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AN OVERVIEW OF HISTORICAL CHANGES IN THE FISHING GEAR AND PRACTICES OF PELAGIC LONGLINERS

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An overview of historical changes in the fishing gear and practices of pelagic longliners[1]

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Summary

Pelagic longline fishers have continuously modified their gear and practices to improve fishing power or the catchability of target species, which has altered the relationship between catch rates and abundance. Advances in technology resulted in the introduction of many electronic devices to assist in navigation, communication, and finding target species. The development of synthetic materials allowed improvements to lines and hooks that increase the probability of hooking target species and landing them. Other changes increased catchability by improving searching efficiency (e.g., satellite imagery) or the time spent on fishing grounds (e.g., freezers).

The number of hooks deployed in daily longline operations has steadily increased since 1951. However, the increased hook numbers have not resulted in longer soak times because of faster retrieval and deployment speeds. There has also been a shift from having all baits available at dawn to having roughly equal proportions available at dawn and dusk. In the 1970s, several longline fleets also began to exploit a much greater depth range, resulting in increased catchability for deep-dwelling species (e.g., opah) and mesopelagic species (e.g., bigeye tuna), and reduced catchability for epipelagic species like blue marlin. Combined with recent studies of factors affecting catchability, the information on fishing gear and practices provides insights into how variations in operations have affected catch rates and biased estimates of abundance. Progressive improvements in expertise and technological improvements in the gear are likely to affect catchability, but are particularly difficult to quantify.

Introduction

Improvements in catchability alter the relationship between catch, fishing effort and abundance, masking declines in fish stocks until the fisheries collapse (Cooke and Beddington, 1984; Arregion-Sanchez, 1996). Catch rates – catch-per-unit-of-effort, or "cpue" – from surveys or commercial fishing are often used as indices of abundance where fishery-independent methods of counting animals are impractical (Paloheimo and Dickie, 1964). Changes to fishing gear and practices have a financial cost that fishers accept when they expect increased financial returns or reduced costs or labor in other areas of their operations. Increased returns can be achieved through improvements in the size, quality, or catch rates of target species.

Catch rates and size data from commercial longliners are the primary source of information on the status of many target and non-target species in the open ocean. However, major changes in longline fishing gear and practices, such as hook design, satellite imagery, and longline depth will affect catchability. If the data are not standardized, those variations will introduce serious flaws to the time-series of abundance and size indices, which will become increasingly difficult to correct in the future. Ward et al. (2004), for example, found that soak time had a negative effect on longline catch rates

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of several small species and positive effects on the catch rates of billfish and sharks. Changes in catchability are also relevant to fishery management arrangements that control fishing mortality through limits on fishing effort and the estimation and control of latent fishing effort or "overcapacity". It is rare to have a single, standard unit of fishing effort in commercial fisheries (Hovgård and Las, 2000), so we include fishing power in our definition of catchability because it influences the probability of catching an animal if the unit of fishing effort is constant, which is the case for pelagic longline fisheries where the standard unit of effort is 1000 hooks.

The current paper is a response to the 2006 Work Plan of the Fishing Technology Specialist Working Group (WCPFC, 2005) to:

(a) Characterise the historical and current operational details of Japanese longline and other major longline fleets in the WCP-CA

(b) Identify, compile and analyse information on gear and technology…that may be useful for effort standardisation.

Those tasks relate to the priority research areas of effort standardisation and estimation of effective fishing effort. We focus on changes in fishing gear and practices since the 1950s, particularly for Japan's distant-water longline fleet. Long time-series of catch and effort data reported by that fleet are the prime abundance index for assessments of most commercially important tuna species and several other pelagic species, such as Pacific blue marlin (*Makaira mazara*) and blue shark (*Prionace glauca*), in all three oceans.

Information sources

Reports of changes in pelagic longline fishing gear and practices have not been centrally documented; they are scattered through the published and unpublished literature. We obtained the information presented in this paper from various experts (listed in the Acknowledgements section) and fishing magazines, journals, and published and unpublished reports from the 1950s through to the 1990s. Important sources include issues of *Safety At Sea* magazine from the late 1980s, the US Fish and Wildlife Service's *Commercial Fisheries Review* (a precursor to *Fishery Bulletin*), *World Fishing*, and *Fishing News International* magazines dating from the 1950s to the late 1990s. We also examined editions of *Modern Fishing Gear of the World,* which consists of papers and reports from FAO World Fishing Gear Congresses convened between 1959 and 1971.

What is a longline?

Pelagic longlines consist of a series of baited hooks, each attached to a branchline. The branchlines, which are also called "snoods" or "gangions", are attached at regular intervals along a mainline. The mainline is suspended from buoys floating at the sea surface. The longlines deployed by large, distant-water longliners span 100 km of the sea's surface and consist of 3000–4000 baited hooks. They are usually deployed and retrieved within 24-hours (Ward, 1996). Shorter longlines, with fewer hooks are used by locally-based vessels. The sparse and patchy spatial distribution of fish, diurnal cycles in their feeding activity, and distance from port usually necessitate 24-hour operations, regardless of catch rates or vessel size.

Vessel design and equipment

Beverly et al. (2003) provides the following summary of early longlining activities. During the nineteenth and early twentieth centuries, sailing vessels equipped with hemp longlines would fish for tuna and billfish up to 30 nautical miles off Japan. By 1912 there were over 100 registered tuna longliners in Japan. The first steam-powered longliners began operating in 1914 (Miyake, 2004), and diesel-powered steel longliners appeared in the early 1920s. Longline fishing was introduced to the rest of the Pacific Ocean in the 1930s by Japanese fishermen. By 1939 there were about 70 Japanese longline vessels of between 60 and 270 gross registered tons (GRT) operating in the western and central Pacific Ocean from bases in Palau, Chuuk, and the Northern Marianas. At about the same time descendants of Japanese immigrants commenced longlining in Hawaii (the “flagline fishery”) (Beverly et al. 2003).

The Second World War limited the geographical extent of Japanese longline activities. The Supreme Commander for the Allied Powers progressively lifted restrictions on those activities and, by 1951, the Japanese again had “freedom of the seas” (Yamaguchi, 1989). Developments in vessel design and freezers have allowed vessels to range hundreds, and eventually thousands of kilometers from port. Air blast freezers were introduced in 1953, which replaced conventional ice cooling systems (Miyake, 2004). In the early 1960s, large, distant-water longliners installed super-cold freezers (–40°C or lower) that allowed them to store sashimi-quality tuna and billfish. Most of Japan’s distant-water longliners were equipped with super-cold freezers by 1970 (Mr. Peter Miyake, pers. comm., 15 April 2006). This technology reduced the need for swift vessels and short fishing trips (Sakagawa et al. 1987). Transshipment, when practiced, also increases fishing power.

Locally-based longline fleets, which air-freight fresh-chilled catches to sashimi markets, developed during the late 1980s. These longliners were based in the equatorial Pacific (e.g., Guam and Koror), South Pacific (e.g., Australia and Fiji), and eventually many other ports in the Pacific and other oceans. At the same time, fisheries that air-freighted swordfish to markets, such as the US, developed in Hawaii, and eventually other areas (Caton and Ward, 1996).

