Concentration profiles and invertebrate fisheries management

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Abstract: The spatial distribution of resources and the behavior of a species lead to a spatial pattern of density which has been called the concentration profile of the species. Some species aggregate and may be found almost entirely at high densities, other species space themselves much more uniformly and are usually found at low densities, and some species are found at a very wide range of densities. The interaction between the concentration profile, fishing, and management behavior leads to a number of surprising consequences. Fishermen will naturally tend to fish in the most profitable places, so that the interaction between the concentration profile of the species and the behavior of the fishermen will lead to a complex spatial pattern in abundance, profitability, and catch per unit effort (CPUE). Among the behaviors that emerge from such analysis are (i) overall CPUE will frequently decline more rapidly than abundance, (ii) CPUE will provide almost no information about abundance that can be used for management except on the smallest of spatial scales, and (iii) changes in price or costs of fishing may have significant impacts on the spatial pattern of fishing effort and the associated CPUE. We illustrate these principles in detail with examples from the Tasmanian abalone fishery on a small scale (tens of metres) and a large scale (hundreds of kilometres). Recognition of the concentration profile of the stock suggests that regulatory measures must be carefully tuned to the biology of the species. CPUE will almost certainly be a very poor measure of stock abundance, while fishery-independent surveys will provide the only reliable method of estimating stock status. Complex spatial structure, with differences in growth and mortality will mean that size limits and harvest rates should be finely tuned to the spatial structure of the stock and cannot be set appropriately over large areas. We consider alternative regulatory schemes such as quotas, seasons, size limits, and territorial fishing rights allocations in relation to concentration profiles and suggest that territorial fishing rights offer the greatest potential benefits.

Résumé : La distribution spatiale des ressources et le comportement d’une espèce mènent à une répartition spatiale de la densité que l’on a appelée le profil de concentration d’une espèce. Certaines espèces se rassemblent et se rencontrent presque exclusivement à des densités élevées, certaines se répartissent de manière beaucoup plus uniforme dans l’espace et, enfin, certaines présentent une répartition selon une très grande variété de densités. L’interaction entre le profil de concentration, la pêche et le comportement de gestion mène à des conséquences étonnantes. Les pêcheurs ont naturellement tendance à pratiquer la pêche dans les endroits où cette activité est le plus rentable, de sorte que l’interaction entre le profil de concentration de l’espèce et le comportement des pêcheurs sera à l’origine d’une distribution spatiale complexe en ce qui a trait à l’abondance, à la rentabilité et les prises par unité d’effort (PUE). Parmi les comportements qui ressortent d’une telle analyse figurent les suivants : (i) le PUE global déclinera fréquemment plus rapidement que l’abondance, (ii) le PUE ne donne presque pas d’information sur l’abondance qui puisse servir à la gestion, sauf à la plus petite des échelles spatiales, et (iii) les changements touchant les prix ou les coûts liés à la pêche peuvent avoir des répercussions substantielles sur la distribution spatiale de l’effort de pêche et le PUE correspondant. Nous illustrons ces principes en détail avec des exemples tirés de la pêcherie d’haliotides de Tasmanie à petite échelle (dizaines de mètres) et à grande échelle (centaines de kilomètres). La reconnaissance du profil de concentration du stock laisse supposer que les mesures de réglementation doivent être soigneusement harmonisées avec l’biologie de l’espèce. Le PUE constituera presque certainement une mesure médiocre de l’abondance du stock, alors que les relevés indépendants de la pêcherie constituent la seule méthode fiable pour estimer l’état du stock. La structure spatiale complexe, comportant des différences en ce qui a trait à la croissance et à la mortalité, signifiera que les limites de taille et les taux de récolte devront être ajustés finement à la structure spatiale du stock et qu’ils ne peuvent être appliqués de manière appropriée sur de vastes étendues. Nous prenons en considération d’autres mesures de réglementation comme l’attribution de quotas, les saisons de pêche, les limites de taille et les droits de pêche territoriaux en rapport avec les profils de concentration et estimons que ce sont les droits de pêche territoriaux qui présentent le plus d’avantages potentiels. [Traduit par la Rédaction]

Introduction

Few invertebrate resources are spatially homogeneous, individuals are almost always found in higher concentrations in some locations. This distribution of concentrations has many implications for the biology and management of invertebrates and its importance has been noted for many years. Gross and Smyth (1946) suggested that very high density concentrations of oysters may be required for reproductive success. Caddy (1975) and Orensanz (1986) described the spatial pattern of...
Fig. 1. Types of concentration profiles.

concentration in different scallop populations and discussed biological and management implications of these distributions.

