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An ecological view of the tuna–dolphin problem: impacts and trade-offs

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Abstract

After a brief description of purse seining and the other methods used to catch yellowfin tuna in the eastern Pacific Ocean, some considerations are made on the tuna–dolphin association and the solution of the problem of dolphin mortality in the eastern Pacific. The association has been observed in other ocenas, but the frequency of setting in the eastern Pacific is much greater.

The mortalities of dolphins through fishing have declined from about 133 000 in 1986 to around 2600 in 1996. The impact of recent levels of mortality on the dolphin populations is not significant from the population point of view. The mortality levels for all the stocks are less than 0.1%, much lower than the 2% value used as a conservative (low) estimate of net recruitment. All dolphin stocks have population sizes between 400 000 and 2 200 000, and most have remained stable for a decade or more.

Fishing operations can cause ecological impacts of different types: bycatches, damage to the habitat, mortality caused by lost or discarded gear, pollution, generation of marine debris, etc. A brief discussion follows, with a more detailed look at the bycatches. For convenience we can separate the effects of the fishery on the target species, and on other species. Of the different ways of purse seining for tunas, sets on dolphins catch tuna close to the optimum size to maximize yields and to allow for reproduction, and result in discards of tunas of less than 1% of the catch. Sets on logs catch small tunas, and result in the highest tuna discards (20–25%). School sets fall in the middle from the point of view of the sizes caught. Obviously, from the ecological point of view, sets on dolphins are the best way to harvest yellowfin tuna.

After a discussion of the different ecological impacts a fishery can cause to other species on the habitat, a comparison is made of the bycatches generated by the different types of purse seine sets. Billfishes, sharks, mahi-mahi, wahoo and sea turtles are taken as incidental catches by purse seiners. Log sets produce, by far, the largest bycatches, followed by school sets and dolphin sets in that order. The bycatch levels in log sets are usually tens to hundreds of times those in dolphin sets. The difference can be attributed to the selection caused by the speed of movement of the tuna–dolphin group (slow-moving species or individuals cannot keep up with the group), an effect that may be magnified by the chase that precedes the dolphin sets. Log sets, on the other hand, are made on a drifting community. The alternatives left to the fishers if they were forced to switch from the current fishing methods to others are briefly discussed, considering their feasibility, and comparing their ecological costs.

From the ecological point of view, and considering that the dolphin mortality is clearly sustainable, the impacts caused by the other types of sets, especially log sets, could be more significant than those caused by the dolphin sets. Some of the species taken in log sets are endangered (e.g. sea turtles), others have unknown status and potential vulnerability because of their low reproductive and juvenile survival rates (e.g. sharks). Overall, the biodiversity of the eastern Pacific appears to be better preserved by a fishery directed to dolphin sets than the other alternatives proposed for the purse seine and for other gears.

Keywords: bycatch, dolphin, tuna

Introduction

The American purse seine fishery for tunas in the eastern Pacific Ocean started in the late 1950s and largely replaced the pole-and-line fishery that had been operating for decades. The new fishery had much higher catch rates, a broader range of operations, and other characteristics that made it very successful from the point of view of increasing tuna catches (Francis *et al*., 1992). However, this new fishery had an unwanted consequence: often the schools of tunas were detected, and eventually encircled together with large herds of dolphins. As the fishers did not have the sophisticated gear or techniques needed to release the dolphins, many of them were incidentally killed in the operations. When the public became aware of the magnitude of this mortality (Perrin, 1968, 1969), the outcry was one of the driving forces behind the passage of the *Marine Mammal Protection Act* of 1972 by the US Congress. The level of dolphin mortality during the 1960s was estimated to be several hundreds of thousands of animals per year (Smith, 1983; Lo and Smith, 1986; Wade, 1995), but the data available were far too limited to provide precise estimates (Smith and Lo, 1983). The mortality was not sustainable, and most dolphin populations declined until the late 1970s (Anganuzzi and Buckland, 1994). By 1996, however, incidental dolphin mortality had been reduced to close to 2500, and the population decline had been stopped. In recent years, some sectors of the environmental community had pushed the US and other governments to ban all fishing for tunas associated with dolphins. If the fishery were to switch to alternative ways of fishing, dolphin mortality in the eastern Pacific might decline even further, but other unwanted consequences of fishing, such as discards and reduced yields per recruit of tunas, and bycatches of other species, would increase considerably. The objective of this review is to bring together the known impacts and trade-offs that would accompany this change, and to try to compare, from the ecological point of view, the different alternatives available to the fishers and to the managers of the fishery in their pursuit of a solution that allows a rational use of the tuna resources while providing for adequate protection for the dolphins and other components of the ecosystem.

Brief history of the fishery

Fishing for tunas has taken place in the eastern Pacific Ocean since early in the 20th century. The main targets are the yellowfin tuna, *Thunnus albacares*, the skipjack tuna, *Katsuwonus pelamis*, and the bigeye tuna, *Thunnus obesus* (all from the Fam. Scombridae). Previous to about 1960, most of the vessels were pole-and-line vessels, operating from California ports. They used live bait, and stayed mostly in coastal waters because of limitations imposed by the need to renew the bait when exhausted. A new technology resulting from several technical developments, the purse seine, began to replace the bait-boats in the late 1950s (Alverson, 1960; Broadhead, 1962; Green *et al.*, 1971; Cole, 1980). Purse seine vessels also fished principally off Baja California and California in the early years of this fishery (Shimada and Schaefer, 1956). The success of the purse seiners (higher catch rates, independence from the use of bait) led to the construction of more and bigger vessels, that expanded rapidly the range of the fishery to the southern and offshore areas. They could at sea for longer periods and they were capable of operating far offshore. These vessels could surround the school of tunas with a wall of netting about 1.6 km long and 200 m deep, and when the circle is completed, a cable passing through rings at the bottom of the net is pulled aboard the vessel, closing the lower part of the net, forming a 'purse'. Each of these operations is called a set. Purse seining, as it is currently practised, is described by Ben-Yami (1994) and Sainsbury (1996). Most of the tunas caught in the purse seine fisheries are used by the canning industry.

Tunas are also caught in the eastern Pacific Ocean by longline vessels (Nakano and Bayliff, 1992). Lines of up to 120 km long with baited hooks are deployed at different depths, depending on the preferred targets. These vessels, most of which are based in Japan or Hawaii, catch several species of tunas, including yellowfin, and also billfishes (Fam. Istiophoridae and Xiphiidae) and sharks. The yellowfin caught are large (modal length 130–140 cm, modal weight 46–58 kg in 1981–1987; Nakano and Bayliff, 1992), but the catch rates of longliners are much less than those of purse seiners. There are several reasons for the difference in efficiency: (i) purse seines are directed at, and take, whole schools of tunas while longlines are passive and take the fish individually; and (ii) longliners' main target is bigeye tuna, not yellowfin, so the gear is deployed at greater depths, where bigeye concentrations are found. Most of the tunas caught in the longline fisheries are used by the sashimi industry or by the fresh-fish market.

Finally, there are still some pole-and-line boats operating in the eastern Pacific. This method of fishing was described by Godsil (1938). They carry live bait in tanks, and when they encounter a school of tunas, they chum the waters with the bait. When the tuna begin taking the bait, the fishers use unbaited hooks to catch them. This technique is limited to some coastal areas because of the difficulties in keeping the bait alive, and the results in catches of mostly small fishes (Tomlinson *et al.*, 1992). In terms of catch per day at sea, it is not very productive. In the past, it has had problems with depletion of bait.

Types of purse seine sets

Purse seining is conducted in three different ways that correspond to three ways of detecting the tuna schools: (a) on free-swimming schools of tuna; (b) on tunas associated with floating objects; and (c) on dolphins.

On free-swimming (un-associated) schools of tuna. A tuna school is detected by evidence of its presence on the surface of the ocean, i.e. the water appears to be 'boiling' or its surface is disturbed by what appears to be a local breeze, etc. Frequently, birds associated with the tuna school are detected from the vessel with radar. This operation is called school fishing, and the sets are called school sets. This technique usually produces small yellowfin (modal size of 50 cm, or 2.5 kg, for the period 1976–1995, Fig. 2(b), below) and skipjack tuna.

On tunas associated with floating objects. Tuna schools tend to associate with floating objects during the night, and then leave them early in the morning. When the fishers find a floating object with tuna around it they surround it with the net shortly after sunrise, capturing the fish associated with the object. Because the most common objects are tree trunks and branches, this method of fishing is called log-fishing, and the sets are called log sets. This technique catches very small yellowfin (modal size of 40 cm, or 1.2 kg, for the period 1976–1995, Fig. 2(a), below) and skipjack tuna.

On dolphins. In the eastern Pacific, yellowfin tuna are frequently found associated with groups of dolphins. It is not known why they associate, but most researchers believe, based in part on the way in which the fishery operates, that the tunas follow the dolphins. Most of the hypotheses proposed to explain the association are based on trophic reasons or predator protection (Perrin *et al*., 1973; Stuntz, 1981; Anon., 1995: 31), but energetic reasons (Edwards, 1992) have also been proposed. When the fishers detect a group of dolphins, of one or more of the species known to be associated with tunas (from the Fam. Delphinidae: spotted dolphin, *Stenella attenuata*, spinner dolphin, *S. longirostris*, common dolphin, *Delphinus delphis*, or, less frequently, striped dolphin, *S. coeruleoalba*), they attempt to confirm the presence of tuna either with the aid of the helicopter, or from the vessel. When fish are present, they launch four or five speedboats that chase the dolphin herd, making a wide arc typically at a distance of 100–200 m to the side and behind the herd. The chase usually lasts about 20 to 30 minutes, and when it finishes, the dolphin herd has slowed down, or stopped. During this process, part or the whole dolphin herd may evade the chase and/or encirclement, or, if it is not carrying tuna, may be deliberately excluded from the encirclement area through the actions of the speedboats. At this point, the seiner begins to surround them with the net, while the speedboats manoeuvre in such a way as to keep them inside the encircled area.

