1. Introduction

SCOPE OF THE REVIEW

Fishers have harvested tunas for millennia, with a variety of gear types that range from beach seines and "almadrabas" (a type of floating trap) to longlines, trawls, gillnets and purse seines. From coastal operations, the fleets began to move farther from their ports with the development of new vessels, and gear technology (Orbach, 1977). The search for tunas began to grow with the use of "baitboats", vessels prepared to catch tuna with pole and line, using live bait. In the 1920s, fishers would catch live bait and start fishing when a school of tunas was detected by chumming the water, and when the tunas entered in a feeding frenzy, naked hooks were enough to catch them. The technique had been used by the natives of Maldives long before (Doumenge, 1998). The need to catch bait, and then to keep the bait alive were major limitations to the geographical extent of the pole and line fishery, and also to the time fishers could spend fishing before having to return to replenish bait (Gillet, 2011). This fishery was thus limited to the coastal region. During their explorations of fishing grounds, fishers noticed that, in some regions, schools of tunas could be seen feeding on the surface in large numbers, sometimes associated with floating objects, in other cases with dolphins or whales. However, their technology did not allow them to exploit these large aggregations in a more effective manner until further improvements happened, affecting vessels and gear. In the late 1960s, the purse seiner brought about a revolution, increasing the production and the range of the fisheries, and introducing a whole array of new technologies for detection and capture of the tunas. The cost of the increase in production was the loss of some of the selectivity of the hook and line fishery.

The objective of this review is to describe the bycatch and the non-tuna catch of the purse seine fisheries targeting tropical tunas in all oceans of the world. These fisheries produce annually 75–90 percent of the world production of these species (skipjack tuna [*Katsuwonus pelamis*], yellowfin tuna [*Thunnus albacares*], and bigeye tuna [*Thunnus obesus*]), which is more than 4 million tonnes. The proportion of the catch taken in purse seines ranges from 35 percent in the Indian Ocean to 82 percent in the Eastern Pacific Ocean (EPO) (ISSF, 2011). These species are very abundant in tropical waters, with skipjack and yellowfin living in shallower habitats and warmer waters than bigeye tunas. In the Western and Central Pacific, skipjack amounts to almost 70 percent of the total catch, while in other oceans it is only 35–41 percent of the total. The proportion of yellowfin in the catch is highest in the Indian Ocean (36 percent) and lowest in the Western and Central Pacific (20 percent). Bigeye tuna is less abundant in the Western and Central Pacific (5 percent) and it reaches about 20 percent in the Eastern Pacific and Atlantic Oceans.

As their vertical distributions are strongly influenced by the location of the thermocline, and the thermocline depth varies from 20 m to hundreds of metres, their vertical ranges are also very variable. Most of the catch in purse seine nets comes from the upper 100 m of the water column. The purse seine fisheries coexist in the tropics with industrial longline fisheries that target mainly bigeye tunas, with yellowfin being another species of interest. Practically all catches of skipjack come from purse seiners or pole and line operations, but not longlines.

The above three species share some characteristics: they grow fast, reproduce early (age at maturity ranges from 1.5 to 4 years), and are short-lived (maximum age for skipjack is 8 years, 9 years for yellowfin, and 16 years for bigeye tunas, but very few reach these ages). Skipjack is the smallest, with a maximum length of slightly more than 1 m, while yellowfin can grow almost to 2.4 m, and bigeye may reach 2.5 m of fork length (Schaefer, 2001; Collette, 2010). They are fast-swimming schooling species, with a diet composed of fish, pelagic crustaceans, and squids. Trophic levels are 3.5–4.5 (Froese and Pauly, 2010). They form multispecies schools, and, frequently, juveniles of bigeye and yellowfin may be found schooling with skipjack schools, as their sizes are similar.

The issue of bycatch in fisheries has been growing in significance from the point of view of management, and for those interested in the conservation of marine species. It is a complex problem that generates widely different reactions among all interested parties. For some it is a waste issue, for others it is a major conservation threat to many long-lived species. Many fishers are also aware of the need to conserve the structure of the ecosystems they live off, and are prepared to work to find solutions. In many cases, those in the fishing industry are being pressed to act because it is a subject that may affect their ability to continue fishing, or it may affect the marketing of their products.

In the tuna fisheries, the bycatch issue became very visible in the EPO because of the mortality of dolphins in the tuna fishery, and its controversies in the 1960s (Perrin, 1969; Hall, 1998; Gosliner, 1999). For many years, this subject dominated the agenda at the Inter-American Tropical Tuna Commission (IATTC), the tuna regional fisheries management organization (t-RFMO), where this interaction was taking place. As the mortality, abated in the early 1990s (Hall, Campa and Gómez, 2003), the interest switched to other conservation priorities.

The declines in some populations of leatherback (*Dermochelys coriacea*) and loggerhead (*Caretta caretta*) sea turtles and of albatrosses became a high priority for conservation organizations and fisheries managers. Very little data were available, but it was known that they were caught in longline fisheries in considerable numbers (Lewison, Freeman and Crowder, 2004). With very few or low-coverage observer programmes, there were no good estimates of the impacts of the different fisheries, but there were indices of the status of the populations based on counts during the nesting season in beaches or rookeries, and some of these showed sharp declines (Spotila *et al.*, 2000). Thus, for most t-RFMOs, the work on bycatch started with this emphasis. Longlines are selective for sizes, capturing mostly yellowfin and bigeye tunas of modal sizes 100–140 cm with low tuna discards, but they have bycatch of seabirds, sea turtles, and sharks that are much higher than for purse seiners. For example, OFP (2008a) and Clarke (2009) show that, for sharks, more than 90 percent of the bycatch is from longliners.

Only recently, with the rapid growth of the purse seine fisheries on fish aggregating devices (FADs), has the issue of other bycatch in the seine fisheries become visible to the public, because of the campaigns of environmental organizations (Greenpeace, 2010), and a challenge to fisheries managers. Because of this sequence of priorities, the agendas of the bycatch working groups in the t-RFMOs have been dominated by longline bycatch in recent years, and there is a considerable prevalence of papers on this subject. Consideration of the impacts of tuna fisheries on sharks is the most recent development, generated by the difficult situation of many shark populations (Fowler *et al.*, 2005; Camhi, Pikitch and Babcock, 2008; Dulvy *et al.*, 2008; Camhi, 2009; Camhi *et al.*, 2009a; Baum and Blanchard, 2010).

Another significant subject that came to prominence with the expansion of the FAD fisheries was the increasing capture of juvenile bigeye and yellowfin tunas in the sets on FADs. Some of these were retained, others discarded, but they added pressures on stocks that were targeted by other fisheries (e.g. bigeye tuna was the main target of important longline fisheries). There were also discards of skipjack tunas that were unmarketable because of size, or other reasons.

FAO has steered these developments through the different international plans of action for sea turtles, seabirds and sharks, workshop reports, and through Technical Consultations and world reports on bycatch issues, reduction of "Wastage", etc. (e.g. Alverson *et al.*, 1994; Clucas, 1997; Pascoe, 1997; Brothers, Gales and Reid, 1999; FAO, 1999a, 1999b, 2006, 2009; Kelleher, 2005; Gilman, Moth-Poulsen and Bianchi, 2007).

2. Definitions and framework

PURSE SEINERS AND THEIR FISHING OPERATIONS

This review covers only purse seine fisheries (Figure 1) that produce tunas as the major component of their catch. The fish are pursued by vessels of a broad range of sizes and capacities, from those capable of carrying only a few tonnes to those capable of carrying more than 3 000 tonnes. The range in vessel lengths is 20–120 m. The net length may reach more than 2 200 m and its depths are usually from 150 m to 350 m; the mesh size varies from 7.5 cm to 25 cm but the vast majority is of 10.8 cm stretched mesh.