Navigation

Japanese tuna longliners first reported using compasses in 1918. Before the introduction of navigational equipment, they estimated longitude by comparing the time of sunrise and sunset observed at sea, with that of the time of sunrise and sunset in Tokyo. Latitude was estimated from sea surface temperature (Yamaguchi, 1989). They probably also used sextants (Mr. Peter Miyake, pers. comm., 15 April 2006)

Loran

American engineers developed Long Range Navigation (“Loran-A”) during World War II to provide accurate positioning of aircraft and ships at sea. The system uses the time interval between radio signals received from two or more shore-based stations to determine a vessel’s position. Loran-C superseded Loran-A system in the 1950s (Anonymous, 1987b). It was replaced by satellite-based navigation systems in the 1970s (Figure 1).

Decca

Decca provides a vessel's position by measuring the phase between two radio waves, transmitted between a master station and several slave stations. The Decca navigation system originated in the United States in 1939 (Anonymous, 1987b). By the late 1950s, about 1400 fishing vessels of all classes were fitted with Decca throughout the U.K. and other countries (The Decca Navigator Co. Ltd., 1959). By the mid 1980s, Decca coverage was quite extensive, with chains of stations in all continents except South America. Japan was an early user of Decca, using the European chain when operating within that area, before establishing its own chain in 1960 (St. John White, 2000). GPS navigation superseded Decca, and the last Decca service in the U.K. was shutdown in 2000 (St. John White, 2000).

SatNav

Civilian use of the US satellite navigation system began during the 1960s. By the mid 1970s, it was widely used by fishing vessels to provide accurate latitudes and longitudes (Miyake, 2004). Japan Radio Company (2006) claim to have developed Japan's first Navy Navigation Satellite System and receiver in 1970. Whitelaw and Baron (1995) report the use of satellite navigation ("SatNav") by Japanese longliners during the early 1980s. SatNav provided accurate positions, but sometimes at long intervals and coverage was not complete across the oceans. In between fixes, the units would deduce position from speed and direction data, but was often inaccurate due to the effects of wind and currents (Mr. David Itano, pers. comm., 14 April 2006).

GPS

GPS replaced SatNav on Japanese longliners targeting southern bluefin tuna in the mid 1980s (Whitelaw and Baron, 1995). Japan Radio Company Ltd developed their first GPS receiver for ships in 1984 (Japan Radio Company Ltd., 2006). GPS was partially complete in 1987 and was only available for a certain number of hours each day, depending on the vessel's location (Anonymous, 1987a). The 24th satellite was launched in 1994, completing the GPS constellation and providing full satellite coverage (Pace et al. 1995). When first deployed, the US military included a 'selective availability' feature in the GPS that introduced intentional errors of up to 100 m. Selective availability was permanently disabled in 2000 (NOAA, 2000).

GPS receivers estimate the vessel's latitude and longitude every second with an accuracy of 30 m by utilizing a system of orbiting satellites to provide a three-dimensional positional fix. This allows fishers to find topographic features, such as seamounts where target species often aggregate. Robins et al. (1998) examined the impact of GPS and plotters on fishing power in the Australian northern prawn fishery and found that vessels that used GPS had 4% greater fishing power than vessels without GPS. The addition of a plotter increased fishing power by 7% over boats without this equipment. Fishing power increased by 12% when both pieces of equipment were used for at least three years, (Robins et al. 1998).

A series of GPS fixes can also be used to compute the vessel's velocity and direction. This is often integrated with an onboard computer to plot the vessel's position on a digital sea chart.

Radar

The US was the first country to equip a military ship with radar in 1937 (Jenkins, 2000). Research on radar continued throughout the 1950s. In 1951, several Japanese companies were manufacturing radars and more than 800 Japanese fishing vessels were equipped with radar instruments (Suiyo-Kai, 1959). Fishers used radar to locate objects above the sea surface such as other vessels, land, navigational buoys, and markers. Refinements to radar systems improved the ability to identify smaller objects, such as floating logs and flocks of birds that may be associated with target species and tuna feeding at the sea surface. Bird radar has been used by many purse seiners since 1987 (Miyake, 2004), but this technology is not used by longliners (Mr. Peter Miyake, pers. comm., 18 April 2006).

Communication

Radio

High-frequency (HF) radio is essential for communication, providing long-range, ship-to-ship and ship-to-shore communication. Fishing masters often share information about fishing locations and catch, and communicate with managers onshore via HF radio. It is also capable of transmitting distress alerts and receiving weather forecasts and marine safety information. Very high-frequency (VHF) radio provides more reliable communication, but reception is limited to about 20 nm between stations.

The radio telegraph is the oldest maritime communication system. The Japanese began using radio telegraph in 1908 for communication between Coshi Coast Station and ships (Telecommunications Bureau of the Ministry of Internal Affairs and Communications, 2006). Yamaguchi (1989) notes the introduction of wireless communication facilities for fishing vessels in 1921. By 1927, 120 Japanese fishing vessels had installed wireless communication equipment (Yamaguchi, 1989). Radio telephony was introduced around 1926, but was not widely available to fishing fleets until the early 1930s (Walsh, 1985).

In 1959, all Japanese vessels over 100 GRT were required to carry radio transceivers (Kodaira, 1959). They always had a dedicated radio operator among their crew, highlighting the importance of radio communication. The large fishing vessels were equipped with MHF (medium- to high-frequency) transceivers, while other vessels were equipped with HF transceivers for long-range communication (Kodaira, 1959). Most smaller vessels also carried MHF transceivers (Kodaira, 1959). International VHF began in 1964 and was used for harbor services, navigation and safety communication (Telecommunications Bureau of the Ministry of Internal Affairs and Communications, 2006).

Satellite communication is now widely used by fishing vessels. Founded in 1979, the International Maritime Satellite Organization (“Inmarsat”) operates 11 satellites that provide global telephony and data services via digital radios called “terminals”. The Inmarsat-A network was commercially available in 1982. It provides voice services, telex services, medium speed fax and data, and high speed data services. Inmarsat-A is the only analogue service on the network and is due to terminate by 2008. Inmarsat-C superseded the Inmarsat-A network in 1991. This network provides electronic mail (“e-mail”), messaging, facsimile, telex, short messaging service (SMS), tracking, weather updates, and maritime safety information (Inmarsat, 2006).

The Globalstar network was launched in 1998 and consists of 48 low earth-orbiting satellites. Full commercial operation began in March 2000 providing coverage in over 120 countries. Globalstar also provides access to the Internet and has a voice communication feature for emergencies (Globalcom, 2005).

The Iridium network was the first to offer a satellite phone with planetary coverage. The original network, consisting of 77 satellites, was launched in 1998, but ceased in 1999. The service was re-established in 2001. In 2005 it consisted of 66 active satellites orbiting the earth from pole to pole (Globalcom, 2005).

Fish-finding

Echo-sounders and sonar

SOund Navigation And Ranging (sonar) is the technology used to locate underwater objects using sound waves. Sonar was developed for military applications during World War I, but was not used by fishing vessels until the early 1950s (Simrad, 2006).