Then, the net is 'pursed', and both the dolphins and the tunas that were associated with them are captured. The technique is called dolphin fishing, and the sets are called dolphin sets. At this point, the fishers wish to release the dolphins and then bring the tunas aboard the vessel. The average size of the dolphin group captured is about 400 to 500 dolphins, but it is common to see groups of more than 1000 dolphins in the net. This technique produces almost exclusively yellowfin, and these are larger (modal size of 70–80 cm, or 6.9–10.4 kg, for the period 1976–1995, Fig. 2(c), below) than those caught by other methods of purse seine fishing. Unfortunately, because of natural factors (currents, etc.), equipment malfunctions, or lack of expertise or motivation of skippers and crews, many dolphins have died during these operations. The incidental mortality of dolphins caused by this technique generated considerable controversy around its legal, economic, political and ecological aspects, which are discussed by Joseph (1994), and Scott (1996).

Figure 1 shows the spatial distribution of the different set types accumulated during the 1979–1996 period. Figure 2 (below) shows length frequencies of yellowfin tuna caught in the different types of sets; the most recent available data, for 1976–1995, are depicted.

Stocks of dolphins

The dolphin species involved in this fishery do not constitute a single group distributed throughout the area; most authors believe that there are geographical subunits, that can be identified by morphological or other characteristics. These subunits with a limited degree of mixing are called stocks, and are used as the units of management on the grounds that there is genetic diversity in the units that must be conserved, and that their population dynamics could differ. The classification used for the stocks is the one proposed by Perrin *et al.* (1985) and Dizon *et al.* (1994). There are two major stocks of spotted dolphins, the north-eastern and the south-western, two of spinner dolphins, the eastern and the whitebelly, and three of common dolphins, the northern, the southern and the central. A subdivision of the northern stock of common dolphins proposed by Heyning and Perrin (1994) has not been implemented because of difficulties and inaccuracies in the discrimination of the different groups by the observers.

The association of tunas and dolphins

The association of yellowfin tunas with dolphins has been observed in other oceans of the world. An annotated bibliography is available (Donahue and Edwards, 1996). For the eastern Atlantic, there are descriptions by Bane (1961), Simmons (1968), Mitchell (1975), Levenez *et al.* (1980), Maigret (1981a, b, c), Coan and Sakagawa (1982), Pereira (1985), Stretta and Slepoukha (1986), Cayré *et al.* (1988) and Santana *et al.* (1991). For the Indian Ocean, Potier and Marsac (1984), Montaudouin *et al.* (1990), De Silva and Boniface (1991), De Silva and Dayaratne (1991), and Leatherwood and Reeves (1991) mention the association. For the central and western Pacific, Pacific Tuna Development Foundation (1977), Stuntz (1981) and Dolar (1994) report on sightings or sets. There are also reports for other areas:

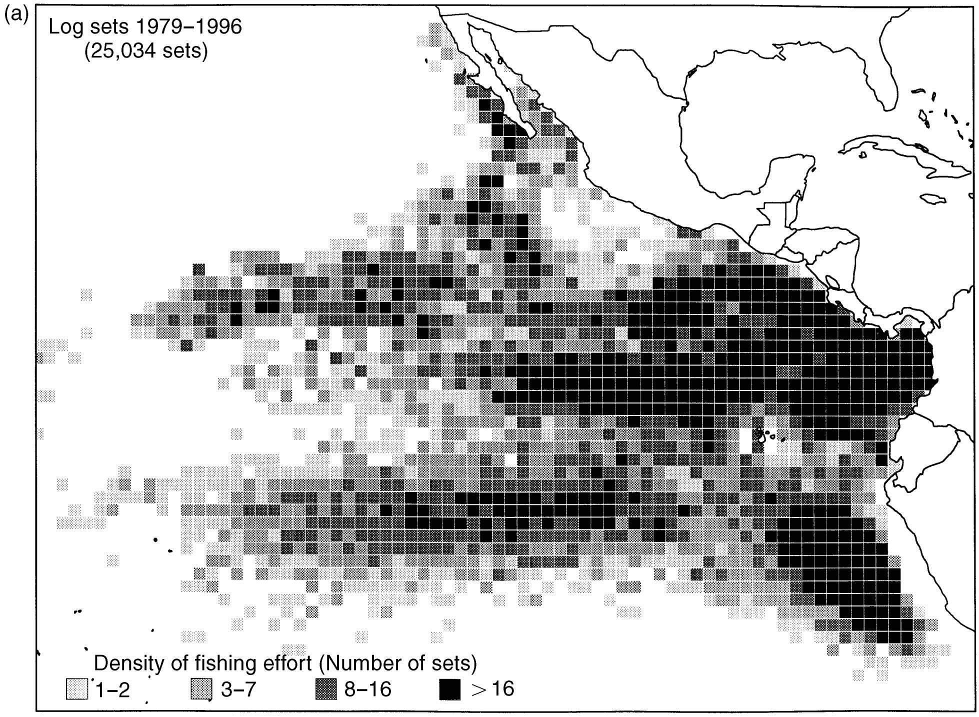


Fig. 1. Maps of the eastern Pacific, showing the density of sets (for years 1979–1996) of the different types in 1 degree × 1 degree squares: (a) log sets; (b) school sets; and (c) dolphin sets. Notice that intervals used are not equal.

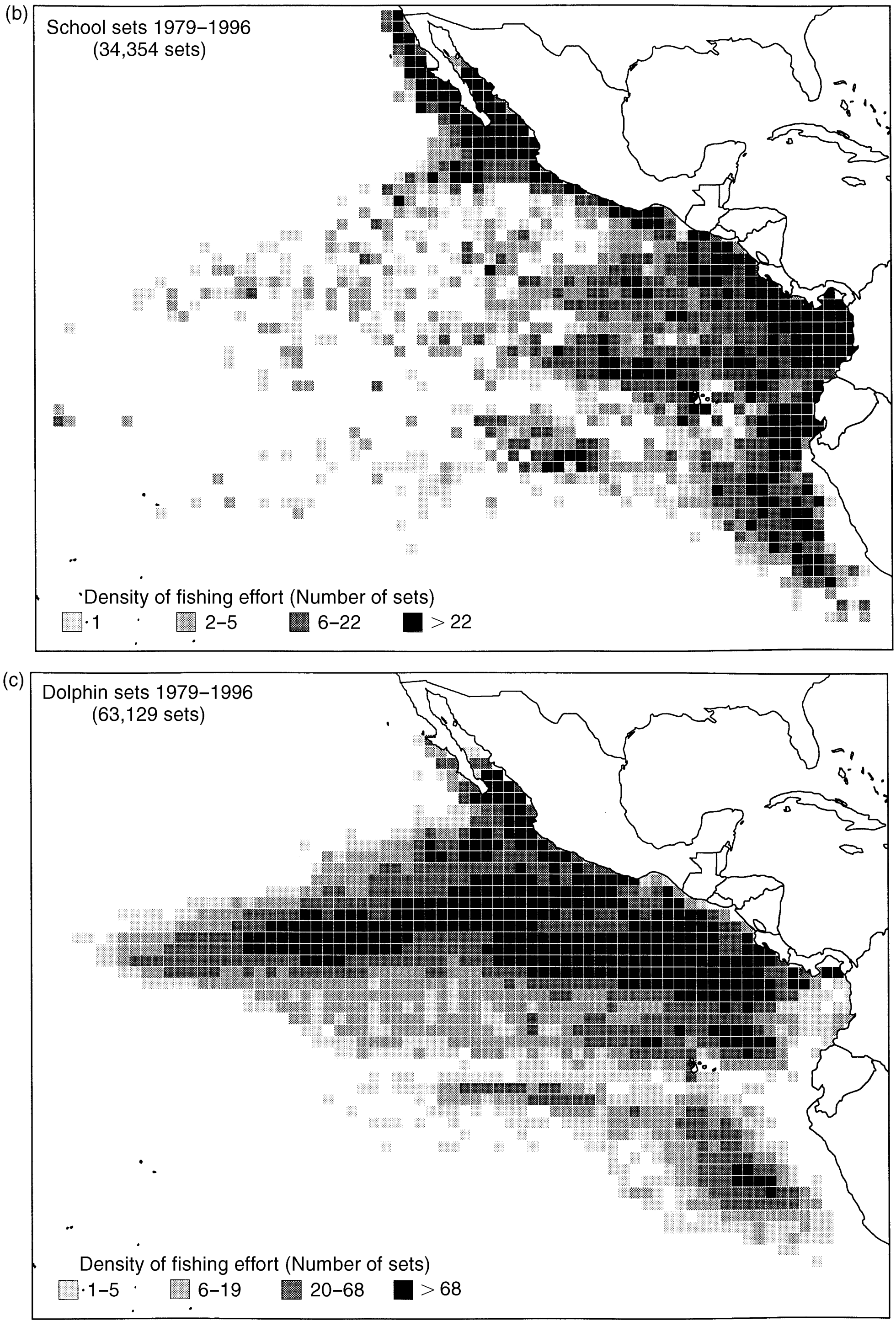


Fig. 1. (*Continued*).

Caldwell and Caldwell (1971) for the western Atlantic, Living Marine Resources (1982) for the Gulf of Mexico, and some mentions in global reviews (Northridge, 1984, 1991). In some cases (e.g. Di Natale, 1990), description of dolphin captures in tuna purse seines in the Mediterranean are presented, but without stating whether the tunas and dolphins were associated or the capture of the dolphins was simply by chance. One reference (Vilicic, 1985, cited in Alegría Hernandez, 1990) seems to suggest that bluefin tuna (*Thunnus thynnus*) in the Mediterranean is found associated with dolphins; however, except for a small proportion of skipjack, and occasionally bigeye, the association seems to be centred on the yellowfin tuna. From the point of view of the dolphins, the genera or species found associated with tunas in other ocean areas are the same or close to the species of dolphins with which tuna associates in the eastern Pacific Ocean.

When sets are described, their frequency seems to be much lower than in the eastern Pacific, (e.g. 0.0–4.7% of the sets in the eastern Atlantic (Cayré *et al*., 1988; Santana *et al*., 1991) versus 45–70% in recent years in the eastern Pacific. The low level of observation in most oceans of the world makes it difficult to reach firm conclusions concerning the significance of this way of fishing or its impact on the dolphin populations.