FIGURE 1
Diagram of a tuna purse seine vessel

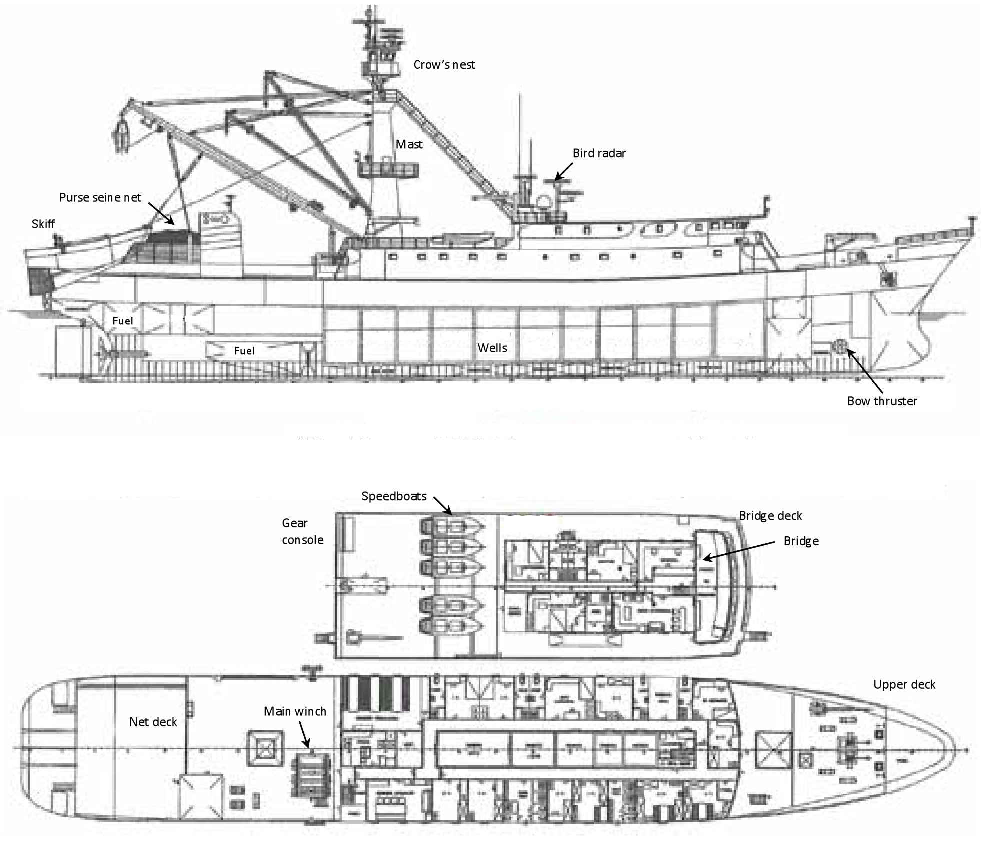
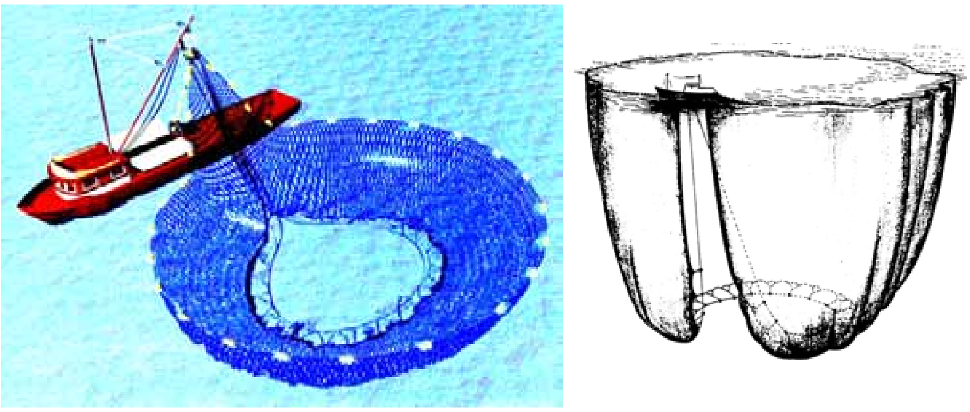


Figure 2 shows a diagram of the structure of most seines used in the tuna fisheries. Figure 3 shows the theoretical maximum area encircled by the net, based on parameters for the EPO (maximum theoretical net diameter about 600 m).

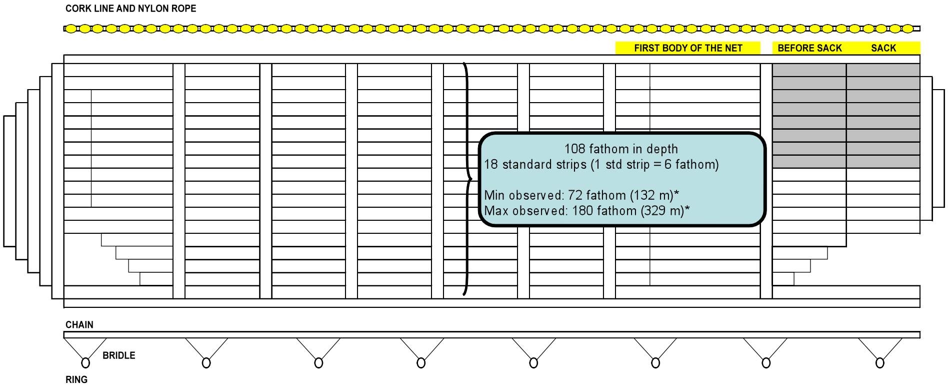
If the length of the towline is added, a 15 percent factor needs to be added to the length. The length and depth of the nets show considerable variability, with length

FIGURE 2
Diagrams of a purse seinel



Graphic by Jim Bean for NOAA/Communications Collective

Purse seine net design (typical EPO net)



* For vessels that made 50% or more
FO sets during 2004-2008 - EPO

modes at 1 280 m and 1 330 m (700–850 fathoms), and depths with a strong mode at 180 m, and a typical range of 180–240 m (100–130 fathoms) (Figures 4 and 5).

The combinations found in the EPO are included in Figure 6. The dimensions change and adapt to different ocean conditions. As an example, dimensions of nets from French seiners operating in the Atlantic increased in length from 700–800 m in the 1960s to about 1 500 m in the early 2000s, with depths going from 100 m to 225 m in the same period (Gaertner and Sacchi, 2000).

Figure 7 shows the trends in the EPO, trying to separate the types of sets where the changes have been more significant. Nets have been becoming deeper in the EPO, especially for the vessels fishing on FADs, and longer for the vessels setting on dolphin.

Bycatch figures for industrial tuna longline fisheries are very scarce, and observer coverage is not sufficient to draw many conclusions. Longlines are selective for sizes, capturing mostly yellowfin and bigeye tunas of modal sizes 100–140 cm with lower tuna discards, but they have a bycatch of seabirds, sea turtles, and sharks that is much higher than for purse seiners (Chapter 1).

FIGURE 3
Maximum dimension of encirclement

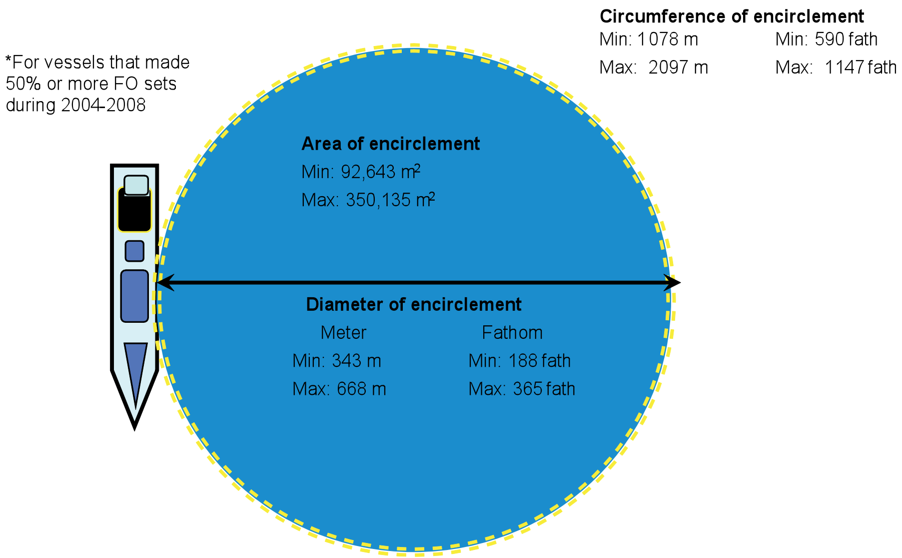
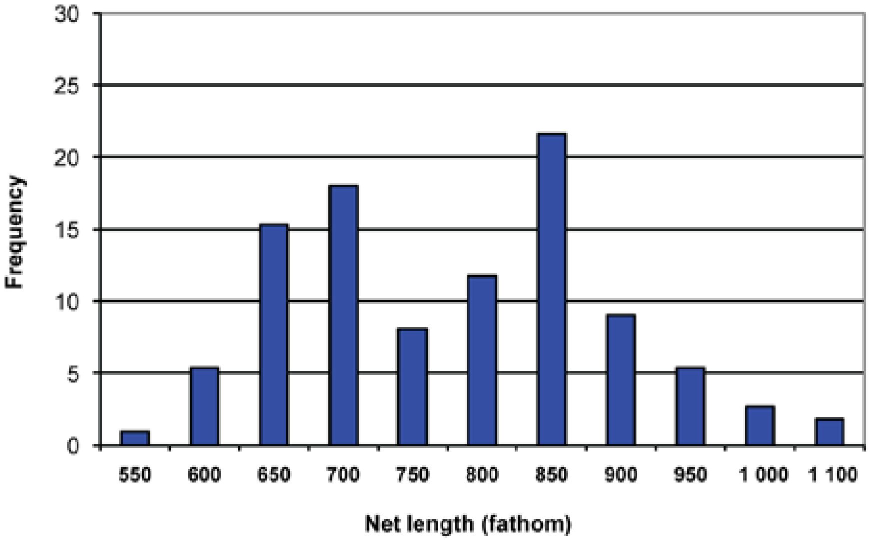


FIGURE 4
Frequency distribution of net lengths for vessels that made 50 percent or more floating object sets in 2004–2008.