There are various types of sonar. Sonar systems that transmit vertically are called "echo-sounders" whereas systems that transmit horizontally are referred to as "sonar" (Bazigos, 1981). Traditional sonar emits a single, narrow beam at specific intervals then captures the returning signal. Multi-beam or omni-directional sonars transmit several sonar beams and, unlike single-beam sonar, provide continuous coverage of the surrounding water mass or seafloor. They can transmit from a towed unit or can be hull-mounted. Side-scan sonar transmits a fan-like beam from a towed unit and also provides continuous coverage of the seafloor (NOAA, 2005).

Echo-sounders are important navigational tools, especially in shallow harbors and passages. They transmit a sound beam through the water column that is reflected from the seabed and displayed as an image. The first commercial echo-sounder (called the "fathometer") was developed by the American Submarine Signal Company in 1924 (Anonymous, 1987c).

Echo-sounders are also used for detecting fish. Balls (1952) refers to the use of echo-sounders in commercial fishing as early as the 1930s. Tominaga et al. (1963) note their use by Japanese longliners in the 1960s to detect the deep-scattering layer, concentrations of plankton and foraging species, tidal shifting and tuna schools. For longliners, echo-sounders are particularly useful for locating seamounts (Mr. Peter Miyake, pers. comm., 15 April 2006).

Sonar is essentially an echo-sounder with a directional capability. Simrad produced their first commercial fishing sonar in 1957 (Simrad, 2006). Sonar was introduced to the Japanese longline tuna fleet in the mid 1980s (Ward and Myers, unpubl.[4]) and allowed vessels to locate and target aggregations of fish or to identify individual fish. Sonar can also be used for navigation.

[4] Ward, P. and Myers, R.A. Preliminary estimates of changes in the catchability of pelagic longline fishing gear.

Weather facsimile

Weather information can help to reduce gear loss and tangles and the time lost due to adverse conditions. Weather facsimile ("weatherfax") technology was reported in 1926, however the modern weather fax program began in 1965 and has changed little since then (Piltch, 2002). Weather charts were originally drawn by forecasters and placed on a cylindrical drum to be scanned and then transmitted to vessels as a radio facsimile (Piltch, 2002). For almost 40 years, fishers have received weather charts in this way. Nowadays, charts are received through a computer that is connected to a single side-band (SSB) radio (Piltch, 2002). Whitelaw and Baron (1995) and Yamaguchi (1989) note the introduction of weather and sea surface temperature faxes to the Japanese longline fisheries during the mid 1980s. Regular bulletins on HF radio were – and still are – an alternative source of weather reports. Satellite imagery is also used to derive infra-red images of cloud, land masses, and sea surface height.

Bathythermograph

Bathythermographs provide information on the thermal structure of the ocean, including the depth of the thermocline. The vertical distribution of target species is often linked to ambient temperature (Bigelow et al. 2002) so bathythermographs allow fishing masters to adjust longline depth to maximize catch rates.

A mechanical bathythermograph was invented in 1937 for submarine warfare. The expendable bathythermograph ("XBT") is an electronic instrument that superseded the mechanical bathythermograph during the mid 1960s (Shea et al. 1995). A similar instrument is described by Hamuro and Ishii (1964). The instrument contains a liquid thermometer and is used to measure water temperatures at depths where fishing gear is deployed. Fishers used correlations between these thermal profiles and catches to locate profitable fishing locations. Observers on Japanese longliners off eastern Australia reported the occasional deployment of XBTs since the late 1980s.

Doppler current meter

Doppler current meters use sound waves to measure the velocity of water across a water column. They can show the location, velocity, and direction of currents at the surface, or at various depths, simultaneously monitoring up to three layers of water. Fishers use this information in determining the depth and direction of longline deployment in order to avoid line breaks and tangles.

Whitelaw and Baron (1995) report the use of Doppler profilers by Japanese longliners since the late 1980s. Before the introduction of current meters, floating objects, such as seaweed and wood, were used to determine current direction and velocity at the surface (Shapiro, 1950) and boundaries between water masses ("tide lines") where target species often aggregate (Mr. Peter Miyake, pers. comm., 15 April 2006).

Sea surface temperature

Orbiting satellites provide global coverage of the sea surface temperature (SST) of the world's oceans. The data received from the satellites are processed to produce color charts. The charts are available to fishing masters via weatherfax receivers or in real-time using dedicated receivers and software. In addition to ambient sea surface temperatures, the charts can be used to identify surface currents, oceanic fronts, eddies and areas of upwelling where target species often aggregate.

The US National Oceanic and Atmospheric Administration (NOAA) has been producing real-time SST charts with an accuracy of 0.5–2ºC since 1973 (Butler et al. 1988). Prior to SST imagery, fishing masters relied on electronic temperature sensors fixed to the vessel's hull or measured SST with a mercury thermometer in a sample of water collected with a bucket.

Ocean color imagery

The color of the oceans can provide information on primary productivity. Fishing masters can use this to locate biologically-rich areas of the ocean where target species may be abundant, thereby reducing search-time and increasing fishing efficiency. Commercial remote sensing services for ocean color have been available since the mid 1980s (Svejkovsky, 1996).

Sea surface height

Geographical variations in sea surface height are used to determine current direction and velocity, areas of convergence and divergence, and oceanic fronts (Keisuke et al. 2004). Unlike sea surface temperature and ocean color imagery, satellite-derived sea surface height information is not inhibited by cloud cover, thus it is a reliable source of information in all weather conditions. Civilian satellite data on sea surface height to a precision of 4 cm have been available since 1992 (Jet Propulsion Laboratory, 2006). However, we located no reports of longliners using sea surface height until the late 1990s.

Integration

Daily facsimiles from fishing companies, which included weather maps, sea surface temperature isotherms, and areas of high catch rates, were a precursor to fully integrated services. Observers on Japanese longliners in Australian waters have reported such facsimiles since the introduction of weatherfax in the 1980s. Since the late 1990s, commercial enterprises have been providing systems that integrate information on ocean color, surface and sub-surface temperatures, thermocline depth, sea surface height, currents, weather, and fishing recommendations, e.g., ORBIMAGE SeaStar Fisheries Service. They include software to allow fishing masters to plot current and past catches on onboard computers.

Longline deployment and retrieval

Radio buoys and Radio Direction Finders

Early navigational equipment used radio frequency signals to determine the geographical location of transmitters. Radio Direction Finders, which came into use during the 1920s (Jenkins, 2000) indicate a vessel's position from a bearing of the transmitting radio station.

Battery-powered radio buoys are attached to the longline at regular intervals. They emit a signal that is received by the radio direction finder at a range of up to 35 nm. This allows fishing masters to locate the fishing gear, thus reducing searching time when mainlines break.

Radio buoys were attached to captured whales and fishing nets by the Japanese during the late 1950s (Kodaira, 1959), but may not have been used for locating longline gear until the 1960s (Yamaguchi, 1989). The use of this equipment was so extensive that interference was a common problem so a new receiver was designed to transmit only upon receipt of a unique signal transmitted by the owner vessel (Kodaira, 1959). Miyake (2004) notes the introduction of these “select-call” radio buoys during the 1980s. Prior to the introduction of radio buoys, simple bamboo flagpoles were used to mark the position of the longline (June, 1950; Shapiro, 1950; Shimada 1951). Light buoys have been used since the early 1950s to mark the location of gear at night (Shimada, 1951). Metallic reflectors have also been placed on floats to aid detection by radar (Mr. Peter Miyake, pers. comm., 15 April 2006).