In a few cases there is information on mortality rates provided by the fishers. Levenez *et al*. (1980) report an average mortality of 15 dolphins per set, and a total number of sets on dolphins per vessel per year of less than 10, based on interviews with fishing captains. Combining these values results in estimates of less than 150 dolphins killed per vessel per year, but we cannot establish a lower bound or average with those values. Most captains interviewed, however, reported never setting on dolphins. For the Philippines, Dolar (1994) presents a mortality rate of one dolphin for every two tons of tunas produced by one of the commercial purse seine fleets operating in the area, or a total of 300–450 dolphins per vessel per year. In both cases, the sample size was small, and the figures were obtained from captains or crew of the fishing vessels. For comparison, in the eastern Pacific the current mortality per set is close to 0.33 dolphins, which translates to one dolphin per close to 70 tonnes of tuna caught, and an annual average per vessel per year of 50 to 60 dolphins.

Estimates of dolphin mortality for purse seining fleets in other areas are practically non-existent. There is an estimate for the eastern Atlantic of 3300 dolphins for 1977–1978, produced by Maigret (1981b, cited in International Whaling Commission, 1982, p. 120).

Information on the characteristics of these associations (i.e. species, sizes) is very scarce. They seem to have similar composition off Sri Lanka and the eastern Pacific (De Silva and Boniface, 1991, yellowfin tuna 100–120 cm in length associated with dolphins). Coan and Sakagawa (1982) describe mostly sets on common dolphins in the eastern Atlantic; that species of dolphin is much less frequent in the eastern Pacific sets (5% of the sets or less).

The tuna–dolphin problem

ESTIMATION OF INCIDENTAL DOLPHIN MORTALITY

The early years

The tuna–dolphin problem was first brought to the attention of the public in the late 1960s (Perrin, 1968, 1969). The mortalities of dolphins in this fishery were heavy during the 1960s, but we'll never have a reliable estimate of their magnitude because of the very scanty and biased database available (Smith and Lo, 1983: Table 4; Lo and Smith, 1986;

Wade, 1993: Table 2; Wade, 1995). For the 1959–1970 period, there are data for only four fishing trips (out of a total of more than 3500); two from a biologist that was allowed to participate in them (Perrin, 1968, 1969), and two from unsolicited letters fron crew members (Smith and Lo, 1983). Of Perrin's two trips, the data for one could not be used, because he had recorded mortality data only for the high-mortality sets; the representativeness of the crew members' letters is questionable. A National Academy of Sciences Committee addressing the tuna–dolphin programme (Francis *et al.*, 1992) concluded: "In summary, the mortality estimates for the period before 1973 (peak values of up to 350 000–653 751 in a year ... have little or no statistical value, and the only conclusion that can be based on the data available is that mortality was very high." During this period, the vast majority of the vessels operating on dolphins were US-flag vessels, the catches were processed by US canneries and sold in the US market.

The Marine Mammal Protection Act of 1972 and its consequences

In response to the US *Marine Mammal Protection Act* (MMPA) of 1972, a scientifically designed and mandatory observer programme was begun by the US government in 1974. The US National Marine Fisheries Service (NMFS) was put in charge of this programme. Observers were placed aboard a sample of fishing vessels to count the numbers of dolphins killed, to make observations which would be used to calculate indices of abundance of the various stocks of dolphins, and to gather information on the causes of mortalities. Observer coverage in this period increased from about 10% in 1974–1976 to about 33% of all trips of US boats in 1977–1978. Besides the observer programme, other actions were undertaken by the NMFS to develop methods and devices that could reduce dolphin mortality (Coe *et al.*, 1984), and many regulations based on these studies were implemented. As a result of these steps, dolphin mortalities declined in the early 1970s, and levelled-off in the early to mid-1980s.

The internationalization of the fishery

In the 1970s, the participation of vessels from other nations began to increase, and the tuna–dolphin problem became an international one. Besides expanding to include more nations, the fishery expanded geographically toward the offshore areas of the eastern Pacific, and soon a very significant part of the catches came from international waters. The markets also expanded to include European and Latin American canneries.

Operating in the region since 1949, the Inter-American Tropical Tuna Commission (IATTC) is an international research organization charged with the collection of data needed to study the population dynamics of the tuna species, of other related species, and of the environment of the region, to provide advice to its member nations on management issues. In 1976, the member nations of the IATTC decided to implement a tuna–dolphin programme with the objectives of: " ... strive to maintain a high level of tuna production and also to maintain dolphin stocks at or above levels that assure their survival in perpetuity, with every reasonable effort being made to avoid needless or careless killing of [dolphins]."

The Agreement for the Conservation of Dolphins and the International Dolphin Conservation Program

In 1992 an agreement initiating an International Dolphin Conservation Program was signed by representatives of the nations participating in the fishery, setting overall annual

'Dolphin Mortality Limits' for the fleets that decline every year from 1993 to 1999 (Anon., 1993a). Those limits have been divided by the numbers of participating vessels, and each vessel has been allocated an annual individual 'Dolphin Mortality Limit' which, if reached, forces the vessel to abandon fishing on dolphins for the rest of the year. A list of infractions and sanctions has been prepared for this programme. Compliance with them is verified by an international review panel which includes representatives of the paticipating governments, the industry, and the environmental community, who are granted access to the information gathered by the observers that accompany every fishing trip.

The Declaration of Panama

In 1996, at an international meeting held in Panama City, all fishing nations from the area, together with many coastal nations and several major environmental groups, produced the Declaration of Panama (Anon., 1997) that, if adopted, would consolidate the gains achieved by the Agreement for the Conservation of Dolphins, and extend its influence. An acceleration of the schedule to reduce dolphin mortality, the introduction of stock-by-stock limits, and addressing bycatches of other species are among the additions of the Declaration of Panama to the previous agreement. As a prerequisite for the implementation of the Declaration of Panama, some changes must be made in the US legislation (lifting of embargoes, re-defining 'dolphin-safe', etc.) These changes are being discussed at the time of the writing of this manuscript. Several issues have been raised in recent months by those opposed to implementation of the Declaration. A brief summary of those is presented in Scott (1996). Many of those issues are neither ecological, nor specific to this problem (i.e. free trade, alleged drug traffic on tuna vessels, etc.)

Databases available

In 1979 observers from IATTC began to depart on vessels from the US (half of the sampled trips) and from other fleets. In 1992, a national observer programme was started in Mexico, with conditions similar to the programme of the United States. In the early 1980s, coverage of the US fleet remained close to 33%, but that of the other fleets was very low (< 6%). In 1986, Mexico, with the largest fleet operating in the area, joined the programme, and the coverage of the non-US fleet climbed to 35% by 1988, while the US fleet coverage was close to 90%. In recent years, the percentage of the trips carrying observers has continued to increase, and since 1991 all trips of vessels larger than 363 tonnes of capacity have been sampled.

Summarizing, the observer coverage for the US fleet prior to 1977 has probably been insufficient to provide reliable estimates of mortality. For the other fleets, the coverage prior to 1984 is insufficient, and only since 1986 have all flags participated in the programme. Since 1991, the coverage has been 100%, and the database is complete. The data gathered by the observers may be affected by 'observer effects,' if the presence of the observer affects the behaviour of the crew or their decisions (Wahlen and Smith, 1985), or by interferences with the observer duties resulting from intimidation, corruption, obstruction, etc. From the point of view of the observer's ability to see the mortalities, after encirclement is complete, the far end of the net is usually less than 200 m away from him/her, who is equipped with binoculars, and on a deck 7 to 10 m over sea level. Unless visibility is impaired (i.e. sets that end in darkness), the observer's view of the net is quite adequate for detecting the presence of dead animals.

Observers also collect data on sightings of dolphin herds that are used to produce indices of relative abundance. Line-transect methods are the main statistical technique utilized for this purpose. Because the vessels are fishing, rather than doing a scientific survey, the data obtained violate many of the assumptions required for the validity of the models (Anganuzzi and Buckland, 1994). Their use requires special adaptations, and they yield estimates of relative abundance only, that is indices that are correlated with abundance, rather than abundance.

Since 1987, IATTC observers began collecting data on the communities associated with floating objects, as a way to understand what makes them attractive to tunas, in order to explore their potential as a source of alternative fishing that could help reduce effort on dolphins. Seeing the diversity and the large numbers of individuals incidentally caught and killed in the fishery, it was thought necessary to start a larger programme in 1992, to study the bycatches (catches of unwanted species; or of undersized or unmarketable tunas) in all types of sets in this fishery.

MORTALITY COMPONENT VARIABLES

There are two statistical components that determine the dolphin mortality level: (1) the average mortality of dolphins per dolphin set; and (2) the number of sets made on dolphins. The first depends on the skill and motivation of the captain and crew, and availability and condition of equipment, and external factors such as occurrence of strong subsurface currents. The second depends on the size of the fleet, the availability of tunas associated with dolphins, regulations promulgated to limit effort on dolphins, and market demand for large and small tunas. In order to reduce dolphin mortality, one of the options is to switch effort away from dolphins, into forms of fishing that seldom or never kill them. If a way of fishing were found that resulted in sustained and high levels of tuna catches, of the sizes necessary to maintain near-optimal yield per recruit, without much higher costs, and with little or no dolphin mortality, it would clearly result in major reduction or elimination of dolphin mortality. But different ways of fishing have different ecological costs, and the reduction of dolphin mortality is only one objective of management.

ESTIMATION OF DOLPHIN ABUNDANCE

Estimates of dolphin abundance have been produced with line-transect methods. Sightings of the dolphin herds, and estimates of group size are combined to produce a value for the number of groups in area, and the number of individuals in them. Three platforms have been used to produce the basic data for this purpose.

1. Research vessel data: surveys are planned following an experimental design. Absolute abundance values have been produced in this way (Wade and Gerrodette, 1993).
2. Tuna vessel data: sightings from the tuna vessel observers are used to produce indices of relative abundance showing the trends in the numbers of dolphins (Anon., 1997).
3. Aerial surveys.