However, the fishing depth is much less than the vertical dimension of the net and it depends on several factors that affect its dynamic behaviour (Misund, Dickson and Beltestad, 1992; Gaertner and Sacchi, 2000; Kim, 2000; Santana *et al.*, 2002; Kim *et al.*, 2007; Kim and Park, 2009). In general, fishing depth ranges between 45 percent and 75 percent of the net vertical dimension, with values of 55–66 percent being the most common (Delgado de Molina *et al.*, 2010). The fishing depth of the net determines the maximum depth at which the vessel can set without risking the loss or damage of the net, and this value should be taken conservatively, because of concerns with map or instruments inaccuracy, and the possibility of topographic features rising from the bottom. Therefore, probably, 90–160 m is the minimum depth for a set, depending

FIGURE 5

Frequency distribution of net depths for vessels that made 50 percent or more floating object sets during 2004–2008

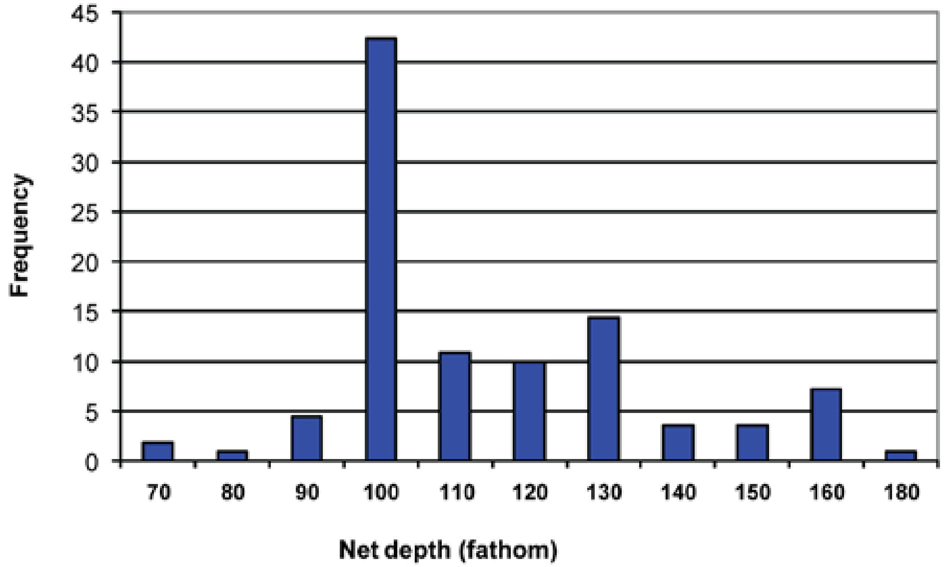
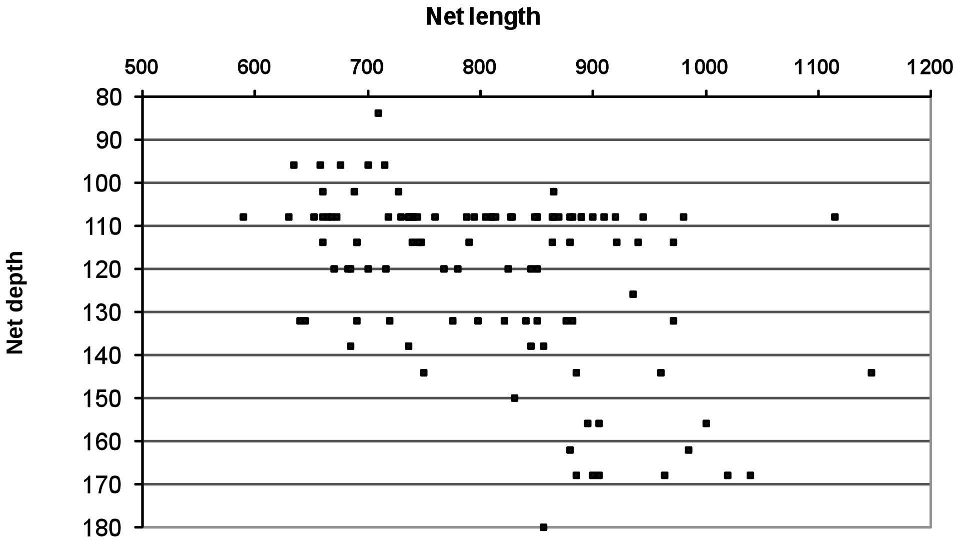


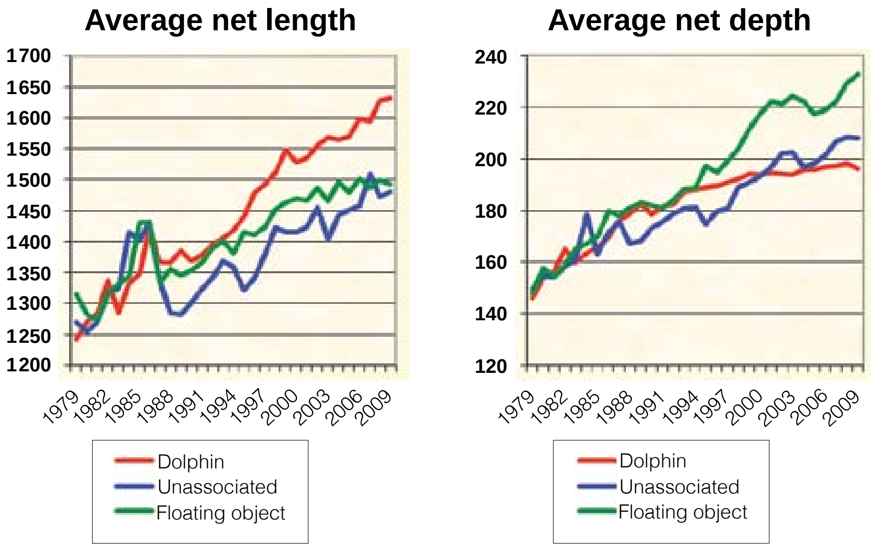
FIGURE 6

Combinations of length and depth in purse seine nets (in fathoms), for vessels that made 50 percent or more floating object sets during 2004–2008



on the net characteristics. The top of the net is hung on a floatline, and the bottom is attached to a leadline, which usually consists of a steel chain with steel rings, known as "purse rings", and is attached below the chain. The purse line that runs through the purse rings is made of steel and allows the pursing of the net. Purse seiners are equipped with a power block to purse the lead line after fish are inside of the net. Descriptions of the gear and operations can be found in Ben-Yami (1994), and Sacchi (2008). Further information is also available at www.fao.org/fishery/geartype/249/en, and video materials in www.tunaseiners.com, and by Internet search for videos using terms such as "tuna seiners" or "tuna purse seine".

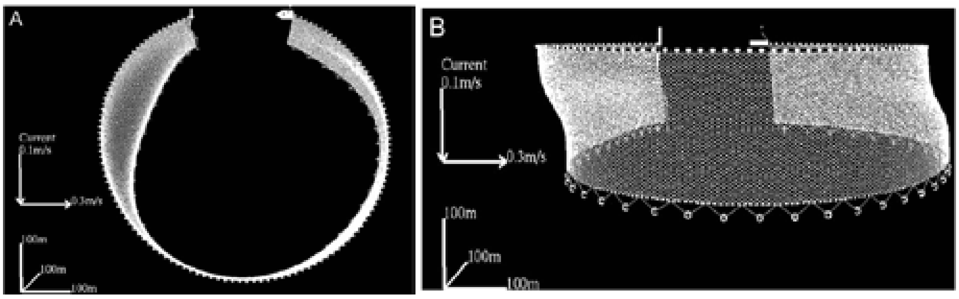
FIGURE 7
Equipment trends (EPO)



The construction of the nets must follow the characteristics of the oceanic areas where they will be used (e.g. thermocline depths), and the behaviour of the target species. While sinking, the net shape will be affected by currents, by its construction (materials, etc.), and by the manoeuvre of the vessel (Kim *et al.*, 2007). Sinking speed is a very important variable that may affect the captures in a set, but it is seldom available. Before encirclement is complete, there are two escape routes: dive under the net, or swim through the open section of the net (Figure 8).

For some species, the thermocline may act as a barrier to keep them from escaping vertically. For other species, their perception of the situation in unclear, given the dimensions of the net, and the escape options are not identified as such. For very large animals, such as whales, a third option is to simply charge the netting and break through. The pursing operation begins to close the bottom of the net. In a later stage, the escape routes are restricted, and when pursing is finished, and the purse cable has closed the bottom opening, there are no more escape routes. As the mesh is more than 10 cm stretched mesh, very small individuals can go through it, although not all species will be willing to squeeze through a tight opening. Some may become enmeshed in

FIGURE 8
Completing the encirclement



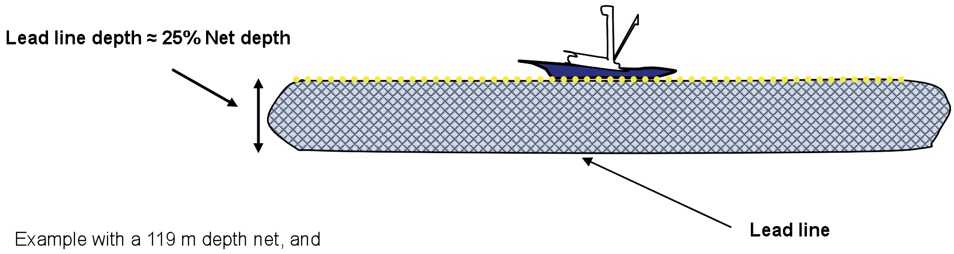
Source: Kim and Park (2009).

the webbing. It is important to understand the escape routes because target schools, and all others species/individuals associated with them, have opportunities to escape, and some may have behaviours (e.g. diving deep when scared) that may result in their escape (Delgado de Molina *et al.*, 2005a; Viera and Pianet, 2006).