Clark (1982) introduced the term "concentration profile" to the fisheries literature and considered a number of theoretical implications of different concentration profiles on the behavior of fishermen and interpretation of catch-per-unit-effort (CPUE). Clark borrowed the term from mining, where the concentration profile refers to how much of the desired mineral can be found at different concentrations in the ground. For any mineral, the profitability of mining depends primarily on how much recoverable mineral there is per ton of material processed. Below some concentrations it is not economic to process the material. A potential miner is not interested so much in how much mineral is in an area as he is in the amount of ore that exists at profitable concentrations.

This is equally true of fishers. Most fish do not occur at densities that can be profitably harvested, yet the key to an economically viable fishery is the number of fish that can be found at high concentrations. Clark introduced four types of concentration profiles, shown in Fig. 1. Type I profiles have a diminishing number of individuals found at higher densities; type II profiles have a uniform distribution; type III have individuals spread out over a range of densities with most found at an intermediate density; and type IV profiles have almost all individuals found at a single density.

Concentration profiles for anchovy in California and skipjack tuna in the western Pacific were shown in Hilborn and Walters (1992). Both showed type III profiles. The data from Orensanz (1986) are shown as a concentration profile in Fig. 2. It appears to be a type II profile.

Concentration profiles result from the interaction of habitat quality, the behavior of the fish, and the harvesting history. For instance, type IV profiles would be expected to result if the fish were highly aggregating, whereas a type I might result if fish density depended exclusively upon habitat quality and there were many more poor than good areas.

The purpose of this paper is to review what is known about the concentration profiles in invertebrate fisheries and consider the implications of concentration profiles for management. We begin with a discussion of the interaction between concentration profiles and fishermen's behavior and then explore examples of the small-scale and large-scale concentration profiles for abalone in Tasmania.

Fishermen's behavior and concentration profiles

The earliest formal theory of how fishermen will respond to the concentration profile of the fish stock was described by Gordon (1953), who suggested that fishermen would attempt to maximize their profits by optimizing the costs of fishing with the rates of return. If the initial abundance of a fish resource was uniform, fishermen would begin by fishing close to home port, and as local stocks became depleted, they would move farther away, at all times assuring that the expected rate of return in all areas fished was the same. If for some reason the rate of return (income minus costs) were to rise in an area relative to other areas, additional effort would flow into that area, and if the rate of return were to drop relative to other areas, then effort would leave.

Beverton and Holt (1957) provide a similar discussion, and the theory was popularized in the ecological literature by Flewell and Lucas (1970) and given the name of "ideal free distribution." Hilborn and Ledbetter (1979) showed that
fishermen in the British Columbia purse seine fishery appeared to behave according to these rules, and Clark (1982, 1985) used this theory in his analysis of the implications of concentration profiles. Since then a number of authors have found that fishermen behave as predicted (Abrahams and Healey 1990; Hilborn and Kennedy 1992).

If we assume that fishermen have good information about the location and density of the population or can learn this in the process of fishing, then it is quite natural that fishers will begin fishing at the highest concentrations and gradually work down to lower concentrations until they reach a concentration at which fishing is no longer profitable. The threshold of profitability will depend upon a number of factors associated with the cost of fishing, which may include distance from port, probability of gear loss, depth, etc. In the aggregate, however, we would expect that the natural pattern would be for the highest concentrations to be removed first.

As discussed in Hilborn and Walters (1992) such a behavior would mean that in a type I profile the CPUE would initially decline more rapidly than abundance. The few very good sites would be fished first and, assuming the CPUE depends on the density in the area fished, as fishermen moved to lower density sites, the CPUE would drop. If the concentration profile had a long right tail, the CPUE might initially drop substantially even if only a very small fraction of the total population had been removed. However, with a type IV profile, the CPUE would stay constant while the population was being depleted, a phenomenon that has been observed with a number of strongly schooling fish.

Assuming there are differential costs of fishing in different areas, the CPUE will reflect the costs of fishing at any time in the development of the fishery, so that the profitability in each area will be the same. Areas with high costs will have higher CPUE. Under such circumstances, changes in price will have a significant effect on CPUE. If the price of the product goes up, areas of high CPUE would be relatively more profitable and areas which had not been profitable before would suddenly become profitable, and it has been shown (Hilborn and Walters 1987) that the average CPUE can increase. Similarly, if prices dropped, CPUE would be expected to decrease. Thus aggregate measures of CPUE are subject to changes in the price and cost of fishing in a rather surprising fashion.