Given the very large area of the fishery, and the limited resources available to produce population estimates, it is quite clear that the coefficients of variation of the estimates will be large, and affected by environmental changes. The uncertainty around them must be taken into consideration while selecting management options.

EVOLUTION OF THE FLEET: TECHNOLOGY AND TRAINING

Purse seine fishing for tunas was made possible by the development of strong synthetic webbing, which is more resistant to rotting and to tearing during the intense strain exerted during fishing operations, of the Puretic power block which efficiently retrieves the net from the water, and to better methods of freezing the catches (Cole, 1980). Most seiners today are around 60 to 70 m long and can carry 900 to 1100 tonnes of tuna. Many carry helicopters to aid in the search for fish and 'bird radar' that can detect even a single frigate bird at distances of over 10 miles (> 18.5 km). Birds and dolphins are some of the most common signs of the presence of tunas. Large purse seiners can spend up to three months at sea, depending on fuel consumption etc., and some of their fishing grounds are far offshore, up to 6700 km from the coast.

A series of technological developments, most of which were originated by the fishers, have been crucial in reducing dolphin mortality. Among these are: (1) the 'backdown' procedure, which consists of putting the vessel in reverse, after encircling the dolphins, which forces the corkline to sink and opens an escape route for the dolphins; (2) the Medina Panel, a section of smaller-meshed webbing in the part of the net with which dolphins most often come in contact, to keep them from entanglement; and (3) the use of rescue rafts and other means of hand rescue of dolphins from the net.

When the countries with vessels participating in the fishery stepped up their efforts to reduce dolphin mortality, many actions were initiated by the IATTC staff, in cooperation with national scientists and technicians, to make sure that all vessels had the right technology and that the fishers were trained in their use. Statistical studies had identified a series of factors that led to increased dolphin mortality. These include environmental factors (e.g. strong subsurface currents), behavioural factors (e.g. some species or stocks of dolphins 'cooperate' with the rescue operations, but others do not), gear factors (e.g. nets not aligned properly, with holes in the webbing, or lacking some of the dolphin-saving equipment), and crew factors (e.g. new, unskilled, or poorly motivated captains or crews). Seminars are frequently held for captains, other crew members, and vessel managers, where these factors are analysed and solutions proposed. The operation of the equipment is tested periodically by IATTC technicians. Trip records are analysed statistically, and the summaries are provided to the industry to facilitate the follow-up of the progress of the captains and crews. Standards of equipment and performance levels are required and enforced by the nations. In 1986, close to 40% of the sets on dolphins had zero mortality; by 1996 this proportion had climbed to about 88%. The average mortality of dolphins per set decreased from over 12 to 0.33 during the same period. These improvements allowed the fishery to continue operating, producing record catches of yellowfin in the late 1980s and early 1990s, while at the same time reducing the impact on the dolphin populations.

The ecological issues

IMPACT OF THE DOLPHIN MORTALITY ON THEIR POPULATIONS

There are several questions that need to be considered under this heading.

- What are the levels of the populations?
- Are any of the populations in danger of extinction?
- Is the mortality sustainable?

- Are the populations increasing, stable, or decreasing?
- Are there trends in the populations independent of the purse seine fishery?

In order to estimate the impact of any level of incidental mortality on a stock, it is necessary to have data on the size of the population, trends in its abundance, and rates of recruitment and natural mortality. During the 1986–1990 period, the NMFS conducted annual research vessel and aerial surveys, using line-transect methods, to assess the condition of the dolphin stocks of the eastern Pacific (Wade and Gerrodette, 1993). Table 1 shows the estimates obtained. All dolphin stocks involved in the fishery have population sizes in excess of 400 000, and there seems to be no danger of extinction for any of them, at least from the impact of this fishery. Even though most of these stocks have experienced serious declines because of the fishery-caused mortality (Smith, 1983; Wade, 1995), studies of their trends in recent years show that most of them have remained at the same level for the past decade (Anganuzzi and Buckland, 1994; Anon., 1997).

Another variable of considerable importance in estimating that impact is the net recruitment rate, defined for delphinids in a simple way as "reproduction in excess of mortality for a population as a whole" (Perrin and Reilly, 1984). Unfortunately, no reliable studies of net recruitment rate are available for any of the stocks of eastern Pacific dolphins, so we use, as a default, the 2% figure of Smith (1983: 9), which is believed to be a conservative estimate of this parameter. Table 1 shows the absolute abundance, and the most recent mortality estimates. It also shows confidence intervals placed around the point estimates for the proportions of mortality (Hall and Lennert, 1994).

To be conservative in assessing the impact of the fishery on the dolphin population, i.e. to minimize the possibility of wrongly believing that the stocks of dolphins are in better condition than they actually are, several sources of uncertainty must be considered. Estimates of population size and rates of recruitment and mortality can be

Table 1. Estimates of population abundance (pooled for 1986–1990; Wade and Gerrodette, 1993), of incidental mortality in 1996, and of relative mortality (with approximate 95% confidence intervals)

Stock	Population abundance	Incidental mortality	Relative mortality (%)	
			Estimate	95% CI
Offshore spotted dolphin				
North-eastern	730 900	818	0.11	(0.085, 0.140)
Western–southern	1 298 400	545	0.04	(0.033, 0.059)
Spinner dolphin				
Eastern	631 800	450	0.07	(0.044, 0.108)
Whitebelly	1 019 300	447	0.04	(0.028, 0.058)
Common dolphin				
Northern	476 300	77	0.02	(0.009, 0.035)
Central	406 100	51	0.01	(0.007, 0.025)
Southern	2 210 900	30	< 0.01	(0.001, 0.002)
Other dolphins*	2 802 300	129	< 0.01	(0.004, 0.005)
All	9 576 000	2547	0.03	(0.023, 0.030)

*Includes the following species and stocks: striped dolphins (*Stenella coeruleoalba*), bottlenose dolphins (*Tursiops truncatus*), Central American spinner dolphins (*Stenella longirostris centroamericana*), and unidentified dolphins.

inaccurate as a result of methodological or other errors. A group of scientists in the United States has been working to develop formulae to determine safe levels of take – a value called “potential biological removal’ or PBR (Anon., 1994; Barlow *et al*., 1995; U.S. Public Law 103–238, Marine Mammal Protection Act, Amendments of 1994). It is a cautious scheme to provide managers with information concerning the levels of incidental mortality (or harvest) that can be extracted from a population with a very low probability of negative impacts. The PBR provides a conservative limit to mortality by multiplying a conservative estimate of abundance by an estimate of recruitment rate and an additional safety factor.

An application of the PBR approach to the eastern Pacific fishery is presented in Table 2 to illustrate the different levels of caution that can be considered. To ensure that the incidental mortality is sustainable, it is necessary to keep the mortality less than or equal to the additions to the population during the period in question. When a population is at its carrying capacity, additions and losses balance out. When a population has been reduced as a result of some impact below carrying capacity, it is expected to have a net increase that will depend on the abundance and reproductive rates of the stock. When we try to estimate these values, we can follow the traditional statistical approach to produce the best estimate, but caution dictates that we err by underestimating population size and growth rate, rather than the opposite. With regard to abundance, the point estimate can be replaced by the lower limit of some confidence interval. The PBR formula uses the 20th percentile of the log-normal distribution of abundance estimates (Wade, 1994b).

Estimates of dolphin net recruitment rates are very difficult to measure. Kasuya (1976) computed a net recruitment estimate of 2.3% and a maximum recruitment rate ($R_{\max}$) of 4.4% for the striped dolphin, *Stenella coeruleoalba.* Wade (1994a) used simulation models and a Bayesian approach to estimate maximum rates of increase of 3.8% for the north-eastern stock of spotted dolphins and 2.2% for the eastern stock of spinner dolphins. However, the lack of observer data for the early years of the fishery leaves some doubt about the usefulness of these results, which rely heavily on extrapolation. The PBR equation uses $\frac{1}{2}R_{\max}$ as an estimate of recruitment, with 2% as a default value when $R_{\max}$ is unknown.

The third component of the equation is the safety factor or ‘recovery factor’. This factor attempts to account for uncertainties in estimates of incidental mortality and to provide additional margin of error for population whose status is unknown or at risk. The mortality estimates in particular are subject to several uncertainties. Some mortalities may not be observed or reported, e.g. observers may overlook mortalities, observers may be intimidated or corrupted to underreport mortalities, predation on dolphins may be facilitated by the fishing operation, or dolphins may suffer injuries that later result in mortality. Some impacts, such as stress or interference with reproduction, may not be observable in the short term. To account for such potential impacts, a recovery factor is set between 0.1 and 1.0. Recovery factors of 0.1 are usually chosen for endangered species (none of which are target species of the tuna fishery), 0.5 for stocks of unknown status or determined to be depleted under the MMPA (north-eastern spotted and eastern spinner dolphins are depleted stocks), and 1.0 for populations known not to be at risk (the little-exploited southern common dolphins). Intermediate values can be chosen as well (the other stocks listed in Table 2 are conservatively given recovery factors of 0.75 because these stocks have been reduced, but are not at risk).

Table 2. Potential biological removal (PBR) and zero mortality rate goal (ZMRG) values compared with 1996 dolphin mortality

Stock	N* (× 1000)	CV*	$N_{\min}$[†] (× 1000)	1/2 $R_{\max}$[‡]	FR[§]	1996 PBR[¶]	1996 $ZMRG$[**]	1996 Mortality
North-eastern spotted dolphins	730.9	0.142	648.9	0.019	0.50	6165	616	818
Western/southern spotted dolphins	1298.4	0.150	1145.1	0.012	0.75	17 177	1718	545
Eastern spinner dolphins	631.8	0.238	518.5	0.011	0.50	2852	285	450
Whitebelly spinner dolphins	1019.3	0.187	871.9	0.02	0.75	13 079	1308	447
Northern common dolphins	713.7	0.288	562.7	0.02	0.75	8441	844	77
Central common dolphins	239.4	0.172	207.3	0.02	0.75	3109	311	51
Southern common dolphins	2210.9	0.217	1845.6	0.02	1.0	36 911	3691	30

*Abundance estimate (N) and coefficient of variation (CV) from Wade and Gerrodette (1993; unpublished data for northern and central common dolphins).