An example of the temporal sequence of the set is illustrated in Figures 9–14, based on the studies by Kim *et al.* (2007) and Kim and Park (2009). Setting takes 7–8 minutes, and pursing 20–25 minutes (Kim and Park, 2009). The whole process lasts less than 30 minutes in general, but sets in adverse environmental conditions, or with malfunctions may take much longer. After the net is closed, the volume of the net is reduced to facilitate the loading of the catch. This phase of the set may last several hours, depending on the volume of the catch, the size of the brailer, etc. The duration of the set is important for judging the level of stress of the individuals captured and their chances of survival if released (discussed below). The geometry of the net during the set is also significant for understanding the vertical dimension of the operation, and the volume enclosed, which may determine which schools and individuals are captured (Delgado de Molina *et al.*, 2010a).

In this technical paper, the definition of a purse seine is as in the International Standard Statistical Classification of Fishing Gear (ISSCFG) standard (Coordinating Working Party on Fishery Statistics [CWP]–FAO, tenth session [Madrid, 22–29 July 1980]), and more recently stated by the International Council for the Exploration of the Sea (ICES)–FAO in 2007.

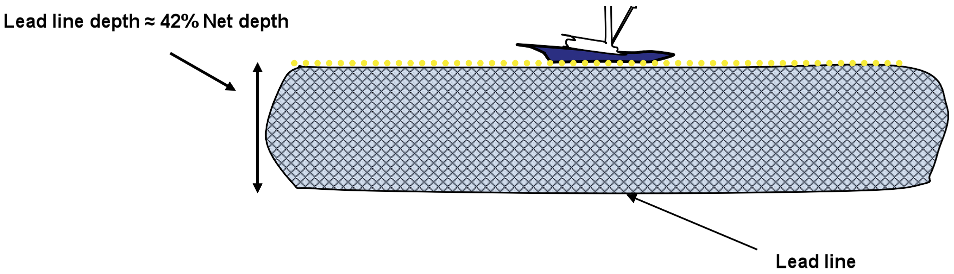
FIGURE 9
Lead line depth estimation during pursing at set start



Example with a 119 m depth net, and 19 min. pursing. Depth taken at the centre of lead line

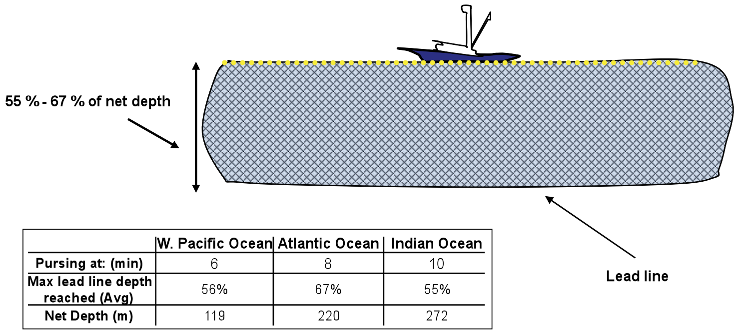
Source: Kim *et al.* (2007).

FIGURE 10
Lead line depth estimation during pursing at 3 minutes



Source: Kim *et al.* (2007).

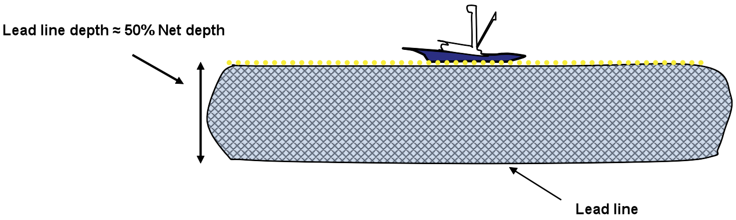
FIGURE 11
Lead line depth estimation during – maximum depth reached by the lead line



	W. Pacific Ocean	Atlantic Ocean	Indian Ocean
Pursing at: (min)	6	8	10
Max lead line depth reached (Avg)	56%	67%	55%
Net Depth (m)	119	220	272

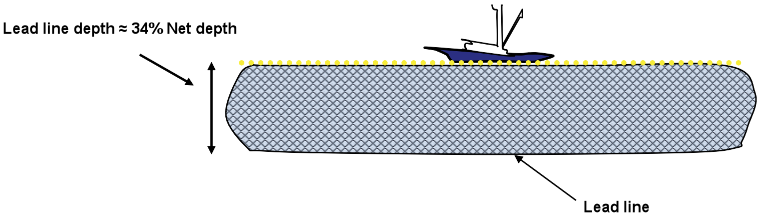
Sources: Kim *et al*. (2007); Santana *et al*. (2002).

FIGURE 12
Lead line depth estimation during pursing at 9 min



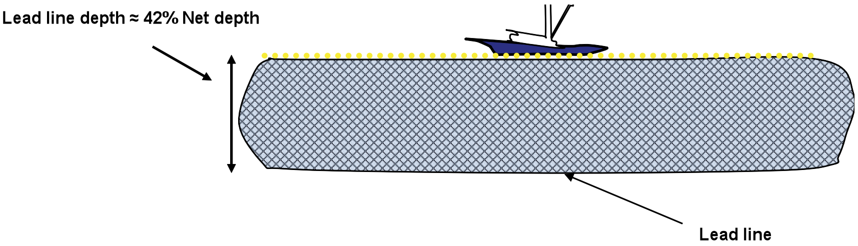
Source: Kim *et al*. (2007).

FIGURE 13
Lead line depth estimation during pursing at 12 min



Source: Kim *et al*. (2007).

FIGURE 14
Lead line depth estimation during pursing at 15 min



Source: Kim *et al.* (2007).

1. SURROUNDING NETS

A surrounding net catches the fish by surrounding them from both the sides and from underneath. It consists of netting framed by lines; a float line along the top at the surface and a weighted line along the bottom.

1.1. Purse seines

Purse seines are designed to catch schooling fish. A purse seine is made of a long wall of netting framed with a lead line and a float line. The purse seine is set from one or two boats to surround a detected school of fish. A purse line threaded through purse rings spaced along the bottom of the net is drawn tight (pursed) to stop the school of fish escaping downwards under the net.

1.1.1. One boat operated purse seines

This category comprises purse seines operated by a single boat, with or without an auxiliary skiff. The strongest part of the net, the "bunt", is where the catch is concentrated and is usually placed at one end of the purse seine. Handling of the gear may be mechanized, e.g. by a hydraulic power block or a net drum." (IICES Working Group on Fish Technology and Fish Behavior Report 2007, ftp://ftp.fao.org/FI/DOCUMENT/rebyc/ices/WGFTFB07.pdf; further information is also availble at www.fao.org/fishery/vesseltype/150/en).

The vast majority of the seiners that participate in the tuna fisheries fall into the category of one boat operated purse seines. The targets in tropical waters are yellowfin tuna, bigeye tuna, and skipjack tunas, and to a much lesser extent, and in some regions, some other tuna or small tuna-like fish such as black skipjack (*Euthynnus lineatus*), frigate tunas (*Auxis thazard*), bullet tunas (*Auxis rochei*), and bonito (*Sarda* spp.). These fish generally feed on baitfish near the surface, or associated with floating objects. In temperate waters, the purse seiners catch either small juvenile bluefin tuna (*Thunnus orientalis*, *T. maccoyi* or *T. thynnus*) when they are feeding on baitfish, or large bluefin tuna while they surface for spawning activities. Also in temperate waters, purse seine is occasionally used to harvest albacore (*T. alalunga*), generally during the night when fish come to the surface to feed. However, these operations producing bluefin or albacore tunas are not the subject of this review.

There are smaller purse seine nets used for less-industrialized fishing near coastal areas, mostly targeting small tuna-like fish, such as frigate tunas, and bonitos. These operations are not well documented, and they are believed to be of minor significance compared with the operations of the major tropical tuna fleets. However, the coastal distribution of their sets may result in encounters with high densities of some vulnerable species near nesting beaches, foraging grounds, etc.

Ben-Yami (1994) describes the process after encirclement is completed: "Once the encirclement is finished, the extremity of the net that stayed attached to the skiff is transferred aboard the purse seiner and the two extremities of the purse line cable are hauled with the winch as quickly as possible in order to close the net at its bottom (this is called 'pursing' because it is similar to pulling the draw string of an old-fashioned purse). It is worth observing that, until the purse seine is not closed, the tunas can still dive below the net or the purse seine vessel and escape. It the net extends all the way from the surface down to the thermocline, the chance of fish escaping through the bottom would be reduced. During pursing, and especially when there is a current, the skiff is attached to the starboard side of the vessel, where it can pull it away from the net in order to prevent the purse seiner from drifting over the net. The pursing operation may take, for large purse seines, about 15 to 20 minutes.

When most of the purse seine has been retrieved, the tunas have been grouped within a restricted area along the portside of the vessel. Then the fish are harvested from the purse seine using a large scoop net called the "brailer" (brailing operation);

several tons of fish are taken on board each time. The duration of this operation will obviously depend upon the quantity of fish in the net, the size of the brailer, and other operational factors. In some operations targeting the bluefin tuna in the Mediterranean Sea, off Australia or off Baja California, a limited fishery for live fish has developed to supply sea ranching operations. In these cases, the pursing is stopped at half way, when the fish are not so crowded. This is to keep the fish alive, as most of the live fish caught are transferred to transport cages for tuna farming.