GPS tracking buoys began to be used in the 1990s (Miyake, 2004). They allow the location of the longline to be projected on an integrated monitor, over laid with other electronic maps (e.g., SST maps). These GPS beacons reduce steaming times because the exact position of the start and end of the longline are known. By contrast, radio beacons indicate the direction and approximate distance.

Plotter

The automatic plotter was developed in 1959 to produce a continuous record of the vessel’s position on a roller-mounted paper chart using a plotting pen (The Decca Navigator Co. Ltd., 1959). Computerized plotters were developed much later. In 1980, about 10% of the Japanese distant-water longline fleet was equipped with computerized plotters (Kawai, 1995). This uptake increased to 100% by 1990 (Kawai, 1995).As well as plotting the vessel’s journey, plotters can help fishing masters visualize current and past operations by displaying the location of catches in relation to location along the longline. Plotters can also display local oceanographic conditions and bathymetric features. When integrated with sea surface temperature maps, plotters allow fishers to target temperature fronts and other oceanographic features (Whitelaw and Baron, 1995).

Line-hauler

Before the introduction of line-haulers in 1923 (Izui Iron Works Co. Ltd., 1959), lines were hauled by hand which was slow and labor intensive. June (1950) describes the use of power winches to haul longlines in the Hawaiian longline fishery, but many smaller vessels were still hauling lines by hand.

Fishers were hesitant to adopt the new method of line-hauling until the device was successfully demonstrated by the inventor. By 1959, over 8000 Izui line-haulers were in use in Japan, Brazil, Hawaii, and mainland USA (Izui Iron Works Co. Ltd., 1959). In 1953, electric haulers were introduced and 1960 saw the introduction of hydraulic pump-type haulers (Yamaguchi, 1989).

Branchline coiler

Large, distant-water longliners are equipped with several hydraulically driven branchline coilers that increase retrieval speeds and efficiency by reducing the time that crewmembers spend in coiling branchlines. Australian observers report the use of branchline coilers on Japanese longliners since the early 1980s (Aaltonen, 1982). Branchlines are still coiled by hand on most small longliners.

Line-shooter

The line-shooter or “line-thrower” is a device that pulls the mainline from the reel or bin at a speed faster than the vessel’s speed. This reduces tension on the line, allowing it to settle at greater depths and access deep-dwelling animals. A slack line also reduces line breaks due to current sheer and the pull of hooked fish, although it can increase the number of mainline tangles (Shapiro, 1950). Shimozaki et al. (1966) describe a longline fishing operation that involved the use of a line-shooter designed by the authors in the early 1960s. Before the introduction of line-shooters, setting the line in a zigzag pattern or reducing the speed of the vessel were used to obtain slack in the line (Shapiro, 1950).

Longline materials

Mainlines

The small vessels that first began longlining around coastal Japan used hand-made longlines consisting of two hemp longlines with three branchlines (Yamaguchi, 1989). In 1918, cotton mainline replaced hemp, but the line near the hook, commonly referred to as "tsurimoto", remained as either hemp or ramie cordage (Yamaguchi, 1989). In the 1950s, tar-coated natural fiber ropes made of cotton, hemp, or Manila were used to construct mainlines (Shapiro, 1950; Shimada, 1951; Yamaguchi, 1989). Chemical fiber lines made from polyester, vinylon and kuralon came into use in the 1980s (Joy et al., 1985; Garven, 1986; Yamaguchi, 1989) . In 1950, a Japanese company introduced a synthetic fiber rope called “Amilan”, although cotton longlines remained popular because they resisted abrasion and shock. They were also easy to coil and maintained their shape in the water (Yamaguchi, 1989). Improvements in materials also increase longevity and durability of gear. This improves profits by reducing gear failure and replacement costs, and improves efficiency by allowing more powerful hauling gear.

The ‘American longlining system’ consists of a nylon monofilament mainline wound onto a hydraulically-powered drum. It was developed on the east coast of USA during the 1980s (Beverly, 2001). The advantage of monofilament mainline is that it is quicker to tie knots, is easier to handle, and repair. However, Japanese longliners did not begin using monofilament mainlines until the early 1990s (Whitelaw and Baron, 1995; Okamoto et al., 2003). There was limited uptake, and most large, distant-water longliners continue to use kuralon mainlines stored in a large bin. Australian observer data shows that during the 1990s, 85% of the Japanese distant-water longliners were using nylon or teteron monofilament branchlines. The remaining 15% used nylon or kuralon multifilament (Ward and Myers, unpubl.).

Japanese longliners began using wire-leaders in 1922 (Yamaguchi, 1989). They have been used almost exclusively by that fleet since the 1950 (Shimada, 1951). Japanese longliners began using nylon monofilament leaders in the mid 1980s (Mr. Peter Miyake, pers. comm., 18 April 2006), with a ratio of two monofilament to one wire-leader often used in the 1990s (Australian Observer data). Similarly, Moon et al. (1999) observed an increasing trend in using monofilament leader by Korean longliners; in 1990, 9% used monofilament leaders compared to 93% by 1995. Canadian longline fisherman began using them during the 1960s, attaching a short (~38 cm) monofilament leader between the tarred multifilament nylon branchline and the hook (Stone and Dixon, 2001).

Clips and swivels

Initially, crewmembers tied branchlines to the mainline. In the mid- to late 1970s, mechanized longline systems were developed with clip-on branchlines. The steel clips were quicker to attach and detach from the mainline, easier to handle and repair, saved deck space and reduced accidents during shooting and hauling (Wray, 1978).

Weighted swivels are used to increase the sinking rate of the gear and maintain branchline depth. Swivels also provide connection points between the main part of the branchline and the leader (Beverly et al., 2003). Shapiro (1950)noted that swivels were often placed at some point along the branchlines used in the Japanese longline fisheries in the 1950s, in order to reduce twisting when a fish was hooked.

Lightsticks

Lightsticks were originally developed to provide a low-heat, non-flammable light source to be used in areas where the risk of fire was high, but their design also allowed them to be used underwater. Recreational anglers began experimenting with chemical lightsticks for catching swordfish off Florida in 1976. Soon after, longliners began using them, and their use became quickly widespread (Berkeley et al. 1981). They are mostly used to improve swordfish catch rates. It is unclear whether they attract small marine animals, such as squid, to the longline, which in turn attract the attention of large predators, such as swordfish, or whether they attract large predators directly. They may also elevate catch rates of other night-feeding species such as bigeye tuna. Whitelaw and Baron (1995) report the occasional use of lightsticks in the late 1980s in the Japanese Southern Bluefin Tuna (SBT) longline fishery. However, they are rarely used by Japanese longliners, not even by those longliners that target broadbill swordfish (*Xiphias gladius*) in the NW Pacific (Ward & Elscot, 2000).

Some fishers believe that the color of the lightstick and lights may influence catch rates for particular species. This has resulted in some operators using specific colors or patterns of colors.