[†] Minimum abundance estimate $(N_{\min}) = N/\exp\{0.842 \times [\ln(1 + \mathrm{CV}^2)]^{1/2}\}$.

[‡] Maximum population growth rate ($R_{\max}$) default is 0.04; values for north-eastern spotted (0.038) and eastern spinner (0.022) from Wade (1993).

[§] Recovery factor $(FR) = 0.5$ for depleted stocks, 1.0 for unexploited stocks, and a conservative value of 0.75 for stocks that have been reduced, but are thought to be above OSP.

[¶] Potential biological removal $(PBR) = N_{\min} \times \frac{1}{2}R_{\max} \times FR$.

[**] Zero mortality rate goal $(ZMRG) = PBR\ 0.1$.

Under this very conservative PBR scheme, limits on fishery mortality can be set that would allow populations to recover. An even more restrictive standard can be implemented, however. The MMPA sets a zero mortality rate goal (ZMRG) for fisheries to achieve. It has been operationally defined as one-tenth of PBR, a level that is thought to be biologically insignificant (Anon., 1994). The result is that we could remove 1% (2% × 0.5) of a depleted population and still allow it to recover. If the removals are below 0.1% (1% × 0.1), the fishery would achieve the zero mortality rate goal.

It is clear that, even under the most conservative scenario, the mortality levels for 1996 are well below the assumed recruitment figures (Table 2), and it appears safe to say that the current mortality levels are at least sustainable and that the fishery has achieved the zero mortality rate goal of the MMPA for all but two of the dolphin stocks. Unless one or more of the sources of uncertainty mentioned above proves to be much worse than anticipated by our safety factors, and under the current fishery conditions (and if all other biotic and abiotic factors allow it), these populations should increase at rates close to the maximum. Given the high variability of the estimates and the long life span of the dolphins, however, it should take several years for these increases to become statistically significant (Gerrodette, 1987).

Reducing the mortality caused by the fishery does not guarantee that the populations will recover to their pre-exploitation levels, however. Changes in the environment, or in the structure and function of the ecosytem caused by the previous impact, or by other impacts may prevent the recovery of the populations. Changes in geographical distribution following oceanographic changes can also affect our estimates of trends (Fiedler and Reilly, 1994). An interesting example in the eastern Pacific is the decrease in the indices of abundance of the ‘northern stock’ of common dolphins (Anon., 1997), even when incidental mortality values were at levels of 0.01% of the stock or less. Studies in central California (Barlow, 1995a, b), to the north of the boundaries of the fishery for tropical tunas, showed a large increase in the population abundance of the same species. These increases have persisted over several years, indicating a large-scale movement of an important part of the population. The causes of that shift in distribution are unknown, but are not dependent on the fishery. A study limited to the boundaries of the fishery would have shown a decrease in abundance that never took place, but it might have been interpreted as a trend.

ECOLOGICAL IMPACTS OF THE FISHING OPERATIONS

Virtually all human activities have some impact on the ecosytem in which they take place, and fishing is not exception. Given the global increase in the human population, it seems unlikely that the utilization of many resources could be halted, so it becomes necessary to find ‘ecologically sound’ ways to utilize them. The meaning of this expression has to be spelled out clearly. In the context of this paper it means that:

1. the use of the resource is concentrated, as much as possible, on the sizes and ages of the target population that allow the greatest yields possible on a sustainable basis – high yield per recruit ratio;
2. the harvest is managed in a way that avoids, or at least minimizes, the loss of genetic diversity;
3. the waste of the resource is kept at a minimum – low [bycatch of target species/catch] ratio;

4. the use of energy by the vessels is minimized – low [energy use/catch] ratio;
5. the level of effort is appropriate for the harvest proposed – high [catch/effort ratio];
6. pollution originated in the fishery is minimized – low [pollution/catch] ratio;
7. the gear used is the best to harvest the resource with the least impact on the habitat – low [habitat damage/catch] ratio;
8. the negative impact of the exploitation on other species of the system (e.g. bycatches, competition for prey species) is kept at a minimum or, if possible, eliminated – low [bycatch of non-target species/catch] ratio;
9. the 'positive' impact of the exploitation on other species of the system ('subsidies') is also kept at a minimum or, if possible, eliminated – low [subsidy/catch] ratio;
10. the population is maintained at levels that assure survival even if there are unexpected, and possibly catastrophic, events such as die-offs.

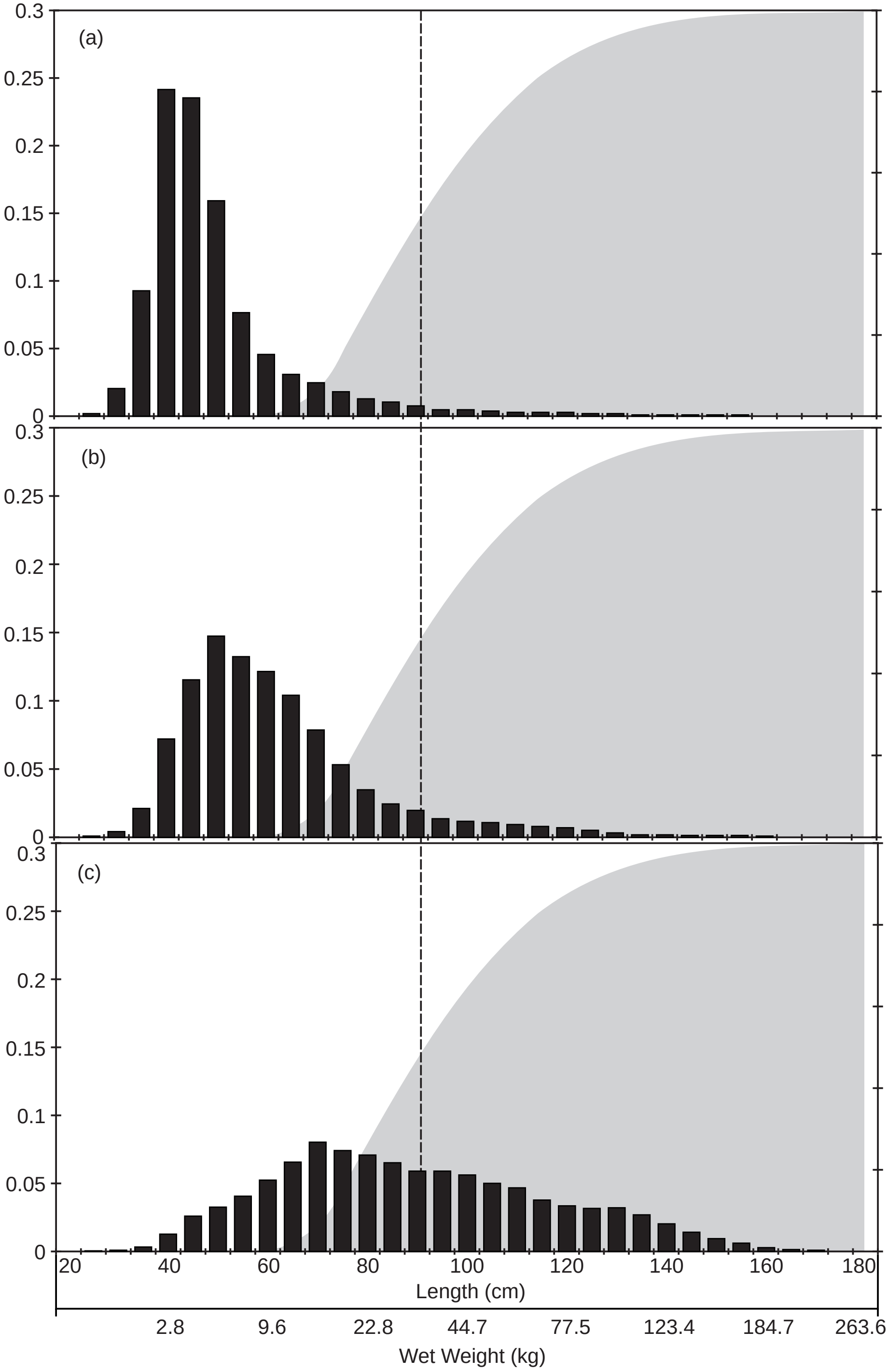
To approach the problem of finding which are the 'ecologically most sound' ways to harvest the tuna populations in a scientific manner, it is necessary to compare the ecological costs of catching them using different gears and techniques. To facilitate this comparison, we can separate the effects on the target population (the object of the exploitation) from those on other components of the ecosystem. This separation doesn't imply any prioritization of the importance of the two groups of effects.

Factors to assess the ecological impacts of different ways of fishing for yellowfin tuna

From the ecological point of view, a fishery should operate in such a way that it meets or approaches the conditions stated before. This view does not include economic or social considerations, which may also be important to humans. For example, yields less than the maximum possible may be preferable if the value of the fish caught or the employment of fishers is increased, but larger catches increase employment in the processing plants.

Maximization of yield per recruit. In the case of yellowfin tuna, the optimum size for maximization of yield per recruit is around 110–120 cm (27–35 kg). Figure 2 shows the length frequencies of yellowfin tuna captured by the different ways of purse seining. Sets on dolphins (Fig. 2(c)) produce catches closest to the optimum size. Based on yield-per-recruit considerations, if the fishery were to switch from fishing predominantly on dolphins towards the other forms, the purse seine catch of yellowfin would decline by about 25% (Punsly *et al.*, 1994). The decline could be considerably greater, however, if some or all the scenarios discussed in that study take place (lower effort, reduction in the range of the fishery, reduction in yellowfin recruitment). The impact might be somewhat mitigated, however, by greater catches of skipjack and exacerbated by greater catches of small bigeye tuna.