A mixture of species and sizes is enclosed in the net, after the smaller ones have escaped, or have squeezed through the meshes. The numbers, species or sizes, and the fates of these escaped individuals are not known (Davis, 2002); they are not visible even when there are observers on board the vessel. The selectivity of the purse seine with regards to the smaller fishes has not been studied, although experiments in other fisheries, comparing small seines with very small mesh experimental nets show that many species and sizes are not retained at all (Massutí, Morales and Deudero, 1999).

Some details need to be added to the above description because of their potential significance for bycatch issues. The individuals retained in the net are brought on board using a brailer (capacity usually 2–8 tonnes). The capacity of the brailer, and the amount of fish loaded may result in different conditions for the individuals brought on board that way, and, for those released, their survival may be affected.

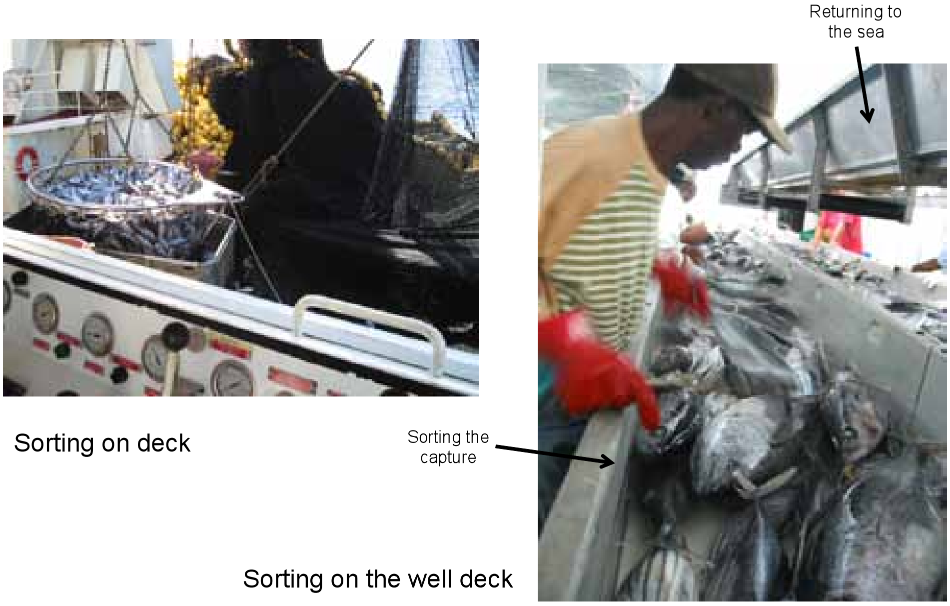
The fish arriving on the deck of the seiner (i) go to a platform on the deck used for sorting (the hopper), and from there down to the wells; or (ii) are transferred directly through an opening on the main deck to the well deck at a lower level, for sorting in a conveyor belt that carries the fish to the wells. The second method is replacing the first one in most vessels. Fishes that are selected to be discarded are set aside and may remain on the main deck, or on the well deck, until the crew has finished handling and storing the catch. In some vessels, another conveyor belt is used to carry the individuals to be discarded to the side of the seiner for release (Plate 1). The tuna catch is kept, in the industrial purse seiners, in wells of 20–100 tonnes each (total well tonnage for the majority of the fleet: 800–3 000 tonnes) with brine freezing at –20 °C. As mentioned above, videos showing the operations of different sizes and styles of vessels in different oceans can be found on the Internet. Readers unfamiliar with the purse seining operation are encouraged to access these materials, which will greatly enhance their understanding of the operations.

Besides the sophisticated technology to handle the net, most seiners carry an array of instruments to facilitate navigation, and detection of tuna schools. They include:

- Bird radar: used to detect seabirds frequently associated with tuna schools. Examples of this would be the S-Band Furuno Model FR-1760 DS (60 kW) FR-2137/2167 (30 kW) or earlier X–Band models (12–25 kW).
- Echo sounder/fish finder/sonar: provides information on the location of targets, school volume/tonnage and the models with multibeam and split-beam transducers can provide some additional information on subjects such as fish size distributions. Examples would be the Simrad ES60 (frequency 120 kHz), and Furuno FCV620 or the Furuno FCV295 or FCV1150 (dual frequency from range 28–200 kHz). The more common sonars include the Furuno CSH5L55. The characteristics of these instruments may be significant from the point of view of identifying sets with excessive bycatch, or with species or size compositions that may help in decision-making.

PLATE 1

Conveyor belts for sorting the capture.



Sorting on deck

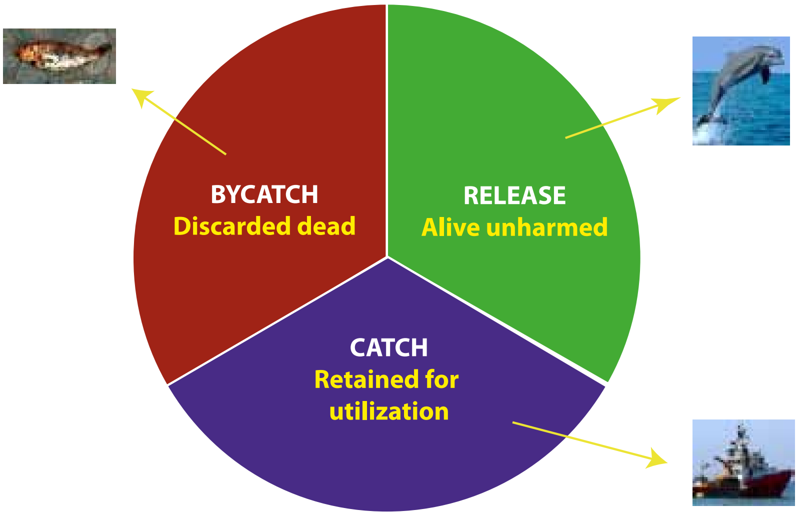
Sorting on the well deck

CAPTURE, CATCH AND BYCATCH

The definition of bycatch has been discussed in many documents, and whichever definition is selected, there will be objections by some. The concept has been applied to issues as diverse as the "trash" fish caught in some shrimp trawl fisheries (Stobutzki, Miller and Brewer, 2001; Stobutzki *et al.*, 2002), the discards of undersized individuals of the species of interest to the fishers, and the incidental mortality of component of the megafauna (marine mammals, sea turtles, seabirds). In an attempt to avoid a long elaboration of the subject, the definitions used in this review are the simplest, and most direct available, considering that one of the main purposes of the definition is to facilitate the communication with the fishers and other stakeholders (Figure 15).

FIGURE 15

Definition of bycatch: capture = catch + bycatch + release



Capture is defined as the total number or biomass of individuals caught (physically retained) in the net or other type of gear. There are three possible alternative fates for the capture:

- Catch is the part of the capture retained for utilization (consumption, sale, use as bait, etc.).
- Release is the part of the capture released alive, and assumed to survive the fishing operation.
- Bycatch is the part of the capture that is discarded dead, or assumed to die as a result of the fishing operation (Hall, 1996).

According to this definition, "bycatch" has a negative connotation, and that is the case with fishers, and with the conservation organizations that identify the concept as a target of campaigns. It is a resource wasted unnecessarily, and everyone can agree that it should be reduced if possible. Whatever is retained, is part of the catch, and as such should be the subject of fisheries management, even if not the main object of a fishery. For example, many marlins and some sharks caught in tuna purse seine fisheries are retained. As they have economic value, they have no negative connotation for the fishers, and the reduction of that component of the capture is not desirable to them. However, the important concept is that of accounting for all fishing mortality, and managing all species that are retained in significant numbers (Alverson *et al.*, 1994; Chopin, Arimoto and Inoue, 1996; Pascoe, 1997; Hall, Alverson and Metuzals, 2000). If the marlins and sharks of the example above are added to the harvest in directed fisheries, and to the bycatch in other fisheries, then the management of those species should decide on the actions to follow, with knowledge of the total impacts of all fisheries on those populations. The management measures could affect catch and bycatch of those species. A major advantage of this definition is that the concepts are dynamic; catch and bycatch are decisions of the fishers that may change over time.

Some authors differentiate between "discards" of the target species and "bycatch" of all other species, but the difficulty of establishing which the target species are, and the dynamics of the fisheries that turn today's bycatch into tomorrow's catch, make the approach used here simpler: bycatch are dead discards. At the same time, the approach selected separates unintended catch of a valuable species from the negative concept of bycatch as catching something that does not have "value" or cannot be retained for legal reasons. The concept is basically the same as the definition used by Hall and Mainprize (2005).

The three terms are: capture = catch + release + bycatch

Catch shows the economic component of the fishing operation, with utilization defined in a broad way, as any use that has economic value for the fishers.

The sum of catch and bycatch shows the ecological impact of the fishing operations, the total removals from the populations. Bycatch happens because:

- A species does not have a market.
- An individual of a marketable species is too small for the market.
- An individual of a marketable species is damaged or spoiled during the fishing operation, during brailing, etc.
- A species or individual cannot be legally retained.
- The decisions on retention are influenced by the limited storage in the vessels, the production of the current trip, and the expectations of future catches. For example, a set made a couple of days prior to the start of a closure may result in a higher level of retention if the vessel is not full. All these reasons may change with time or with economic conditions as:

- A market may develop for a species.
- If the value of a species increases (e.g. because of scarcity, or a very high demand for other reasons), it may be profitable to retain and/or process smaller individuals.
- The damaged individual may be kept for lower quality utilization (e.g. fishmeal instead of direct consumption market).
- The regulations may change.