Small-scale concentration profiles

The nature of small-scale concentration profiles was demonstrated in an experiment conducted by Prince (1989). A small reef in Tasmania, named George III rock, had been maintained as a reserve for abalone for a number of years. In July of 1987, four volunteer licensed abalone divers spent seven days fishing this reef, recording each dive location and the catch. In the first few days most divers concentrated on the shallow areas of the reef where most abalone were found. As the shallower areas were fished down, the divers moved to deeper areas of the reef where densities had initially been lower. Figure 3 shows the CPUE in abalone per minute at the beginning of the experiment and at the end. Whereas initially the CPUE was much higher in shallow sites, by the end of the 7 days of fishing the CPUE was higher in deeper sites. This is all consistent with the theory that divers prefer to work in shallow water because of health and comfort considerations, and that in a “developed” fishery, the CPUE will be higher at high-cost (in this case deeper) sites.

The reef was divided into 29 roughly equal-sized areas and an analysis of the initial densities in each area revealed a type III or type IV concentration profile. This experiment demonstrated that concentration profiles exist on very small scales; the George III rock was <1 km². This distribution of differential densities after the fishery is presumably what the
Fig. 3. Kilograms of abalone captured per minute plotted against depth shown for the first days diving (light bars) and the last days diving (dark bars) from the George III reef.

Fig. 4. Total catch (light line) and effort (dark line) for the Tasmanian abalone fishery.

fine scale structure of abalone abundance looks like throughout Tasmania and likely wherever species like abalone occur and are fished. The key observation is that the initial high concentration sites will be fished down and the remaining concentration profile will reflect the cost of fishing, with deep areas having higher concentrations than shallow areas. Areas that have high costs of fishing for other reasons would also be expected to have high concentrations.

Large-scale concentration profiles

We can use this understanding of the determinants of where
Fig. 5. CPUE trends in Tasmanian abalone fishery. The thick line in the middle represents average CPUE, the thin line on top is the CPUE for west coast sites, and the thin line on the bottom is CPUE for east coast sites.

Fig. 6. Map of Tasmania showing statistical areas; circles represent number of individual licensed divers with a home in each community.

Historical trends
Prior to 1963, the Tasmania abalone stock was essentially untouched, but by 1963, modern diving equipment and the recognition of Asian markets provided the needed basis for the modern industry. Figure 4 shows the catch and effort trends in the fishery from 1965 to 1987. Total catch rose rapidly from 1963 to 1967, fluctuated between 2500 and 3500 tons between 1967 and 1975, and rose steadily until 1984, when a system of individual transferable quotas was introduced. Effort shows essentially the same trends with somewhat less variation between 1967 and 1975.

Figure 5 shows the trends in catch-per-unit-effort, measured in kilograms per diver-hour under water for the west coast, east coast, and total. The total pattern is rather stable, with a small initial drop in CPUE, a rise in 1970 and 1971, followed by another small decline, and then minor fluctuations. If we were to assume that CPUE is proportional to abundance, our interpretation would be that there had been only a minor decline in abundance since the development of the fishery. The fact that CPUE has remained essentially unchanged since 1974 while effort and catch have tripled, suggests either that the stock is remarkably resilient, or that CPUE is not proportional to abundance. We consider alternative interpretations of the CPUE trend in a later section, but to do this it is necessary to first examine the mechanics of the abalone fishery.

Abalone are taken from rocky bottom areas between 2 and
30 m in depth around the entire coast of Tasmania. There are 125 licensed divers who must do their own diving. Divers operate from small, outboard-powered boats, either 4-m dinghies or 7-m runabouts, using hookah gear which pumps air to the diver from the surface. Nearly all divers employ a surface deckhand who manipulates the boat and lifts nets of harvested abalone into the vessel. The divers typically spend 4–5 h per day under water and move along the bottom, harvesting all abalone above the legal size limit. Although diving methods do differ between individuals, divers typically might search 20 m²·min⁻¹ and encounter 0.1–2.0 abalone·m⁻².