Maximization of reproductive rate. With regard to reproduction, the vast majority of the tunas caught on logs and on free-swimming schools are less than 100 cm in length, and therefore most are sexually immature (Anon., 1993b; Fig. 2(a) and (b)). If the fishery concentrated on these types of sets as an alternative to fishing on dolphins, the number of fish reaching sexual maturity would decline. However, as tunas are extremely fecund, it is not certain that this decline would impair future recruitment. The information available up to now (Anon., 1993a: 69–70, 78) has not shown any relationship between the level of the


(a)
(b)
(c)
0.3
0.25
0.2
0.15
0.1
0.05
0
1.0
0.8
0.6
0.4
0.2
0
20
40
60
80
100
120
140
160
180
Length (cm)
2.8
9.6
22.8
44.7
77.5
123.4
184.7
263.6
Wet Weight (kg)

parental stock and the level of the recruitment, but it is possible that futher reductions in the parental stock, outside the range of the data available, may show some impact.

Minimization of discards. With regard to discards, only relatively large tunas can keep up with the cruising speed of a group of dolphins (Edwards, 1992) and stay with them during the chase. That generates catches which are almost totally of market-size fish, and of the most sought-after tuna species (discards are less than 1%). In contrast, drifting objects produce catches of the smallest tunas caught in the fishery; there is no selection of size, and almost 20% of the catch has to be discarded because it is below the market minimum requirement for size or condition. Sets on free-swimming schools have discard levels of about 2%, and most of the fish retained are well below the optimum size in terms of maximizing yield per recruit.

It is clear, from the point of view of maximizing yellowfin production and minimizing bycatch, that fishing on dolphins is a much sounder way of fishing than the alternatives.

Factors to assess the impact of fishing on the rest of the ecosystem

There are many ways in which a fishery can affect an environment, and it would be very difficult to analyse all of them. A brief list could include: (1) bycatch of different species; (2) impact of the fishing operations on the habitat; (3) impact of lost and discarded gear; (4) generation of pollution and marine debris; and (5) 'subsidies' to some species. The following section will discuss some of those impacts for the purse seine fishery.

Bycatches. Dolphins. In the eastern Pacific fishery, the trophic relationships between tunas and dolphins are not well known. It is not even known to what extent, if any, they compete with one another or help one another. When the fishery started, it was a pole-and-line fishery that extracted tunas from the ocean without any dolphin mortality. This fishery lasted for decades, until it was largely replaced by the purse seine fishery. In the early years of the puse seine fishery, dolphin mortalities were extremely high, and for a decade or so remained at a high level. Afterward, dolphin mortality declined for several years, went up again during the late 1980s, and then declined again. The impact of these differential mortalities on the interactions between tunas and dolphins and on the ecosystem as a whole are not known, and it is not possible to gather enough information to recreate with adequate precision the processes that took place during the 1960s and 1970s.

It is clear that the dolphin populations associated with tunas experienced significant declines, caused by the fisheries-inflicted mortality, until the late 1970s. It has been suggested that there may be other impacts on the dolphin populations: (1) cryptic mortality: the fishing operations, by disrupting the social structure of the dolphin group, may facilitate attacks on dolphins by sharks and other predators: (2) abortions: the chase prior to encirclement may cause females to lose their foetuses; (3) injuries: even though severe injuries seen by observers are recorded and can be accounted for (about

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Fig. 2. Length-frequency distribution of fork lengths in centimetres (expressed as percentage of the catch, *y*-axis at left), of yellowfin tuna caught in the different types of sets in 1976–1995: (a) log sets; (b) school sets; and (c) dolphin sets. Shaded curve shows the proportion of fish that are sexually mature at each length (values on right vertical axis). Broken vertical line is the length at which 50% of the tunas are sexually mature.

2% of the total mortality), other injuries may not be detected or assessed properly: (4) stress: the stress caused by the fishing operations may have a cumulative impact on the individuals, reducing their ability to survive, reproduce, or grow (Myrick and Perkins, 1995). Unfortunately, there are no reliable data on the occurrence or level of any of these potential problems. Sharks are frequently seen close to the nets, and there is one report of sharks preying on dolphins or, more commonly, feeding on dead dolphins inside the net or when released. Abortions associated with fishing have not been documented. The long-term effects of injuries are hard to assess. Indications of stress have proved difficult to define and measure, and no conclusive evidence one way or the other has been published.

Fishing on floating objects or on unassociated schools results in lower bycatches of dolphins. If all the effort directed towards dolphins were directed towards these ways of fishing, dolphin bycatch would be a few dozen animals per year.

Bycatches of species other than dolphins. One of the ecological costs of fishing is the bycatch of species which are not the target of the fishery. In purse seining operations the following species are caught incidentally, and are not usually retained:

small tunas (Fam. Scombridae): undersized yellowfin, bigeye, and skipjack tunas, bullet tunas (*Auxis* spp.), black skipjack (*Euthynnus lineatus*), bonito (*Sarda* spp.);
billfishes: Fam. Istiophoridae: striped marlin (*Tetrapturus audax*), shortbill spearfish (*T. angustirostris*), black marlin (*Makaira indica*), blue marlin (*M. nigricans*), sailfish (*Istiophorus platypterus*); Fam. Xiphiidae: swordfish (*Xiphias gladius*);
rainbow runner: *Elagatis bipinulatus* (Fam. Carangidae);
yellowtail: *Seriola* spp. (Fam. Carangidae);
wahoo: *Acanthocybium solandri* (Fam. Scombridae);
sharks: Fam. Sphyrnidae: hammerhead shark (*Sphyrna* spp.); Fam. Carcharhinidae: blacktip shark (*Carcharhinus limbatus*), whitetip shark (*C. longimanus*), silky shark (*C. falciformis*), dusky shark (*C. oscurus*), other sharks (*Carcharhinus* spp.);
rays: Fam. Mobulidae: manta ray (*Mobula* spp., *Manta hamiltoni*); Fam. Dasyatidae: pelagic sting ray (*Dasyatis violacea*);
sea turtles: Fam. Chelonidae: olive ridley (*Lepidochelys olivacea*), green/black (*Chelonia mydas, C. agasizzi*), loggerhead (*Caretta caretta*), hawksbill (*Eretmochelys imbricata*);
mahi-mahis (dolphin-fish): Fam. Coryphaenidae: *Coryphaena hippurus, C. equiselis*;
triggerfishes: Fam. Balistidae;
other large fish: Fam. Serranidae (sea bass, cabrilla) and Carangidae (jacks).

The list is far from complete, but it gives an idea of the main species caught, although it is heavily biased towards the larger species which are easier to see and identify. Many individuals of small species are also caught; the fishers refer to some of them as ‘baitfish’ (forage for tunas) (anchovies, fam. Engraulidae; herrings and sardines, fam. Clupeidae; grunts, fam. Haemulidae, etc.) but not others (flying fish, fam. Exocoetidae, etc.). In order to compare the bycatches in the different ways of purse seining for tunas, three measurements have been used: (1) the cost of producing 1000 tons (909 tonnes) of tunas (yellowfin, skipjack and bigeye), in Table 3; (2) the cost of producing 1000 tons of yellowfin tuna, which is the main target of the fishery, in Table 4; (3) and the cost per 10 000 sets of each type, in Table 5. The choice of

1000 tons is arbitrary; the choice of 10 000 sets is based in the fact that in the last decade there have been, on average, about 10 000 sets on dolphins each year. The bycatches are estimated by using individual counts in each set, or total weights divided by average weights.

Of the three types of sets, those on floating objects have, by far, the greatest bycatches. As the logs are drifting, fish of all sizes and body configurations, slow or fast-moving, can aggregate under them. On the other hand, groups of tunas and dolphins cruise at high speeds, and prior to setting there is a chase at even higher speed, so that when the group is encircled almost no small or slow-moving species of fishes or other animals are encircled. Aside from dolphins, the bycatches of dolphin sets consist of a few sharks and, occasionally, billfishes, mahi-mahi, wahoo, and/or sea turtles. The billfishes may have been travelling with the tuna–dolphin aggregation, but others were probably by chance in the water encircled. In comparing the columns of Tables 3, 4 or 5, it is clear that dolphin sets are by far the 'cleanest' in this respect. Sets on unassociated schools have moderately low bycatches (in descending order of magnitude) of sharks, yellowtail, mahi-mahi, billfishes, sea turtles and wahoo. Log sets have large bycatches of mahi-mahi, wahoo, sharks, rainbow runner, yellowtail, billfishes and sea turtles. Not included in these considerations are the aggregate classes 'other small' and 'other large fish' because of uncertainty about their identity. The invertebrates taken incidentally are almost always jellyfishes, and the observers' estimates of weights or numbers of individuals are not reliable.

Table 3. Bycatches in numbers of individuals and discards of tuna (in tons)* per 1000 tons of tuna loaded for the different types of sets, based on combined data for 1993–1996. The numbers in parentheses are sample sizes

	Log sets ($n = 10\,607$)	School sets ($n = 13\,112$)	Dolphin sets ($n = 19\,570$)
Dolphins	0.0	0.1	34.1
Marlins	10.2	4.1	1.5
Sailfish	0.4	6.6	2.9
Other billfishes	0.7	0.3	0.1
Blacktip sharks	145.2	89.2	15.8
Silky sharks	51.1	16.3	3.8
Whitetip sharks	34.8	3.6	2.4
Other sharks and rays	59.3	86.1	17.0
Mahi-mahis	4722.7	193.8	2.4
Wahoo	2034.6	26.7	0.6
Yellowtail	110.7	553.8	9.9
Rainbow runner	130.0	36.5	0.0
Other large bony fishes	54.1	457.3	0.2
Triggerfishes	4774.6	75.6	7.4
Other small fishes	7286.3	1091.5	358.3
Unidentified bony fishes	7.3	4.6	10.6
Sea turtles	0.6	0.6	0.3
All tuna discards (tons)	228.5	33.6	9.9

*1 ton = 0.909 tonne.

Impacts of fishing operations on the habitat. In the case of the tuna purse-seine fishery, there appears to be virtually no impact of the fishing operation on the habitat. As opposed to bottom trawls that may have an impact on the bottom, the seine rarely, if ever, has any contact with it.

Impacts of lost or discarded gear. Because of the nature of the seining operation, gear is seldom lost. Occasionally, pieces of webbing that have been replaced, or that may have become irretrievably entangled with cables or propellers, may be discarded. There have been no reports of fish or other animals entangled in lost or discarded purse seine webbing; without floating elements, it should sink. The impact of these pieces on the bottom communities is unknown.