The terms "target species", "primary target species", and "bycatch species" are avoided in this review because of the dynamic situations described above, and also because of the inability to know, in most cases, what fishers have in mind when they decide on a fishing ground or gear. The economic decisions that skippers and boat owners make probably include all the components present in those grounds.

One could argue that tuna purse seine fisheries have a clear target, because of the gear, the fishing methods, and even the characteristics of the storage system (a brine solution that is not adequate for preserving other species). However, the retention of non-tuna species (discussed below) has been growing in recent years and, as it is possible to adapt the wells to retain other species, with time they are becoming a larger proportion of the vessels' production.

The term tropical tunas refers mostly to the skipjack tuna, yellowfin tuna, and bigeye tuna. Black skipjack tuna (*Euthynnus lineatus*), kawakawa (*E. affinis*), bonito (*Sarda* spp.), frigate tunas (*Auxis thazard*), and bullet tunas (*A. rochei*) are other tuna species present in the fishing grounds, but their retention is less significant because of their lower value, or their catches are rare. In some cases, they are retained and sold in large quantities in local markets such as Abidjan, Côte d'Ivoire (Romagny *et al.*, 2000; Goujon, 2004a).

3. Purse seining

A few technological developments, such as synthetic materials for the netting (nylon), and a hydraulic system to manipulate the seine (the power block), allowed the switch from a pole and line fishery to a purse seine fishery (McNeely, 1961; Orbach, 1977; Francis *et al.*, 1992). These innovations were introduced in the Eastern Pacific, but spread rapidly to other ocean areas.

When purse seining was adopted, in the mid-1950s, it was natural to use the information on these associations to locate and catch tunas with the new gear, and the purse seine fishing operations, called sets, were frequently made encircling the tuna schools, floating objects, whales, or groups of dolphins.

TYPES OF PURSE SEINE SETS

Although the purse seining operation is always basically the same, there are different ways in which tunas are detected and encircled, and this gives rise to a classification of purse seine sets in several types. The detection may happen because of some behaviour of a tuna school that makes them visible, or because of an association of a tuna school with objects or with other species (seabirds, dolphins, whales, whale sharks, etc.). The main types are described below.

School sets

In these sets, the tuna school is detected because of its activity at or near the surface of the water. Typically, a disturbance on the ocean surface is detected from the vessel. A tuna school in a feeding frenzy or other type of very active behaviour close to the surface has caused the disturbance. Fishers recognize and identify, with different names, a variety of school sets. Breezers, jumpers, boilers and foamers are some of the descriptive names they apply to these signals of the presence of fish. Although there are situations where many schools are encountered in an area, in a given season, this type of set is the least predictable of all because fish behaviour may change abruptly in response to environmental or biological factors, and the schools may go deep, flee from predators, etc. The other difficulty with school sets is that the target tuna school is moving freely, and it is not “fixed” in space, as happens in other types of sets. Thus, the encirclement with the net is much more difficult, and the evasion of the school, or a misjudgement on the direction of movement of the school, may result in a “skunk” set, an appropriately named failed operation with no or little capture.

Many types of school sets are found in the IATTC databases, according to the records obtained copying from fishers’ logbooks for the period 1955-current. The main types and their relative frequencies are shown in Table 1. Classes with less than 1000 records, and sets that were “estimated” (e.g. assigned) were arbitrarily excluded, to simplify the issue.

Are all these sets the same type of set from the point of view of the catch and bycatch they produce? Some names may be synonyms arising from regional differences in jargon, but many reflect different perceptions by the fishers, and their knowledge is very valuable. Perhaps research on the local ecological knowledge on this subject could advance the discussion (Moreno *et al.*, 2007a). There are reasons to believe that the school set group is heterogeneous. For example, fireballs are night sets, while breezers tend to be day sets, because the observation of a breeze on the surface is more difficult at night, except perhaps with a full moon.

TABLE 1
School set categories (in percentage terms), 1960–2009

Description	1960-64	1965-69	1970-74	1975-79	1980-84	1985-89	1990-94	1995-99	2000-04	2005-09
Breezers	58.7	67.9	67.0	74.0	71.8	76.7	75.7	86.8	89.9	95.1
Jumpers	21.0	12.9	18.9	16.3	15.8	13.6	19.6	11.0	8.8	4.7
Foamers	5.0	6.2	2.2	1.8	4.8	6.5	2.4	0.9	0.6	0.0
Black spot	3.5	6.0	3.9	2.7	2.0	1.0	0.8	0.4	0.3	0.0
Boilers	4.3	2.7	4.0	2.5	3.6	1.0	1.0	0.5	0.3	0.1
Finners	2.0	1.6	1.9	1.1	0.6	0.3	0.0	0.0	0.0	0.0
Fireballs	3.3	1.3	1.4	0.7	0.7	0.6	0.1	0.2	0.0	0.0
Shiners	1.2	1.1	0.7	0.8	0.8	0.2	0.3	0.1	0.0	0.0

Source: From IATTC logbook database.

The behaviour of tunas, and the accompanying species, by day and by night may result in different species or sizes being vulnerable in different periods. However, the numerical dominance of the breezers is so clear, that the statistical "noise" created by combining these classes into one may diminish the significance of the heterogeneity. However, if jumpers, foamers, and boilers have different characteristics in species, or sizes of all species involved, it would be preferable to limit any analysis of trends in average capture per set, etc., to a more homogeneous group such as breezers, or do a comparative study, when the data allow that, to decide on the validity of the pooling operation.

Understanding the differences in the tuna behaviours reflected by the fishers' nomenclature may also help improve bycatch estimates, and also other fisheries estimates (e.g. catch per unit of effort [CPUE] figures because of the possibility of different search systems being used according to the type of detection made). It is also possible that the extensive use of bird radars to locate tuna schools, which started in the early 1980s and has expanded continuously, may have resulted in an effective search system that tends to detect breezing tunas rather than the other behaviours. There could be cases where the classification of a set is difficult. Is a school of tuna found close to a live whale or whale shark associated with the animal, or is it simply a spatial coincidence caused by their attraction to a common stimulus, or environment, e.g. they are both feeding on the same prey aggregation, or in a highly productive patch?

SCHOOL SETS OR UNASSOCIATED SETS?

Two names, school sets and unassociated sets, have been used for the same type of set. In recent years, part of the literature has replaced school sets with unassociated sets. School set seems to imply that this is the only type of set where a school is captured. Unassociated set is a definition by a negative, and the tuna schools are frequently associated with other schools of different species, and also with seabirds, that facilitate the detection. Both terms can be used, but school set is preferred because the fishers use and understand this one to describe these sets. This is one case where researchers try to impose a definition that is meaningful to them, replacing one that is meaningful to the fishers. As one of the objectives of tuna researchers should be to communicate with fishers, it makes sense that they follow the language of those that spend their time fishing, and understand their logic. When a vessel makes a set, it is made on a log, on a FAD, on dolphins, or on a school of tunas. The description is correct and accurate, and the logic is obvious.

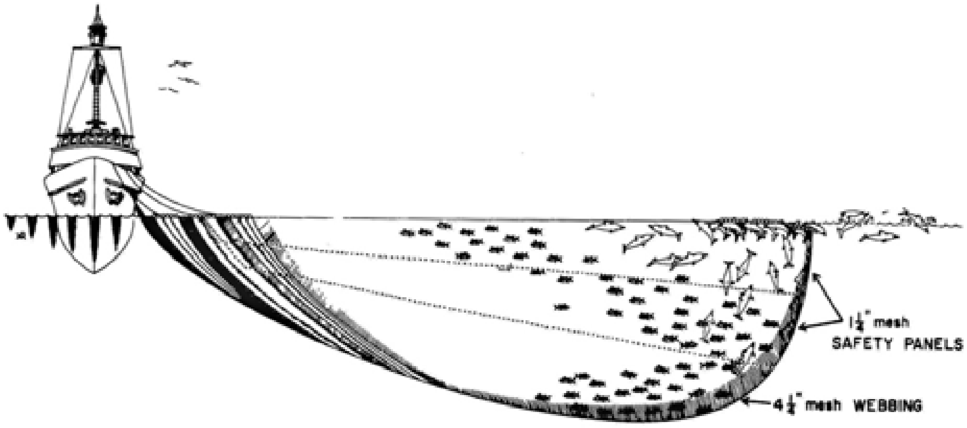
However, the numbers of these sets are low, and their influence on the statistics is probably negligible.

Dolphin sets

Yellowfin tunas can also be found in the Eastern Pacific in association with dolphins of the genera *Stenella* (*S. attenuata,* and *S. longirostris*) and *Delphinus* (*D. delphis*). This association is quite common in some regions of the Eastern Pacific but very rare or absent in other ocean areas (Donahue and Edwards, 1996). The other major tuna species are very rare in these sets. The fishers detect a group of dolphins; give chase with several speedboats until the group is “turned” and stops. Then they encircle the group of dolphins, and the yellowfin associated to them that stayed with them during the chase. A manoeuvre, called the “backdown” follows. It consists of putting the vessel in reverse, and pulling the net. The net first elongates, and then it sinks several metres below the surface in the farthest section from the boat. This allows the dolphins to exit the net, while at the same time the vessel is pulling the net under the dolphin group (Figure 16). After the dolphins are out of the net, and using several techniques to liberate any left in the net, the set continues in the usual way (Francis *et al.*, 1992). This fishery is practically monospecific for yellowfin tuna, and the sizes of tunas caught are quite large, with the vast majority being more than 80 cm in length, with average weights in the different regions of 14–31 kg (IATTC data).