Beverly (2001) reports on a new fishing light to replace chemical lightsticks for longline fishing. The Electralume™ light consists of two diodes (LEDs) that emit light for up to three weeks without the need for changing batteries. The electrical fishing lights are available in five different colors and are considered more environmentally friendly than the chemical lightstick because they are less likely to be discarded at sea. Since the 1980s, luminescent chafing gear such as line tubes, thimbles and beads are often attached near longline hooks to attract fish.

Hooks

Japanese longliners in the 1950s used larger hooks (extended length of up to 140 mm; (Shapiro, 1950)) than those used in the 1990s (110–120 mm). However, those large hooks are unlikely to have limited the minimum size of sharks, marlins or large tunas taken in the 1950s, because the mouth of those animals is considerably larger than the hook's gape (30–40 mm) and the jaw's width is smaller than the hook's gape. Erzini et al. (1996) report increasing catchability with decreased hook size. We therefore expect the introduction of small hooks to have extended selectivity to animals with a small gape (e.g., skipjack tuna). Smaller hooks may, however, increase the risk of hooks tearing out of larger fish.

Hooks used in the 1950s were straight-shanked “J-shaped” hooks made of tin-plated iron and tempered steel (Shapiro, 1950; Otsu, 1954). Joy et al. (1985) report the use of square-type galvanized iron hooks in the Indian Ocean longline fisheries of the 1980s, whereas Yamaguchi (1989) reports the use of zinc-coated hooks made of steel by Japanese longliners. Since then, galvanized high-carbon steel hooks have been used in most longline fisheries. More durable, non-corrosive stainless steel hooks have been common in most longline fisheries since the mid 1990s (Beverly, unpub. 2004[5]).

Circle hooks have been proposed as a means of reducing bycatch in pelagic longline fisheries. Several studies indicate they may produce higher catch rates than traditional patterns (Falterman and Graves, 2002), whereas other studies indicate that large circle hooks resulted in a decrease in catch rates of bigeye and yellowfin tuna (Dr. Dae-Yeon Moon, pers. comm. 19 June 2006). Several commercial longliners used circle hooks in the 1960s and 1970s because they were believed to be more efficient at catching fish and keeping them alive until hauled aboard (Montrey, 1999) and because they reduced injury rates among crewmembers. The “Japanese tuna hook”, which is an intermediate style between J-hooks and today’s circle hook (Figure 2), has been in widespread usage since the early 1980s (Whitelaw and Baron, 1995).

Fishing practices

Bait

In the 1950s, Japanese longliners deployed South American pilchard (*Sardinops sagax*) or Pacific saury (*Colalabis saira*) bait almost exclusively (Shapiro, 1950; Ego & Otsu, 1952). Observer data from Japanese longliners off eastern Australia in the 1990s (N = 129 longline operations) indicate various combinations of baits, including mackerels (43% of all baits), squid (23%), pilchards (23%), and saury (4%).

These days, a wider range of bait is available. Fishers select bait on the basis of expected financial return of catches combined with bait costs, availability, storage and handling considerations, and how long the bait will stay on the hook. They tend to use expensive bait, like squid, for high-value species, such as bluefin and bigeye tuna. Squid is also preferred for swordfish. A recent increase in the price of squid has prompted some Korean longliners to use artificial (rubber) squid on deep hooks (Dr. Dae-Yeon Moon, pers. comm. 19 June 2006). In the late 1990s, Hawaiian fishers dyed squid bait a blue color in an attempt to mitigate sea turtle bycatch. Some have continued to use dyed bait because they believe that it increases catch rates of target species.

Shapiro (1950) reports that Japanese longliners occasionally experimented with live mackerel as bait in the equatorial western Pacific during the 1950s. Its use, however, was limited by the lack of live bait wells on board the vessels. Other descriptions of longline operations in the 1950s do not mention use of live bait (Otsu, 1954; June, 1950; Shimada, 1951; Ego and Otsu, 1952). In the mid 1980s, Vietnamese-Americans began using live bait to target tuna with longlines in the Gulf of Mexico (Pacific Ocean Producers, 2006). Between 1992 and 1998, 13% of US longline operations in the Gulf of Mexico used live bait (Scott et al. 2000).

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[5] Beverly, S. Hooks used in longline fishing

In the tropical Pacific, live milkfish (*Chanos chanos*) is sometimes used because it tolerates handling and holding in bait wells and can remain alive until the longline is retrieved. The live bait industry flourished during the mid 1990s, particularly in Guam. It produced elevated catch rates of yellowfin tuna, but did not affect catch rates of bigeye tuna (Fitzgerald, 1996). By the late 1990s, however, live bait production ceased with increased availability of cheaper bait, such as mackerel and saury (Beverly, 2001).

Australian longliners have used live yellowtail scad (*Trachurus novaezelandiae*) and, to a lesser extent, blue mackerel (*Scomber australasicus*), since the mid 1980s. Almost all longliners that target yellowfin tuna off NSW now use live bait. It is believed to greatly improve catch rates of yellowfin tuna and striped marlin, although it is less effective during full moon periods for several target species (Ward, unpubl.).

Number of hooks

The number of crewmembers, their skill, and the degree of mechanization are key determinants of the number of hooks deployed in each operation. The efficiency of fishing operations has progressively increased over time. The number of hooks deployed in each operation by Japan's longliners increased from as few as 1200 hooks in the 1950s to well over 3000 by the late 1990s (Campbell 1997). Fresh-chilled longliners deploy far fewer hooks, typically ranging from 500 to 1500 hooks per operation. In many areas (e.g. Hawaii and Australia) the number of hooks per operation has doubled, or tripled, as fleets have developed (Ward and Elscot, 2000).

In using the number of hooks as the measure of fishing effort, it is assumed that the catchability of each bait is not affected by nearby baits. However, the catchability of each bait must eventually decline as the distance between branchlines decreases (Skud, 1978). We estimated a mean distance between adjacent hooks of 45.4 m (SD ±4.5 m) from the longline dimensions of 25 longliners in the study area in 1950 (Shimada 1951). Longline dimensions reported by observers on 38 longliners in the study area (P. Williams, pers. comm.) indicate a mean spacing of 38.3 m (SD ±15.6 m) during 1994–2003. However, the lengthening of longlines to access deeper waters also affects the distance between baits. The 1990s longliners also used shorter branchlines (24 m on average) than the 1950s longliners (30 m). The shorter branchlines and the lengthening of longlines offset the reduced distance between hooks so that hook density did not change between periods.

The extent to which pelagic longline hooks fish independently is largely unknown. Polacheck (1991) also found statistically significant affect of hooks per operation on catch rates of bigeye or yellowfin tuna in the tropical western Pacific Ocean. From fine-scale survey records of yellowfin tuna catches in the Indian Ocean, Hirayama (1972) estimated a swept area of 2–6 km^2 for longline bait. Indices derived from catch divided by the number of hooks deployed will underestimate abundance if there is competition among bait along the longline.

In using the number of hooks as the measure of fishing effort, it is assumed that the catchability of each bait does not decline with the increased distance covered by the longline. Particular features, such as temperature fronts or seamounts, where target species may aggregate, may be smaller than the distance covered by the mainline (the longline's "area of action"). Hooks that are deployed in less suitable areas will have lower catch rates on average. Therefore, an increase in the number of hooks and distance covered by the mainline may reduce overall catch rates.