Generation of pollution and marine debris. Air pollution is generated by burning fuel while searching for tunas, and given the high consumption of fuel of a seiner compared with other types of tuna fishing vessels, it could be a considerable amount. Vessels fishing for dolphin-associated fish use more fuel than vessels fishing for log fish, but the former fish farther offshore, on average, than the latter. The former also carry a helicopter in most cases, while the latter frequently do not. Water pollution is generated by the vessels when they dump fuel, oil or other substances to the water. Occasionally, when large catches are made soon after a vessel leaves port, the fuel stored in a well may be dumped overboard to make room for the catch. The amount of marine debris, such as garbage in plastic bags, or discarded containers, generated by the different fleets is

Table 4. Bycatches in numbers of individuals and discards of yellowfin (in tons) per 1000 tons of yellowfin loaded for the different types of sets, based on combined data for 1993–1996. The numbers in parentheses are sample sizes

	Log sets ($n = 10\,607$)	School sets ($n = 13\,112$)	Dolphin sets ($n = 19\,570$)
Dolphins	0.1	0.2	34.7
Marlins	58.4	6.1	1.5
Sailfish	2.2	9.9	2.9
Other billfishes	4.2	0.5	0.1
Blacktip sharks	829.8	132.8	16.1
Silky sharks	292.1	24.3	3.9
Whitetip sharks	199.1	5.4	2.4
Other sharks and rays	339.1	128.1	17.2
Mahi-mahis	26 987.2	288.4	2.4
Wahoo	11 626.2	39.8	0.6
Yellowtail	632.6	824.4	10.1
Rainbow runner	743.0	54.4	0.0
Other large bony fishes	309.0	680.6	0.2
Triggerfishes	27 283.4	112.5	7.5
Other small fishes	41 636.4	1624.6	364.5
Unidentified bony fishes	41.9	6.9	10.8
Sea turtles	3.6	1.0	0.3
Yellowfin discards (tons)	189.1	17.3	8.7

unknown. To determine the significance of the problem, and compare the different gears, evaluations are required (Natural Resources Consultants, 1990).

'Subsidies' to some species. The issue of 'subsidies' to some species is a difficult one. Many species of marine organisms have learned to use fishing activities to their advantage. Fish, birds and mammals follow fishing vessels to catch prey which are made vulnerable by the fishing operation (forced to abandon shelter, confused, separated from their school, etc.), 'steal' prey from deployed gear (Nitta and Henderson, 1993), or feed on discards (Britton and Morton, 1994; Couperus, 1994; Garthe and Hüppop, 1994). This type of interaction may also be important, because the fishery may be tilting the competitive equilibrium among different species. At the same time, the impact of this situation is difficult to perceive or quantify, because in most cases it is not clear which species are at a disadvantage in this situation. Some studies, such as those of Mearns *et al.* (1981) and Olson and Boggs (1986), have been made of trophic relations of the upper-level predators of the offshore pelagic zone of the tropical eastern Pacific Ocean, but not enough is known to predict the effects of selective removal of various components of the ecosystem. In the case of the tuna purse seine fishery, it is likely that some species of birds and fish take advantage of the species that are made more vulnerable by the fishing operation or to feed on the discards. Research is needed to determine which species are benefiting and which are being harmed by this. Even the most basic questions, those referring to the tuna–dolphin interaction itself, have not been answered (why are tunas and dolphins together? which species benefits from the association? which, it any, is harmed by it? or do both benefit?). Over the years, the fishery has extracted tunas and not dolphins (prior to 1959), then dolphins at a much higher rate (in relative terms) than tunas, and more recently fewer and fewer dolphins and more and more tunas. If tunas and dolphins are competitors, as the studies on diet overlap suggest (Perrin *et al.*, 1973), then the early stages of the fishery favoured the dolphins, then, during the years of high dolphin mortality, the tunas, and more recently the dolphins again. If the relationship is beneficial to both, then any reduction in one of them would be harmful to both.

Alternative ways of purse seining and other fishing methods

If fishing on dolphin-associated schools were eliminated the fishers have four options.

REMAIN IN THE AREA AND SWITCH TO PURSE SEINING ON SCHOOLFISH OR LOGS

Some idea of the effects of switches to schoolfish or logs can be obtained from Table 5, which shows the bycatches which might be obtained if there were 10 000 sets made on unassociated schools or logs. Actually, the bycatches would probably be less than indicated in the table for two reasons: (1) adding artificial logs to increase the number of those sets may result in logs 'competing' for the individuals, with lower densities per log; and (2) the abundance of many of the species would be reduced, which would reduce the subsequent bycatches. If sets on dolphins were replaced mostly by school sets, the bycatches would be far less than if they were replaced mostly by log sets. It seems more likely that dolphin sets would be replaced mostly by log sets, as it happened in the period 1978–1982 (Anon., 1997: Table 4). Advances in knowledge of behaviour of fish relative to oceanographic conditions or improvements in methods for detecting fish might make it

Table 5. Bycatches in numbers of individuals and discards of tuna (in tons) per 10 000 sets, based on combined data for 1993–1996. The numbers in parentheses are sample sizes

	Log sets ($n = 10\,607$)	School sets ($n = 13\,112$)	Dolphin sets ($n = 19\,570$)
Dolphins	6	11	4521
Marlins	3717	631	298
Sailfish	138	1030	571
Other billfishes	266	47	25
Blacktip sharks	52 800	13 827	3145
Silky sharks	18 587	2532	764
Whitetip sharks	12 669	562	477
Other sharks and rays	21 576	13 337	3374
Mahi-mahis	1 717 107	30 026	474
Wahoo	739 738	4141	124
Yellowtail	40 252	85 816	1967
Rainbow runner	47 277	5661	6
Other large bony fishes	19 661	70 854	31
Triggerfishes	1 735 960	11 714	1474
Other small fishes	2 649 192	169 125	71 309
Unidentified bony fishes	2664	717	2105
Sea turtles	232	100	64
All tuna discards (tons)	83 091	5210	1964

possible for fishers to catch more fish in unassociated schools. However, fishers have recently been deploying artificial logs, called fish-aggregating devices (FADs), to catch bigeye and skipjack tuna with considerable success, and it seems likely that if they were required to cease fishing on dolphins most of them would switch to fishing on logs or FADs. In the eastern Pacific, the number of log sets in 1996 was the highest of the decade, and it is almost twice the figure from 1991, the first complete year under the ‘dolphin-safe’ policy. As a result of that development, the increasing catches of small bigeye, and perhaps the much higher discards of small fish, have created a conflict with the longline fishery which is experiencing a decline in their catch rates (Anon., 1997). There are various factors which make it impossible to predict the outcome of a switch from dolphin to log fishing. It is possible, for example, that there are already enough logs in the eastern Pacific Ocean to be close to a ‘saturation level’ to accommodate all the fish that wish to associate with them, so the addition of FADs will increase the catches only until the ‘saturation level’ is reached, and then further additions would only decrease the average number of fish per log or FAD. The average log set produces about 36 tons of tuna, of which about 9 tons is yellowfin, the preferred target for the fishers, whereas the average dolphin set produces about 18 tons of tuna, all of which is yellowfin. Besides, when a vessel is fishing on logs it usually makes only one set per day, early in the morning, whereas a vessel fishing on dolphins usually makes more than one set per day. Most of the catch of log sets is skipjack tuna, which brings a lower price than yellowfin. At times canneries have refused to accept skipjack, so all skipjack caught in log (and school) sets had to be discarded. Also, the abundance of skipjack is more variable than that of yellowfin (Forsbergh, 1989; Anon., 1993a: 81), which makes fishing on logs more risky, financially, than fishing on dolphins. Most log sets are made in the coastal zone of northern South America and southern Central America, within the Exclusive Economic Zones of several coastal nations, generating access problems for some fleets. On the plus side, log fishing requires less fuel than dolphin fishing.

The tables are based on groupings such as ‘sharks’, ‘sea turtles’, ‘billfishes’, aggregate classes that are not adequate as management or conservation units. The observers record the species whenever possible, which it is in most cases; the groupings used are only a device to reduce the size of the table. A more detailed study that includes all the species, the interannual variability, and the seasonal and spatial changes in bycatches is being prepared. Even when we can break them down to the species level, we don’t have a clear idea of the stock structure, abundance, or other sources of mortality. As the fishery on floating objects is more localized geographically, as was mentioned before (Fig. 1), than the fishery on dolphins, its impact could be felt by only one or a few stocks of the species involved.

At the same time, however, the tables illustrate some of the different costs of the different types of sets. If we maintain this scheme of a set-by-set switch, we can compare, for instance, the type of set with the greatest bycatches with that with the least by: (1) subtracting the average mortality per set on dolphins from the average on logs for all the common species; (2) dividing both sides by the average mortality per set for the dolphins, to obtain a crude correspondence showing the differential impacts of the two ways of fishing. The following ‘equation’ is the result of those operations:

Differential costs of fishing

Dolphin sets	Log sets
1 dolphin +	15 620 small tunas +
0.1 sailfish +	382 mahi-mahi +
0.1 manta ray =	190 wahoo +
	7.6 rainbow runners +
	11.0 blacktip sharks +
	4.0 silky sharks +
	2.4 whitetip sharks +
	0.4 hammerhead sharks +
	2.9 other sharks and rays +
	0.3 black marlin +
	0.3 blue marlin +
	0.1 striped marlin +
	0.1 other billfishes +
	4.3 other large fish +
	428 triggerfishes +
	800 other small fish +
	0.04 sea turtles

Except for the dolphins, the sailfish, and the manta rays, the bycatches of all other species are much greater in log sets than in dolphin sets. The protection of the one dolphin on the left side of the equation results in the mortality of many other organisms. How can we compare these impacts from the ecological point of view? The answer to the question: how many sharks is a dolphin worth? is not to be found in the ecological literature. We do not know what is the impact (even for the dolphins!) of the mortality on the right side of the equation. Are all these species plentiful? Is this level of mortality sustainable, or negligible? In the case of the dolphins, the current level of mortality is not only sustainable but so low that it should allow these species to recover to levels approaching those which existed before the advent of the purse seine fishery for tunas.