FIGURE 16

Diagram of a dolphin set: net cross-section during backdown using fine mesh, double-depth safety panels



Source: Peters (1979).

Sets on seamounts

In many regions, tuna schools are found associated with seamounts (Yasui, 1986; Fonteneau, 1991; Holland, Kleiber and Kajiura, 1999; Holland and Grubbs, 2007; Pitcher *et al.*, 2007; Morato *et al.*, 2008), and the category is used to classify sets. A recent review of the impact of seamounts on longline catch (Morato *et al.*, 2010) shows some significant impacts on catch rates for all tuna species, and some of these may also affect purse seine catches. However, there are very few detailed studies with large sample sizes, and it is difficult to make comparisons of catch or bycatch rates because even the definition of what constitutes a seamount is not obvious (is it taller than x metres from the bottom, or the tip reaching less than y metres from the surface?;

are oceanic ridges just a sum of seamounts or is there a ridge effect also?), and the distance at which it may affect catch rates is not easy to determine (is it the same in all directions? are there up-current/down-current differences? are effects influenced by current speed? by the slope of the seamount?). It is quite likely that "seamount" is a heterogeneous category, including very different shapes and sizes.

Amandè *et al.* (2008a) show figures for the Indian Ocean, but the database contains only 34 seamount sets, and they estimate that seamount sets are close to 1 percent of all sets. Their definition of seamount is "within 5 miles from known seamount location". Most of the species found in seamount sets are also found in the other types of sets in the region, but the list described for seamounts is shorter than the lists generated from other set types, perhaps reflecting the small sample size. The expectation is that seamounts will have a higher biodiversity (Pitcher *et al.*, 2007).

As there are probable ecological differences near seamounts, as compared with the open ocean, it is possible that the bycatch in these sets is different, but the analyses will have to be performed with a much higher data density.

Floating object sets

Many species are found growing on or under floating objects, and the association with the objects, ranging from physical attachment to looser associations, affects their biology, ecology and biogeography. A discipline of ecology named "rafting ecology" addresses the subject, and a major review has been published recently (Thiel and Gutow, 2005a, 2005b; Thiel and Haye, 2006). A list of more than 300 fish species associated with floating objects has been compiled (Castro, Santiago and Santana-Ortega, 2002). Several tuna species of commercial and recreational value are included among them. Fishers discovered the association of tuna schools with floating objects early on, and took advantage of the opportunity offered by a behaviour that made the detection and the capture easier than for unassociated schools, because of the strength of the association that kept the school relatively fixed in space, drifting with the object. The fishery on floating objects started as an opportunistic operation, whenever an object was encountered. References describing the early fishery on floating objects in different oceans can be found in Stretta *et al.* (1997), Scott *et al.* (1999), and Le Gall, Cayré and Taquet (2000a).

Especially productive were the coastal waters in regions where there were significant inputs from the continent, such as those with abundant forests, and tropical rivers that could carry a lot of material during the floods that mark the beginning of the rainy season. This is expected close to the areas where the Inter-Tropical Convergence Zone intersects the continents. In these regions, tree trunks and branches, aquatic plants, and other materials coming from the land were carried out to sea, and the tunas present in those areas associated with them (Caddy and Majkowski, 1996). The purse seine sets made on these objects were called log sets by the fishers because tree trunks and branches were the most common type of object. In some regions without coastal forests, or major rivers (e.g. Central, Southern and Baja California), bundles of seaweeds called kelp "patties" played the role of the logs, but their abundance was frequently limited. These "patties" originated in kelp beds (*Macrocystis pyrifera*), when plants were uprooted by storms or other causes. As these seaweeds are quite large and have floats, they form structures that persist in the ocean (Graham, Vasquez and Buschmann, 2007).

The list in Table 2 shows the main types of objects sighted and set on in the period 1987–1990 (from IATTC observer database [Hall *et al.*, 1999a]). The largest category is a broad set of plant materials (tree trunks, branches, etc.), mostly unidentified trees, but also bamboo and other canes, palm trees, and mangrove trees. Kelp patties were the predominant type of object in the northern section, on the California Current system, but few of them produced sets. This group was followed by two categories of objects of anthropomorphic origin (crates, pallets, lost fishing gear, etc.). There is another grouping composed of dead animals (whale sharks, sharks, very few whales, and other animals including pinnipeds as the main component). A small proportion of the sightings consisted of FADs, but they led to many sets. Stretta *et al.* (1997) describe the types of objects from the Atlantic and Indian Ocean fisheries. In the Atlantic Ocean, plastic objects prevailed, while in the Indian Ocean tree trunks and branches were the most common by far.

TABLE 2

Types of floating objects observed in the Eastern Pacific Ocean, 1987–1990

Type of object	Sightings % (n= 2723)	Sets % (n= 2492)
Plant material	48.2	47.2
Kelp	5.5	0.8
Dead animals	4.8	3.2
Wooden artefact	16.9	17.8
Bycatched equipment	13.7	11.8
Non-wooden artefact	5.9	5.8
FADs	3.1	12.6
Others and unidentified	1.7	0.7

Note: A sighting is an observation that did not lead to a set.
Source: From Hall *et al.* (1999a, 1999b).

Sets on tuna schools associated with live whales are considered a separate type because of the behaviour of the animals that creates different conditions for the association. They are quite rare, and the main whale species involved is the sei whale (*Balaenoptera borealis*), in the Indian Ocean (Stretta *et al.*, 1997; Romanov, 2002), and in the Western Pacific (Hampton and Bailey, 1999). Stretta *et al.* (1997) found that in the Atlantic the Bryde's whale (*B. edeni*) is the most common, followed by the fin whale (*B. physalus*). Other cetaceans such as the minke whale (*B. acutorostrata*), pilot whales (*Globicephala macrorhynchus*), and the rough-toothed dolphin (*Steno bredanensis*) have been reported with much lower frequency. The rough-toothed dolphin is occasionally captured in floating object sets, and it may associate with them. The samples available are not large enough to make comparisons. In almost all cases, these animals escape under or through the net, which they can break. Table 3 shows all captures in the Eastern Pacific over a decade. No mortality was observed in the period, and only three individuals were released by the crew. These captures may not be the result of an association, but of a simple common attraction to prey schools, or environmental conditions (Fréon and Dagorn, 2000). These sets may be defined as whale sets, or as school sets. They are so infrequent that it is difficult to make them a category of their own, and in almost all cases they are not associated with floating objects.

Sets on tunas associated with whale sharks (*Rhincodon typus*), are also infrequent (< 0.5 percent of all sets), or about 80 sets/year in the Eastern Pacific; less than 0.1 percent of the sets in the Western Pacific (Harley, Williams and Hampton, 2009), but in some regions are quite significant (32 percent of sets in the Western Atlantic–Caribbean [Gaertner and Medina-Gaertner, 1999]). When they are captured, they have to be released by the crew, and some mortality may result from the capture, handling and release process. In the Eastern Pacific, there have been no observed mortalities. Not all mortality would be observable in this case if there are post-release impacts.

Cooperative fishing between a seiner and a bait boat, that becomes an attractor, is practised in different regions (e.g. off Ghana), but it is not common, and sample size limitations make difficult to produce the comparisons needed.

TABLE 3

Sets involving whales in the Eastern Pacific Ocean, 1999–2009

Common name	Sets	Evaded encirclement	Escaped by ripping net before capture	Captured in the net	Escaped by ripping net after capture	Released by crew	Killed
Unidentified Baleen whale	134	153	113	5	5	0	0
Unidentified large whale	35	76	26	2	2	0	0
Fin whale	15	84	14	3	2	1	0
Bryde's whale	9	9	1	2	1	1	0
Unidentified whale	7	5	6	0	0	0	0
Sei whale	5	3	3	0	0	0	0
Blue whale	4	5	1	0	0	0	0
Humpback whale	3	6	0	1	0	1	0
Sperm whale	1	1	0	0	0	0	0

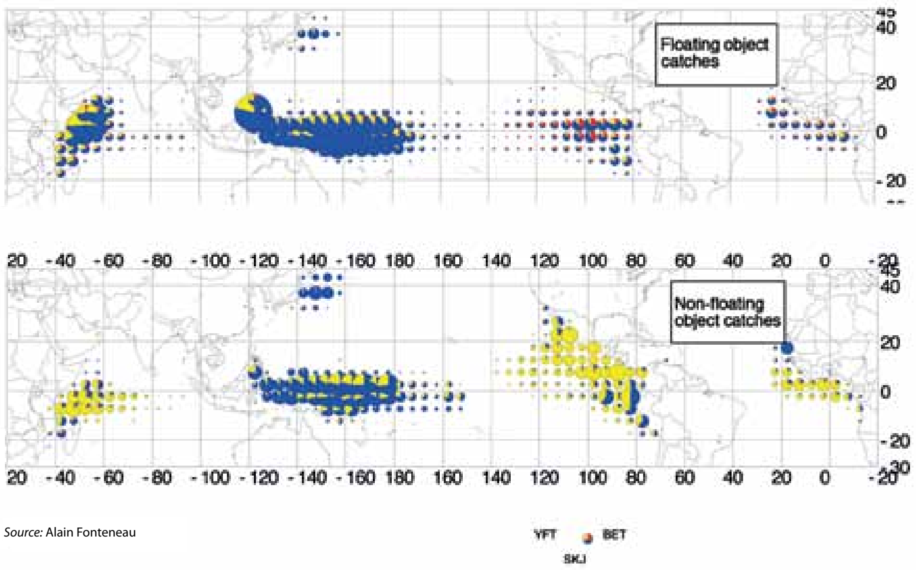
Source: IATTC observer database.