Soak time

Longlines are usually "counter-retrieved"; the last hook that had been deployed is retrieved first (Hirayama, 1969). It is much easier to locate the last float than it is to find the other end of the longline. Counter-retrieval also reduces fuel costs unless the vessel master is intending to head the next day in the same direction as the longline was deployed (Yamaguchi, 1989). The observer data sets analyzed by Ward et al. (2004) indicate that most operations are counter-retrieved. Observers on fresh-chilled longliners of the Western Pacific Bigeye fishery report that about 80% of operations are counter-retrieved. Higher frequencies of counter-retrieval are reported in the South Pacific fisheries (~90% of operations) and almost all Central Pacific Bigeye and North Pacific Swordfish operations are counter-retrieved.

The total time that a hook is in the water is termed the "soak time". In counter-retrieved operations of the South Pacific fisheries it ranges from about 3 hours for hooks at the beginning of retrieval up to about 21 hours for the last hooks retrieved. In contrast, the hooks of longlines that are "return retrieved" have a narrower range of soak times (8–16 hours). However, the average soak time of all hooks in return retrieval (9.4 hours) is similar to that of counter-retrieved hooks (10.0 hours).

Many aspects of the fresh-chilled fishing operations, such as hooks per operations and soak time, vary between fleets, between vessels, and even for the same vessel during a fishing trip. By contrast, distant-water longline operations tend to vary much less (senior author's pers. obs.). Fresh-chilled longliners, which undertake trips ranging from a few days up to several weeks, also maintain 24-hour operations. However, they deploy fewer hooks than distant-water longliners. Line tangles, line breaks, mechanical failures, and rough weather sometimes prolong the duration of longline retrieval. High catch rates may also extend operations because fresh-chilled longliners have fewer crewmembers.

Distant-water longliners rarely need to slow the longline retrieval speed to bring a hooked animal on board, even when the animal is large and alive. However, when distant-water longlining commenced in the 1950s, the catch rates of many species were an order of magnitude higher than they were in the 1990s. We suggest that high catch rates may have sometimes prolonged the duration of retrieval in the earlier years. Devices, such as line-haulers and snap-clips, have further enhanced hauling efficiency.

Figure 3 highlights operational differences between distant-water and fresh-chilled longline operations. During the 1990s, Japan's longliners had much faster deployment and retrieval speeds than fresh-chilled longliners. However, the fresh-chilled longliners had long wait times between retrieval and deployment. Consequently, the average soak time of their hooks was much longer than those of Japan's longliners. Analyses presented in Ward et al. (2004) show that the differences in soak time would have a major effect on the catch rates of most species.

We might expect the increased hook numbers to result in longer soak times. However, Campbell (1997) highlights how doubling the number of hooks per longline operation does not double the number of hook–hours (the sum of the time that each hook is in the water). Furthermore, the increases in hook numbers were accompanied by increased retrieval and deployment speeds and reduced wait and search times. Consequently, the average soak time of each hook actually decreased, from about 11.5 hours in the 1950s to 10.0 hours in the 1990s (Figure 3). Ward et al. (2004) estimated an expected catch rate for swordfish of 0.94($\pm$ 0.06) per 1000 hooks for a soak time of 11.5 hours compared to 0.82($\pm$ 0.06) per 1000 hooks for 10.0 hours.

Operation times

To catch tunas, longliners usually commence deploying their longlines several hours before dawn (Figure 3). Deployment takes about five hours and is completed some time after dawn. There is then a waiting period of about four hours before retrieval, which commences in mid afternoon. Retrieval takes about 13 hours. A new operation will then commence after a brief period (about two hours), which we call the “search time”.

Line tangles, line breaks, and mechanical failures sometimes result in operations that last longer than 24-hours (Yamaguchi, 1989). Subsequent operations would involve reduced wait and search periods to allow a return to a 24-hour cycle that maximizes the availability of baited hooks at peak feeding times. Longliners occasionally deploy fewer hooks or forego a day’s fishing after a prolonged retrieval or when transiting between fishing grounds.

Longline catch rates are closely linked to whether baited hooks are available during peak feeding times. Generally, longliners that target swordfish deploy their longlines at dusk and commence retrieval at dawn so that baited hooks are available at night and during crepuscular periods. The opposite cycle is used to target tuna, such as yellowfin and bluefin; longlines are deployed at dawn and retrieved in the late afternoon and evening (Ward and Elscot, 2000).

The operations of longliners from different fleets targeting the same species show variations in operation times. Longliners in the Western Pacific and Central Pacific Bigeye fisheries deploy after dawn and retrieve after dusk. Consequently almost all their baited hooks are available at dusk, but rarely are they available at dawn. By contrast, approximately equal proportions of the hooks are available at dawn and dusk in the South Pacific (Figure 3).

In addition to differences in timing between fleets, there is evidence of historical variations in timing. During 1960–80, Japan’s longliners commenced deployment at midnight and began retrieval soon after dawn. Consequently about 50% of baited hooks were available at dawn, but many were retrieved before dusk. By the 1990s they had adjusted operation times so that more hooks were available at dusk and fewer were available at dawn (Figure 3). The change is at least partly related to a shift from targeting yellowfin tuna to bigeye tuna. Analyses presented in Ward et al. (2004) show that the differences in operation times between fleets and over the years would affect catch rates of target and non-target species. For example, the expected catch rate for bigeye tuna for bait that is available at dawn and dusk is about double that for bait available at dawn only (where other factors, such as depth, location, and soak time, are the same for the two periods).

Moon phase

Fishers have long been aware of the influence of the lunar cycle on their catches through its effects on tides, currents, light levels, and behavioral adaptations of many species, e.g., the timing of spawning, feeding, and migration (Omori, 1995). Moon phase is often a statistically significant correlate that is included in models used to standardize fishing effort, e.g., Bigelow et al. (1999), because catch rates of many pelagic species are strongly correlated with moon phase. Fishers time their trips to coincide with full moons to maximize their catch rates of swordfish. Observers report that Japanese distant-water longliners sometimes targeted swordfish around full moons with shallow-set squid baits deployed at night over seamounts off eastern Australia (Ward and Elscot, 2000). Similarly, Chinese and Taiwanese deployed shallow longlines at night to catch bigeye tuna in the equatorial western Pacific during the 1990s (Mr. Peter Williams, pers. comm., 20 April 2006).

Longline depth

The vertical distribution of most pelagic animals depends on their behavioral responses to various physical and biological conditions that are depth-dependent, e.g., ambient temperature, oxygen concentration, light levels, and the distribution of prey and predators (Dagorn et al. 2000). The depth range of baited hooks determines which components of the pelagic community are exploited and thus longline catch rates and the species- and size composition of catches.

During deployment, fishers routinely adjust the longline's depth range by varying the vessel's speed, the mainline's tension, and the distance between floats. Line-shooters, are used to slacken the mainline (see longline deployment and retrieval section). They were first used in the early 1960s, but were not widely used until the late 1970s when several fleets began to target deep-dwelling species like bigeye tuna.