Most divers prefer to undertake daily fishing trips from their home ports using the larger, twin-hulled, 7-m runabouts. The range on these trips is generally 20–40 km from the point of launching, although distances as great as 80 km may be traveled if the weather is favorable. The best fishing grounds, however, are on the isolated west coast of Tasmania. Divers fish these areas on extended trips (3–7 days), operating from 15 to 30 m motherships, with each diver and his assistant using a 4-m dinghy for daily trips up to 15 km away from the mothership.

Spatial structure
Figure 6 shows a map of Tasmania with the statistical areas used for the collection of abalone data. Also shown are the major home ports of abalone fishermen, with the size of the circle representing the number of divers who live in those communities. Nearly all divers live on the east coast which is well serviced by roads and has many small communities. In contrast, the west coast is very isolated, has only one real access point at Strahan, and is far from the major urban centers of Hobart and Launceston.

Figure 7 shows the distribution of abalone catch (bar graph), with totals from 1965 to 1986 by statistical area. The catch comes predominantly from the west coast and a second area of major productivity on the south and east coasts. The north coast and Flinders and King Islands are unproductive. Figure 7 also shows the average catch rate (kg·h⁻¹) from 1965 to 1986 by statistical area. The data lump quite nicely into two groups, the west coast (areas 5–12) and the south and east coasts (areas 13–31). We can ignore areas 1–4 and areas 32–49 simply because the total catch in these areas is trivial. We therefore consider the fishery as consisting of two major areas, the west coast which is far from home, exposed to the prevailing winds and has few safe shelters, and the east coast which is close to home, to the leeward, and has many ports and protected anchorages. The west coast has high catch rates, the east coast has low catch rates.

Alternative hypotheses
Alternative hypotheses to explain the trend in CPUE have been discussed by Harrison (1983) and include increased mechanical efficiency, motivation, and skill. Harrison's primary concern was to attempt to calibrate the data to be used in stock assessment. In this paper we are primarily interested in describing the characteristics of the fishery and how different mechanisms interact to produce observed CPUE trends. We will not attempt to produce a final 'calibrated' CPUE trend and, indeed, we believe this cannot and should not be done.

We begin by discussing alternative hypotheses, the details of the hypotheses, and how the concentration profiles, on the small and large scale, would impact them. In the subsequent section we will look at particular aspects of the spatial structure and the CPUE trends to try to understand the relative importance of the different mechanisms.

Fishermen's movement
The spatial structure of the fishery and the sedentary nature of
the exploited stocks assure that movement patterns will have an important effect on catch rates. This has been noted previously as an important factor for other abalone fisheries. In the simplest case, we might imagine a pattern of sequential depletion where divers simply clean out reefs that are close to harbors and anchorages and then move farther and farther away. The CPUE could easily stay constant while the total abundance declined drastically. Abalone fisheries would therefore be more like mining operations than fisheries. However, we believe more complex interactions between movement, stock abundance, and motivation of divers continue to occur over the complete range of spatial scales and these will be examined below.

**Increased mechanical efficiency**

Two major technical changes have taken place since the beginning of the fishery. Before 1969, hookah equipment displaced SCUBA equipment, extending the time available for diving, and reducing the amount of equipment required, and since about 1971, divers employ deckhands who follow them with the vessels and untangle air hoses, allowing unrestricted movement. Moreover, diving suits continue to be more efficient and more comfortable, enabling divers to spend more time underwater. The use of dive computers and motherships have also been noted as technical innovations increasing efficiency.

We expect these increases in mechanical efficiency to affect the fishery in two substantially different ways. The use of hookah equipment and improvements in diving suits increased the number of hours spent diving each day without a major effect on the hourly catch rate, whereas the use of deckhands should have directly affected the catch rates without increasing the total hours worked.

**Increasing knowledge and skill**

Diver skill can vary within the fishery both individually and collectively. The rudimentary skill of hookah diving is easily acquired, but the real skill of an abalone diver is his ability to quickly locate abalone stocks in unfamiliar areas and to be able to find these stocks again in the future. Another aspect of diver skill involves the knowledge a diver accumulates about stock abundance and his general familiarity with fishing sites. We examined the catch rate of new divers against the number of months they had been in the fishery and found that while their initial catch rates were about 30 kg·h⁻¹, within five months they were catching 60–70 kg·h⁻¹ and this did not change with more experience. This rise in catch rate will reflect both increasing skill/experience and may also reflect a willingness of new divers to fish at deeper sites. This we cannot document but it is related to motivation.