The locations and seasonality of the log fishing areas were well defined in most oceans (see Stequert and Marsac, 1989; Ariz *et al.*, 1999, for the Atlantic; Hall *et al.*, 1999a, for the Eastern Pacific; Hallier and Parajua, 1999, for the Indian Ocean; and Hampton and Bailey, 1999, for the Western Pacific). A review of the fisheries on floating objects in all oceans was the object of two workshops in 1992 (La Jolla, the United States of America) and in 1999 (Martinique) (Scott *et al.*, 1999; Le Gall *et al.*, 2000a), and a map of their initial distribution can be found in Fréon and Dagorn (2000). For the Caribbean, Gomes *et al.* (1998), and Gaertner and Medina-Gaertner (1999), describe the use of floating objects in fisheries for different pelagic species. The global map of these areas is in Figure 17, comparing areas with different set types, on floating objects and others. Others include mostly school sets in all oceans, but in the Eastern Pacific dolphin sets are also included.

Figures 18–21 show the detailed distributions of catches on floating objects and non-floating objects in the major fishing areas (Eastern Pacific, Western and Central Pacific, Eastern Atlantic, and Western Indian Ocean, courtesy of A. Fonteneau).

FIGURE 17

Floating object and non-floating object catches, 1997–2006



Source: Alain Fonteneau

FIGURE 18

Floating object and non-floating object catches in the Eastern Pacific Ocean, 1997–2006

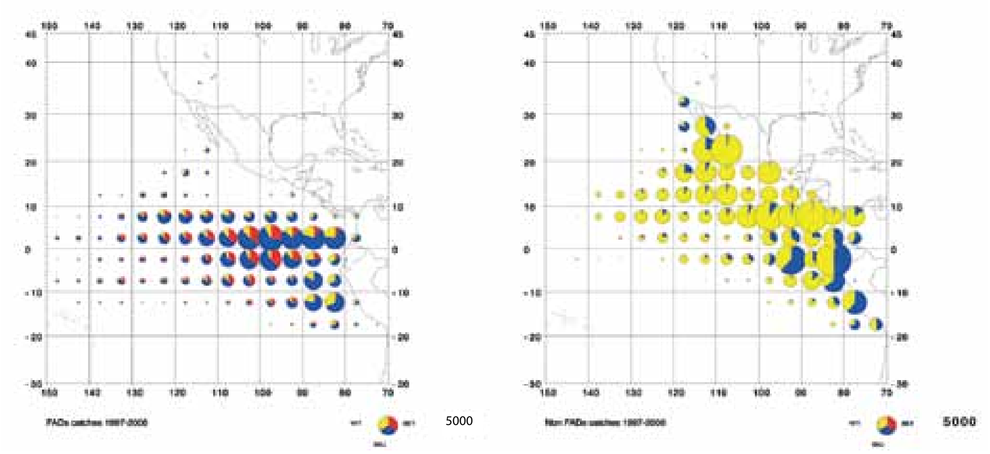


FIGURE 19

Floating object and non-floating object catches in the Western and Central Pacific Ocean, 1997–2006

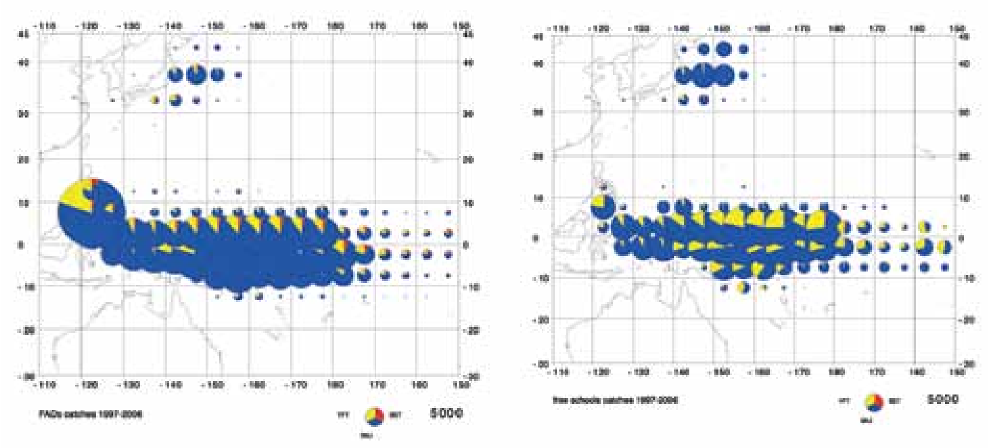


FIGURE 20

Floating object and non-floating object catches in the Eastern Atlantic Ocean, 1997–2006

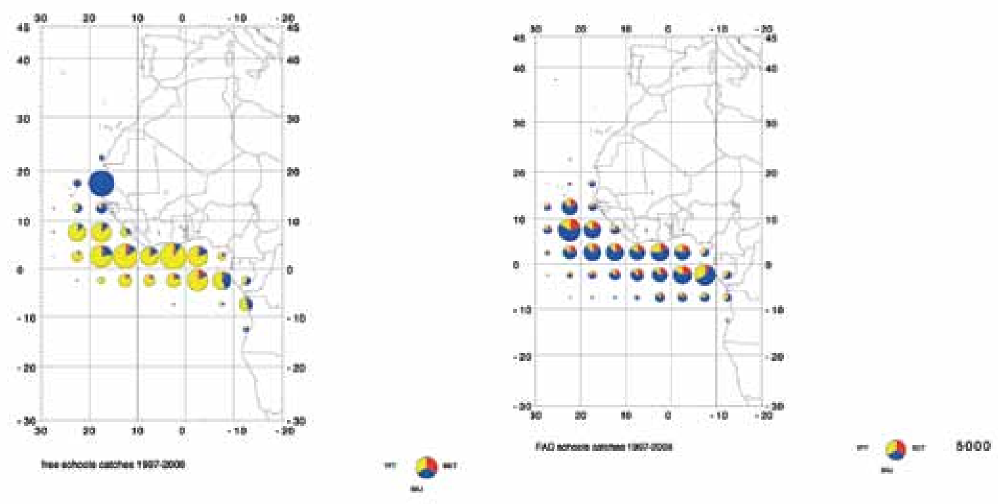
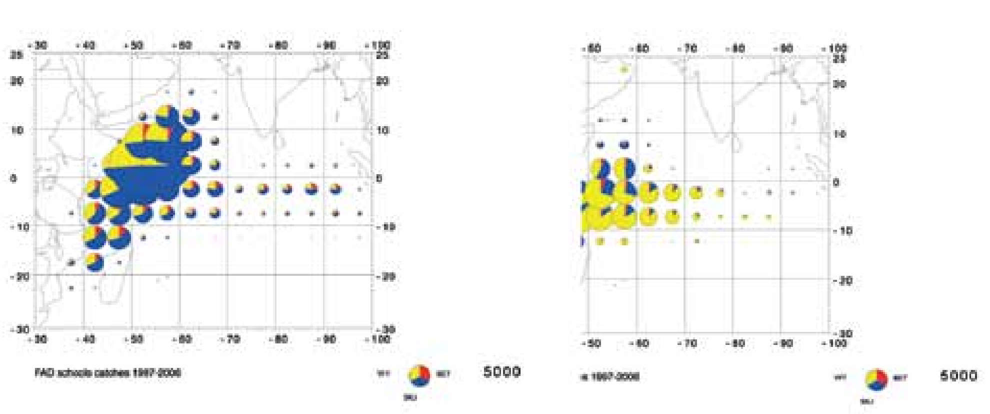


FIGURE 21
Floating object and non-floating object catches in the Western Indian Ocean, 1997–2006



With the increases in human populations in coastal areas, in marine shipping, fishing, and other marine and coastal activities, the introduction of anthropogenic objects increased, and tunas also associated with them. In contrast, natural objects such as trees may be decreasing in some areas because of deforestation (Caddy and Majkowski, 1996). The name log set was applied by extension to sets that were not exactly on logs, but on human-made objects found adrift. The objects that attracted tunas were of a wide range of shapes, sizes, colours, and other characteristics. Among the commonest types of floating objects were wooden objects of human manufacture (boxes, crates, planks, etc.), discarded fishing gear, dead animals (e.g. dead whales or sea lions), and kelp "patties". There seemed to be no clear connection between the characteristics of the objects, within the range of the natural objects observed, and the amount of tuna present under them (Hall *et al.*, 1999b). The common characteristic of all log sets, is that they are made on "encountered" floating objects.