This equation emphasizes that there are two problems, not one, competing for our attention. Solving one at the expense of exacerbating the other is not the ecologically sound way out of this situation. Even though many people have a stronger aversion to mortalities of dolphins than mortalities of sharks or other species, this preference has no scientific basis. The bycatch in log sets is an issue that can and should be addressed with a combination of management and technological innovation. Reducing its magnitude is another goal that should be pursued. Intensifying its impact to eliminate the mortality of dolphins through fishing does not have a sound ecological basis.

MOVE TO OTHER OCEANS AND FISH ON SCHOOLFISH OR LOGS

Moving to other oceans is not a good solution to the problem. In the first place, tunas in the original area would be underutilized and there would be massive unemployment in many coastal communities. In the second place, most stocks of tunas in other oceans are already fully exploited, and the entrance of more vessels into those fisheries would cause problems for the vessels already there. There is very little information on the composition and level of bycatches in other ocean areas, but it is known that the communities associated with floating objects are similar in most oceans, so the bycatches in this type of sets occur but in other oceans (Bailey *et al*., 1996). Transferring the problem to another ocean is therefore not an ecologically sound solution.

CHANGE GEAR AND REMAIN IN THE REGION

Switch to pole-and-line fishing

The need for live bait limits the geographical range of this fishery to coastal waters, and therefore the catches are limited mostly to small tunas (Hennemuth, 1961). It is quite inefficient from the point of view of catch per unit of fuel consumed or catch per unit of time, because of the time and energy spent in a ‘double’ fishery for bait and then for tunas. The bait should be considered a bycatch, and we should remember that this way of fishing may have led to depletion of bait species in some areas of the fishery (Longhurst, 1971). On the other hand, there are no dolphin bycatches, and the bycatches of most other species are minimal. It is unlikely that pole-and-line fishing, under present conditions, could supply the need for tunas by the canning industry.

Switch to longlines

Kanasashi (1960), Yoshida (1966) and Sainsbury (1996) describe the gear used. This method catches small numbers of large tunas, billfishes and sharks. Most of the yellowfin caught (Nakano and Bayliff, 1992, Figures 63–65) are larger than the critical size of 116 cm (Anon., 1995: 58). If large numbers of longline vessels were constructed for fishing in the eastern Pacific Ocean, and if these vessels all deployed their gear in area-time-depth strata in which yellowfin were most likely to be caught, their total catches would still be much less than those of the puse seine fishery, as that fishery, especially when directed at dolphin-associated fish, takes fish which are closer to what yield-per-recruit analysis indicates is the optimum size for harvesting than does the longline fishery. In order to make longlining profitable, is is necessary to have a market that pays a high price for these catches, which is the case with the Japanese market for some fresh tunas. Because this market is limited, and because the supply of large tunas is limited, the catches of tunas by the longline fishery are much less that those by the purse seine fishery. Setting the longlines at different depths changes the selectivity of the gear (Boggs, 1992; Nakano and Bayliff, 1992). There is not much information of longline bycatches in the eastern Pacific, but longlines are known to cause bycatches of sharks, billfishes, sea turtles, sea birds and other species in other areas (Witzell, 1984; Brothers, 1991; Rey and Muñoz-Chapuli, 1991; Hoey, 1992; Stevens, 1992; Nitta and Henderson, 1993).

Switch to gill nets

Gill nets are used to catch tunas in the oceans of the world. There is no experience with offshore gill nets in the eastern Pacific fishing grounds, but it seems unlikely that it will be a more selective way of fishing than purse seining with respect to tunas and to other species. In any case, a United Nations resolution has banned the use of high-seas gill nets. Coastal gill nets fishing for tunas produce incidental mortality of dolphins in most fisheries that have been studied (Shomura, 1963; Perrin *et al*., 1994). Francis *et al*. (1992: 101) recommend against gill nets for fishing for tunas. Fishers are trying to increase the selectivity of gill nets, but when we have data, the costs in dolphins, other marine mammals, and other species can be high. The Sri Lanka gillnet fishery, which targets mainly tunas, results in an incidental mortality of dolphins of between 5200 (Dayaratne and Joseph, 1993) and 9000–12 000 (Leatherwood, 1994). As the total catches of that fishery are close to 20 000 tonnes of 'fish' (Dayaratne and Joseph, 1993), most of which is tuna, the cost in dolphins of producing that tuna is close to one dolphin per 4 tonnes of tuna (of dolphin-safe tuna!), if we use the lowest mortality estimate, and one dolphin per 1.7 tonnes if we use the highest. These figures compared with one dolphin per 70 tonnes of tunas in the eastern Pacific tuna fishery.

REMAIN IN THE AREA AND DEVELOP NEW TECHNOLOGIES

Can we develop ways of fishing that catch the right sizes of tunas, without involving dolphins, and without impacts on other species of the system? Using the purse seine technology, that boils down to: (1) finding other ways to locate the schools of large yellowfin tuna that are not associated with dolphins (if there are enough of them), or (2) finding a way to attract the large yellowfin tuna, or (3) finding a way to separate tunas from dolphins before capture. Several technologies have been proposed to detect tuna schools, based on laser (Oliver *et al*., 1994), acoustics, radar, etc. Up to now, the issue is at an early experimental stage, and we have seen no great advances in the recent past.

FADs. To attract large yellowfin, the hopes are placed on the possibility of deploying FADs (fish-attracting devices) in areas and times where some records show that sets have occasionally been made on large tuna in schools or associated to floating objects (Anon., 1991: Fig. 25). If those fish could be attracted (Armstrong and Oliver, 1995), without large amounts of small tunas and other species, then the solution could be ecologically sound. However, in the eastern Atlantic, where FADs have been used intensively, the majority of the tuna vessel owners operating there have implemented a voluntary ban on the practice in a time-area stratum (A. Fonteneau, pers. comm.), which suggests that they perceive the negative effects of the practice to be quite significant. Experiments are needed to answer this question.

Separating tunas from dolphins. Several methods have been proposed to separate tunas from dolphins during or prior to encirclement, based on herding the dolphins or using sounds, chemical substances, or other means to attract or repel tunas or dolphins (Coe *et al*., 1984; Edwards, 1996). Again experiments are needed because there are no clear data on such methods; the issue of herding dolphins has proved quite intractable up to now. We need to know a lot more about the social structure and schooling behaviour of both tunas and dolphins to devise an effective way of separating them. Some recent experiments attempting to explore the behaviour of tunas and dolphins are discussed by Anon., (1993a: 60–63; 1995: 51–52).

Mid-water trawls. Prado (1988) describes a trawl fishery for albacore tuna (*Thunnus alalunga*) in the Bay of Biscay, and unsuccessful tests performed in the Gulf of Guinea in 1977. There are no reports of trawling for tunas in the eastern Pacific. One study based on experimental fishing in the western Atlantic shows higher dolphin bycatches per tonne of fish caught (roughly one dolphin per 4–5 tonnes of tunas, Gerrior *et al*., 1994) than for the eastern Pacific purse seine fishery. The most recent studies (Goudey, 1995, 1996) show very variable bycatch rates: one small cetacean per 124 tonnes of tunas in 1994, and one per 10–11 tonnes of tuna in 1995. The cetaceans included pilot whales and two species of dolphins, and the tuna catches were composed of albacore, yellowfin and bigeye tuna. For comparison, the bycatch rate observed in the eastern Pacific purse seine fishery is one dolphin per 70 tonnes of tuna. Given the experimental nature of the pair trawl fishery, it is possible that with more information on the distribution, seasonality and causes of the bycatches, and the development of auxiliary technology, the bycatch rates could be lowered substantially. As recently as 1986, the eastern Pacific purse seine fishery had bycatch rates of the order of one dolphin per 1.6 tons of tuna caught. Ten years after that, the rates have been reduced by 97%. This example shows the difficulty of making a fair comparison between a new fishery and a mature one.

Conclusions

In comparison with all the other gears and techniques mentioned above, fishing on dolphins produces yellowfin tuna closer to the optimum size required to maximize yield per recruit, allows them to reproduce, and wastes very little of the resource. The bycatches of turtles and other species of fish are very low, and the bycatches of dolphins have been brought under control, to levels that permit the recovery of the dolphin populations, and eliminate the conservation concerns that gave this issue its high profile. A ‘perfect’ solution for the dolphins, one that eliminates all mortality and disturbance, and provides them with total protection would be very costly, under current fishing practices, for all other species in the ecosystem, and for the fishers.

Considerable further study is needed to produce a full assessment of the ecological characteristics (positive and negative) of each way of fishing. If wise management decisions are to be made, it will be necesasry to evaluate the alternatives (DeMaster, 1992), and to have a much better knowledge than available today of the ecological costs of fish production. To eliminate the ecological impacts is impossible, as removal of fish, particularly selective removal of one or a few species, causes ecological impacts. But we can choose among the impacts, and work to mitigate them.

Some recommended areas for research are:

1. identification of management units for all species (stocks);
2. estimation of mortality rates and abundances for all species (stocks);
3. ecological fate of bycatches discarded at sea;
4. ecosystem interactions, especially those involving the target species with species taken incidentally and with species subsidized by the fishery;
5. modelling studies to assess the impact of management actions concerning bycatches;
6. technological improvements to increase gear selectivity;
7. development of techniques for pre-sorting the catch before loading it (floating cages, fish chutes, etc);
8. techniques to increase the survival of unmarketable species and individuals;
9. utilization of bycatches through marketing, changes in operations, etc.

If we can solve the tuna–dolphin problem in a satisfactory manner for most of those involved, it would set up a model that can be used for other fisheries. The approach should be an international one, based on science and on the education of the fishers to produce the needed changes. It should not create a false dichotomy between the use of a resource and the conservation of the ecosystem, or between jobs and the environment. The industry should be held accountable by the nations and by the rest of the community represented by non-governmental organizations, which are given access to the basic information needed for monitoring the progress and the compliance with the programmes agreed to. The solution should be based on scientific facts and on a complete ecological perspective of the fishery.

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