detect fish 5 km from the ship. The cost of this information to the vessel owner is low, relative to the long-term gains. There is the initial capital cost, which might be as much as \$100 000 for the very powerful Furuno system, but, thereafter, only maintenance charges are required. In the context of a capital outlay of around \$10 million for a new pelagic trawler, the cost of information is low. This suggests that effort could be regulated by imposing a much higher cost on this information, perhaps by taxing the vessel owner every time advanced information systems are used. Such a tax would have to be applied to the use of all technology that reduces the costs of fishing by providing information that lowers uncertainty. The level of taxes would have to be based on a detailed knowledge of the impact information has on the cost benefit equation determining the application of effort. We hope to have shown in this paper how such information can be gained.

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