**Motivation**

Once we accept the small-scale and large-scale concentration profiles and the interaction between costs of fishing and CPUE, motivation determines individual diver’s choice of where to fish. On the small scale this reflects how frequently they will be willing to dive deep, and on the large scale how frequently they will go to the west coast. The need to earn income can be a primary influence on a diver’s motivation. A diver seeking to service debts, establish himself financially, and purchase fishing equipment in the early years of his career will almost certainly be willing to dive deeper or go to the west coast more often than divers who are financially secure.

The price offered for abalone has fluctuated widely at times (Fig. 8) and has also affected the motivation of divers. High prices encourage divers to work hard and take advantage of “windfall profits,” while low prices may reduce or increase the motivation of divers depending on their financial need. Those with a high need may be forced to work harder, while others may choose not to land catch at the lower price.

Competition is also a source of motivation. Harrison (1983)
reported that established divers without financial needs increased their fishing activity purely to compete with the new, harder-working divers who entered the industry after 1974.

Motivation determines how a diver allocates his effort over a range of fishing sites. Divers will seek to minimize their risk and maximize their comfort both within their general life-style and within their diving practice. To maximize comfort, divers favor short day trips from their home ports rather than extended trips. This gives them more time to enjoy being at home with their families. Many divers prefer to work exclusively from their home ports and avoid extended trips to the west and south coasts. The preference for fishing close to home has been discussed in the literature as theoretically reasonable (Gordon 1954, Beverton and Holt 1957), and has been demonstrated empirically (Hilborn and Ledbetter 1979).

A constant concern is diving-related diseases, particularly dysbaric osteonecrosis, exacerbated by diving time and depth, which causes divers to favor diving in shallow depths (<10 m). This concern and the concerns about the bends are the two major reasons for divers' preference of shallow areas.

Specific events

We can use our understanding of the interaction of concentration profiles and divers' behavior to analyze the historical development of the fishery. In this section we divide this history into a number of periods, characterized primarily by licensing changes and consequent changes on motivation and license price, and discuss what we believe explains the changes that occurred.

1965–1968 Development of the fishery

Until 1969, anyone could enter the fishery for an annual $5.00 license fee. There were few full-time abalone divers since most divers held full-time jobs outside the fishing sector. Figure 5 shows the CPUE trends for the total fishery, as well as west coast and east coast areas separately. The total CPUE declines rather strongly during this period, dropping roughly 35% between 1965 and 1968. This is almost certainly due to declining abalone abundance, moderated by considerable improvement in diving equipment, practices, and knowledge of the diving areas. Harrison (1983) estimated that diving efficiency was twice as high in 1969 as in 1965. Much of this increasing efficiency would have been communal rather than personal since anecdotal information suggests a great turnover of divers during this period. Of particular interest is the marked decline of the fishery on the east coast during the first ten years, without developing a similar pattern on the west coast.

1969–1974 Limited entry, but nontransferable licenses

In 1969, limited entry was introduced. Fishermen had to earn their income primarily from the fishery, forcing them to be full-time divers. These measures, along with the introduction of an annual $100 license fee decreased the number of divers from over 250 to 120 (in 1973, an additional five restricted divers were allowed entry). This resulted in an overall decrease in effort between 1968 and 1969 (Fig. 4). The drop is not proportional to the number of divers leaving the fishery because the number of hours per diver-day increased slightly and the number of days in the water per diver increased by approximately 40%. During this time, licenses could not be transferred; a diver wishing to leave the industry relinquished his diving entitlement to the state fisheries department which reallocated the license to the next person on a waiting list of applicants. Because of this very few divers left the industry during this period. The year 1969 provides a major breakpoint in terms of professionalism and motivation. While the price remained relatively low, the divers involved had the economic need to upgrade their equipment to a professional standard and the desire to establish themselves economically.

Divers' motivation is thought to have dropped considerably during 1972–1974. This is consistent with the fact that the number of hours dived per day declined while the number of days dived remained stable. Moreover, the proportion of effort expended on the west coast declined. This should be expected, since the divers did well financially during 1969–1971. They are likely to have had low levels of debt as they did not have to buy an entitlement to enter the industry. They also had the benefit of fishing relatively virgin stocks on the west coast.