Fishers use timers to maintain a constant distance (~45 m) between branchlines and consequently between floats. The number of hooks between floats or "hooks-per-basket" is often used as an index of longline depth if the mainline is assumed to form a catenary curve between floats. Variation in longline depth caused by adjustments to the distance between floats has received close attention in assessments and in the literature (Suzuki et al., 1977; Hinton and Nakano 1996; Bigelow, 2002). In brief, fishers initially deployed their longlines at relatively shallow depths (25–170 m) by maintaining tension on the mainline and having long distances between floats relative to the mainline length (about 4–6 hooks-per-basket). Japanese longliners began using deep longlines in the Pacific and Indian Oceans in the early 1970s and in the Atlantic Ocean in the late 1970s (Suzuki et al., 1977; Sakagawa et al., 1987). Deep longlines consist of 10 or more hooks-per-basket, with a depth range of 25 to 300 m or deeper. They continue to be used by Japanese longliners in tropical waters and many other fleets that target bigeye tuna where the thermocline and oxycline are deep, e.g., Hawaii, Fiji and, more recently, Taiwan.

Observed depths (obtained using depth sensors) often differ from depths predicted by the catenary formula. The weight of the longline causes a gradual shortening in the distance between floats during the operation. Consequently, longline hooks may sink to deeper depths than predicted. At the same time, wind and current sheer may cause hooks to rise towards the surface or "shoal" (Hanamoto, 1987; Mizuno et al., 1999; Bigelow et al., 2002). Bigelow et al. (2002), for example, estimated that hook numbers three and ten of longline gear with 13 hooks between floats, shoaled by about 20% when subjected to a current velocity of 0.4 $m \cdot s^{-1}$. However, Ward and Myers (2006) report that commercial fishers adjust their fishing practices to maximize the availability of longline hooks to target species, such as deep-dwelling bigeye tuna. Since the late 1980s, many longliners have used Doppler current profilers to monitor the velocity and direction of subsurface currents. Most fishers minimize shoaling by deploying their longline in the same direction as prevailing currents. In recent years, fishers have become interested in temperature-depth recorders (TDRs) and hook timers that researchers use to determine the true depth of longline hooks and the exact time when animals are hooked. Observers also report that Australian fishers sometimes remove every second float to sink the longline when initial catches indicate that target species are deep in the water column.

In addition to adjusting longline depth by modifying longline dimensions, fishers may vary the buoyancy of longlines and the lengths of branchlines and floatlines. Weights are sometimes attached to the branchlines to make them sink more quickly and reach greater depths. Different materials have different buoyancies, e.g., nylon monofilament has a specific gravity of 1.1 compared to 1.3 for kuralon (Asia Oceanic Industries Inc., 2001). Consequently, monofilament lines will tend to have a shallower depth range than kuralon. Changes in materials and line lengths tend to be long-term rather than day-to-day because they are expensive and labor-intensive.

Several fishery management agencies have introduced weighted swivels to reduce seabird bycatch, e.g., Australia since 2005. Other recently introduced mitigation measures, such as bird-scaring lines (“tori lines”), night-deployment, complete thawing of bait, sub-surface setting chutes, and side-setting, also increase fishing power by reducing bait loss.

Operational considerations largely determine the length of floatlines; they must be long enough to keep the mainline out of the range of propellers and to prevent waves at the surface tangling the gear. Long floatlines are difficult for crewmembers to haul and bulky to store. To target swordfish, fishers often use short floatlines (5–10 m) so that baited hooks settle close to the sea surface (Mr. Steve Beverly, pers. comm., 31 March 2006).

Tangling is the main determinant of branchline length because long branchlines are more likely to tangle with adjacent branchlines. To prevent hooks fouling the vessel’s propeller and rudder, branchlines must be shorter than the distance between stern and the hauling block. The time and effort required to coil long branchlines is another consideration. With rope gear, floatlines were shorter and branchlines longer because of the greater resistance to hauling the mainline from deep depths. Monofilament nylon mainlines present less resistance. Long floatlines allow shorter branchlines. Animals may also survive longer on a long branchline because they are less likely to become entangled they are better able to escape scavenging sharks.

The distance between branchlines is now fairly consistent at about 45 m among the various fleets. If the branchlines are too far apart, the longline must span a greater distance or fewer baited hooks can be deployed per day. Timing is also a consideration, with crewmembers unable to haul more than one branchline every seven seconds, thereby limiting the total number of hooks that can by deployed in a 24-hour operation (Mr. Steve Beverly, pers. comm., 31 March 2006).

Discussion and conclusions

Our review highlights four themes in the evolution of longline fishing gear:

1. Improvements in the properties of longline materials and hooks throughout the fishery's history.
2. The adoption of navigational technology in the 1950s.
3. Improved ship-to-ship and ship-to-shore communications through refinements to radios, the introduction of facsimiles and, more recently, satellite-based communication systems.
4. The introduction of satellite-based systems for navigation and environmental monitoring as an aid to fish-finding.

The introduction of technology based on computer-chips and satellites in the 1980s was essential for improvements to navigation, communication, and fish-finding. The most recent development is the introduction of management measures intended to reduce bycatch through restrictions on fishing gear and practices. These include weighted swivels, area-season closures, dyed bait, and night-setting to reduce seabird bycatch; large fish baits, circle hooks, and shallow longlines to reduce sea turtle bycatch; and bans on wire-leaders to reduce shark bycatch. Bycatch mitigation measures, the progressive exclusion of distant-water longliners from 200 nautical mile exclusion economic zones (EEZs) during the late 1980s, and the apparent "deskilling" of longliner crews (Kawai, 1995) are the few factors that may have reduced the catchability of target species.

Overall, the many developments in fishing gear and practices are likely to have increased the catchability of target species (and any non-target species that are closely associated with those target species). Bait, hooks, lightsticks, and leaders directly interact with the species; they change catchability by affecting the probability of an animal attacking bait, being hooked or landed. Other changes may increase catchability by increasing the availability of baited hooks (e.g., deeper longlines), improving searching efficiency (e.g., satellite imagery), or increasing the time spent on fishing grounds (e.g., freezers), thereby providing fishers with more time to adapt to local conditions and to "follow the fish". In addition to increasing catch rates, improved fishing gear and practices reduce operating costs. Labor-saving devices, such as line-haulers, reduce costs, but do not directly affect catchability. Our review does not cover the effects of changes in fishing gear and practices on the size ("selectivity") or quality of target species.

Fishers on large longliners have quickly adopted new technology, partly because the costs of such equipment represent a small proportion of their total operating budget. For a typical large longliner in the late 1990s, for example, the purchase price of electronic devices was about $US 150 000 (Figure 1). This is a very small proportion of the value of a large longliner's annual landings (about $US 2.435 million per year; Reid et al. 2003). Recent developments in marine electronics have produced electronic devices that are cheaper, smaller, faster, and easier to use with greater versatility and reliability than previous. Cathode ray tube (CRT) screens have been replaced with liquid crystal displays (LCDs). Smaller, waterproof units are now available and new systems integrate the various technologies. For example, satellite imagery, radar, GPS, plotters, and depth sounders can be interfaced on computers to provide sophisticated, multi-dimensional images.