In other Australian fisheries this had already happened, effectively allowing fishermen to sell their fishing entitlement on the open market. In 1972, the government announced that it would implement this system of license transfer to promote a turnover of divers and ameliorate the effect of diving diseases, but later that year it reversed its decision. The effect was that most divers felt the change would eventually be made and those divers wishing to leave the industry remained in it anticipating a 'windfall' profit when the legislation eventually changed. This can also be expected to have decreased the divers' incentive.

1975–1984 Transferable licenses

In August 1974, the government allowed divers to sell their licenses to people wishing to enter the industry. This period was marked by generally rising levels of effort as divers fished more days of the year and more hours each day. This resulted in rising catches, as would be expected, but it was also associated with a slight overall rise in the CPUE, particularly on the west coast. There is evidence that a range of the factors discussed above influenced these trends.

The initial period of license transferability was marked by an influx of experienced abalone divers, particularly in 1977, from the more northern Australian state of New South Wales (NSW) which resulted in a jump of the price of Tasmanian entitlements from $10 000 to $40 000. The abalone fishery in NSW was being reviewed at this time and the long-term outlook was poor, prompting many NSW divers to buy into Tasmanian entitlements. These divers had a more professional approach to their diving, having come from the most competitive and heavily exploited abalone fishery in Australia. Their attitude introduced new techniques and a new competitive spirit. Because of the warmer northern waters, NSW divers expected to dive more days per year than their Tasmanian counterparts. This may explain why the total level of effort increased. The rise in CPUE observed on the east coast at this time is almost associated with the widespread introduction of deckhands.
In the period from 1983 to 1984, divers were anticipating the imposition of some restrictive management policy to conserve stocks which greatly increased their incentive as they tried to maximize cash flow before any restrictive legislation was passed. Effort and catch both increased by about 20–25%, effort because of more days and more hours per day dived as well as more fishing on the west coast. This was accompanied by marked and sustained increases in CPUE in 1969–1970 and 1975–1976, but when the level of exploitation was lower in 1983, it resulted in only a slight increase in CPUE, and CPUE declined in 1984.

In 1984, it was announced that individual transferable quotas would be introduced in the following year. Many divers believed that the immediate reduction in the average catch from 36 to 31 tons per diver would substantially reduce the value of entitlements and sold out during 1984. This led to a large number of new and inexperienced divers entering the industry. However, it is difficult to determine what changes this inexperience wrought, since it is confounded with the major structural changes caused by the introduction of individual, transferable quotas (ITQs).

1985–1986 Individual, transferable quotas

In 1985, a system of individual, transferable quotas (28 units per diver, each unit being initially valued at 1.1 tons) was introduced. The level of catch was further reduced in 1986 (each unit being valued at 1.0 ton). The introduction of ITQs directly decreased the level of catch and effort, and this, combined with rapidly rising prices ($14.00 per kg in 1986), has meant that there is less incentive for divers to dive in risky or uncomfortable areas. Divers say that the level of competition between them has gone down sharply since the introduction of ITQs, further reducing motivation. This reduction in motivation has been associated with a declining CPUE throughout the state, a fall in the percent of fishing effort allocated to the west coast, and a reduction in the number of hours dived each day and the number of days dived per year. Other factors have undoubtedly also influenced the latest decline in CPUE, including the level of aggregate experience which declined through 1984 and declining stock abundance, both of which have already been discussed.

Summary of Tasmanian abalone fishery

Figure 7 in many ways summarizes the large-scale picture of the Tasmanian abalone fishery. The average CPUE in each area should reflect the abundance at the best fishing areas, and we can see that this is driven by costs of fishing; the west coast has consistently higher CPUE than other areas. It may be obvious, but CPUE is entirely unrelated to total abundance of abalone in a statistical area, high CPUE areas 7 and 8 have no more total removals than most of the east coast areas (20–31). Areas that have almost no catch at all (37–46) still have the same CPUE as most other areas.

We were able to quantitatively discuss changes in one key motivational factor, price, and showed that changes in price are associated with changes in the behavior of divers. We believe that indebtedness is an even more important factor in motivation but have not been able to quantify levels of indebtedness.

The historical approach to fisheries stock assessment was to try to calibrate CPUE sequences from large spatial areas as shown in Fig. 5 and use this as an index of abundance as Harrison (1983) did. With spatially complex fisheries such an approach is very difficult, and we find it hard to imagine a circumstance under which it would prove useful. Since CPUE will be the result of a complex interaction between the spatial structure of the resource, and the fishermen’s motivation and cost, it is hard to imagine how all these factors could be accounted for.

Implications of concentration profiles for management

We have shown how concentration profiles make use of any aggregate CPUE data as an index of abundance very difficult. If one could obtain CPUE data on the spatial scale of the resource, that is patch by patch, catch and effort data could form a very effective monitoring tool. One could follow the evolution of effort, catch, and CPUE and probably understand the evolution of the fishery quite well. We know of no fisheries where such a detailed data collection system is currently in place, and there are many obstacles. First it would require very accurate mapping of catch and effort, at least for abalone, at a resolution finer than that offered by current GPS systems. For abalone such a system would have to be used by the diver under water. Even if such a system were possible, it is likely that the CPUE data would simply record when individual patches were fished to commercial extinction; the natural behavior of fishermen would be not to sample many sites with CPUE lower than those obtainable at other sites. Thus one would always be uncertain how many sites were available at CPUE less than the current commercial norm.

The alternative to detailed mapping of CPUE would be to have a very intense stratified survey system, which would record both the number of patches of different densities as well as the total area of the patch. If each of the 120 licensed abalone divers were to dive two days per year in known areas and record the catch for that area, we would have an extremely valuable data base at very little cost to the management agency. In a situation such as this, with ITQs, it would probably be very easy to convince the divers that it was in their own interest to conduct such systematic surveys. Even if only half of them actually participated, the data would be most valuable.

As more fisheries move to ITQ management, concentration profiles will play a major role in affecting the resulting CPUE. When ITQs are imposed on a fishery that has taken place in a very short period as, for instance, in the U.S. and Canadian fisheries for Pacific halibut, we might expect that CPUE would drop as the economic incentives for maximizing catch rate are replaced by economic incentives to maximize profits. However, if the fishery has taken place in a very short period of time, the high CPUE sites were probably subject to intense competition for access, and many participants were likely forced to fish in lower CPUE sites. Under an ITQ fishery, with months instead of days to take the total catch, fishermen may then concentrate on the high CPUE sites and we should not be surprised at all by a rise in CPUE.

A key biological concern is that reproductive success depends on spawning density in many invertebrate species, and the natural behavior of fishermen is to fish the highest density sites and thus destroy the most valuable breeding concentrations. None of the current management tools in use, seasons,
size limits, total quota, or ITQ will prevent this rather natural behavior. Two possible methods to prevent the depletion of high-density sites are to set up sanctuaries at these sites, or to set up territorial fishing rights where the territory's owner(s) would have natural incentives to maintain the most valuable high-density concentrations. If reproductive concentrations are seasonal, then temporal closures could present overexploitation of these concentrations.

Concentration profiles pose a number of difficulties for tagging studies. If we are dealing with a large number of distinct populations, it will be natural to tag where high CPUE can be obtained, and indeed it is unlikely we would ever apply many tags in areas of low CPUE. If the population is not evenly mixed, this means we would effectively be estimating the population in the high CPUE sites and ignoring, in our population estimates, those individuals found in low CPUE sites. This may not be critical to the individual study as the tagging study may be aimed at determining attributes of the high CPUE sites, but any attempt to estimate total abundance in a spatially structured fishery is bound to produce an underestimate.

Thus far our discussion of concentration profiles has centered exclusively on the distribution of density. In spatially complex fisheries other factors differ from site to site and these too have an important impact on management. If, for instance, there is a complex spatial pattern of growth rates, as there is for abalone, then the appropriate size limit for one site may be very different from another one. Individuals in low productivity, slow-growth sites may never reach the legal size limit.

When we expand our thinking of concentration profiles beyond pure abundance and begin to think of the invertebrate resources as complex spatial patterns, we see that many of the management approaches we have used are far from optimal.

The presence of concentration profiles poses many challenges to managers. It is difficult both to monitor the stock abundance and find management regulations that will be appropriate for the biology of the stock. One possible solution to both of these problems is territorial fishing rights. If cooperatives, or individuals, are assigned the exclusive right to fish in certain areas, it will be in their interest to set up a survey system that monitors the abundance and to use harvest policies that are appropriate for the spatial variation in growth and mortality. Just as one cannot imagine large-scale regulation of what crops to plant or how much fertilizer to use for farmers facing a range of different soil types, it is impossible to imagine that any large-scale fishing regulations would be appropriate for spatially structured stocks. Detailed top-down monitoring and regulation by small spatial area is certainly another possibility, but this would be very expensive to maintain.

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