Commercial enterprises rarely provide systematic analyses of the comparative performance of new products; and there are few published studies on the effects of particular innovations on catchability. It might be assumed that commercial fishing is a tough testing ground for new fishing gear and practices – fishers will only adopt gear and practices that clearly increase their returns. However, it is extremely difficult for individual fishers to quantitatively compare the performance of existing and new gear because of the variability in the temporal and spatial distribution, abundance, availability, and catchability of target species in the open oceans. Large companies and fleets that freely share information might gain some insights into the performance of new gear and practices. However, it would be useful to determine the extent to which fishers adopt new gear and practices on the basis of what their peers use.

The most daunting aspect of our review is how to identify specific technologies that have a significant effect on catchability and, the next step, which is how to quantify those effects. Subtle improvements in longline gear and practices will significantly affect catchability. These include improvements in the expertise of operators and interpretation of information by fishing masters, the development of communication networks for group searching behavior, and technological improvements, such as the range and precision of sonar. There is also considerable variation in skill among fishers, so that a particular device might significantly affect catchability for one vessel, whereas it might be used incorrectly or not used at all on another vessel. Empirical comparisons of performance will therefore be complex and comparisons made when new fishing gear and practices was first introduced are likely to underestimate their true effects on fishing power and catchability.

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Figure captions

Figure 1. Time-line of the uptake of fishing gear and electronic devices by pelagic longliners. Indicative purchase price is shown for equipment used on a typical distant-water longliner in the 1990s.

Figure 2. Examples of circle hooks and Japanese tuna hooks used by pelagic longliners (Robins and Kreutz, 2005).

Figure 3. Schematic representation of the duration of the various types of longline operations discussed in the present paper. Also shown is the average number of hooks deployed per operation and the average soak time for all hooks in each type of operation. The daily cycle is chosen to consist of 11 hours of night, 1 hour of dawn, 11 hours of day, and 1 hour of dusk. Each tic mark represents 100 hooks so that the density of tics reflects deployment and retrieval speeds. All operations are counter-retrieval, except for the return retrieval shown for Japan's longliners in the South Pacific Yellowfin fishery. The historical series is based on data for the South Pacific Yellowfin fishery for the 1980s and 1990s. For other decades the series uses published sources for Japan's longliners fishing yellowfin and bigeye in the tropical Pacific Ocean.

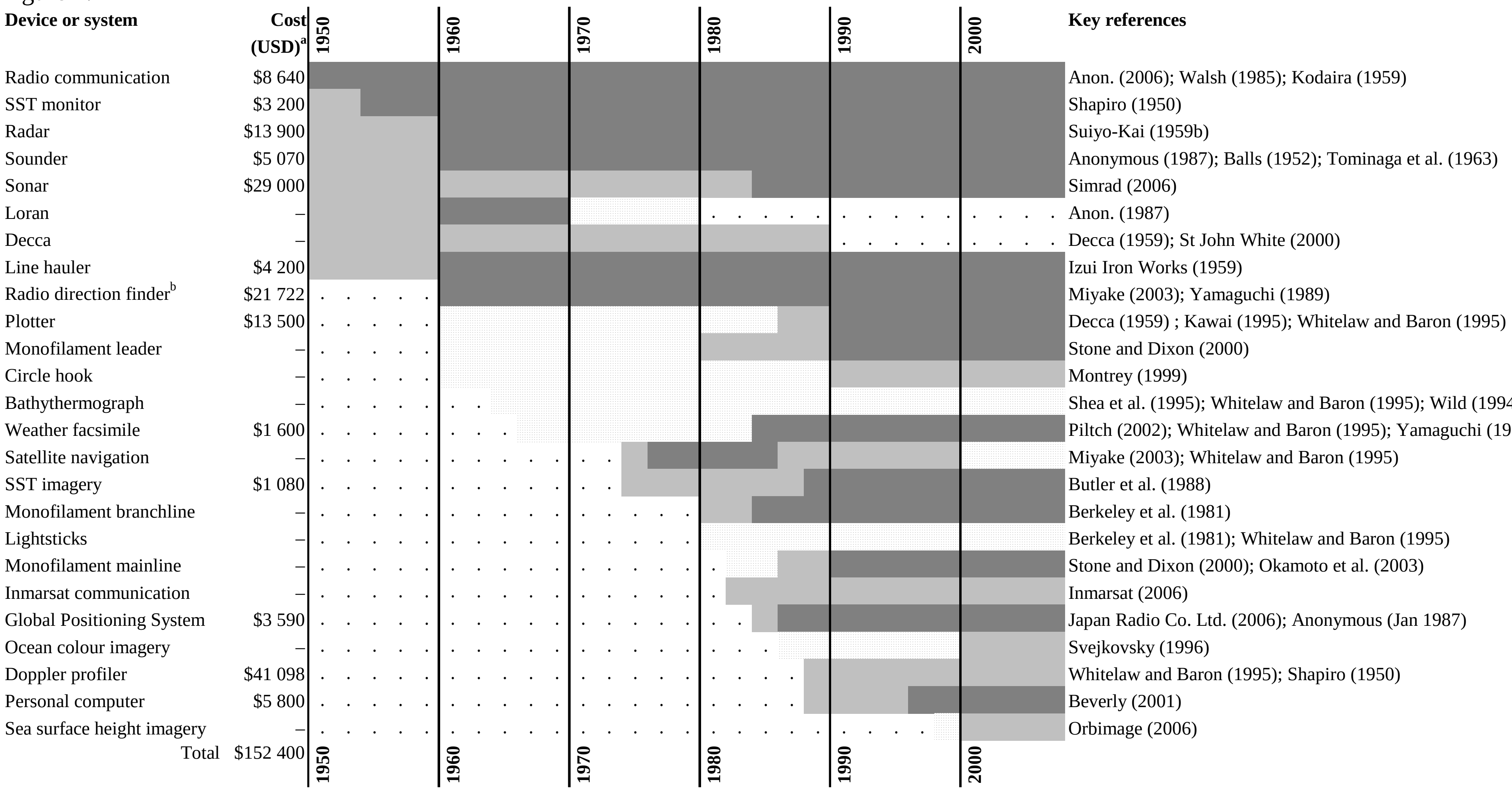
Abbreviations of fishery names:

NP	North Pacific	WP	Western Pacific
CP	Central Pacific	SP	South Pacific

Sources:

- *(a)* Australian Fisheries Management Authority observer data (South Pacific Yellowfin fishery, 1992–97)
- *(b)* Australian Fisheries Management Authority observer data (South Pacific Bluefin fishery, 1992–97)
- *(c)* Yamaguchi (1989, p. 15)
- *(d)* Au (1985, p. 377)
- *(e)* Sivasubramaniam (1961) and Maéda (1967)
- *(f)* Shapiro (1950) and Shimada (1951)
- *(g)* US National Marine Fisheries Service observer data (1994–99)
- *(h)* Secretariat of the Pacific Community observer data (1990–99)

Figure 1.



[a]Purchase price of two units of each device in the late 1990s, excluding annual fees, installation, and maintenance costs.

[b]Includes the cost of 23 radio buoys.

Legend:
- no record of use by longliners
- limited use or used by specific fleets
- used by <50% of longliners in most fleets
- used by most longliners in most fleets

Figure 2.

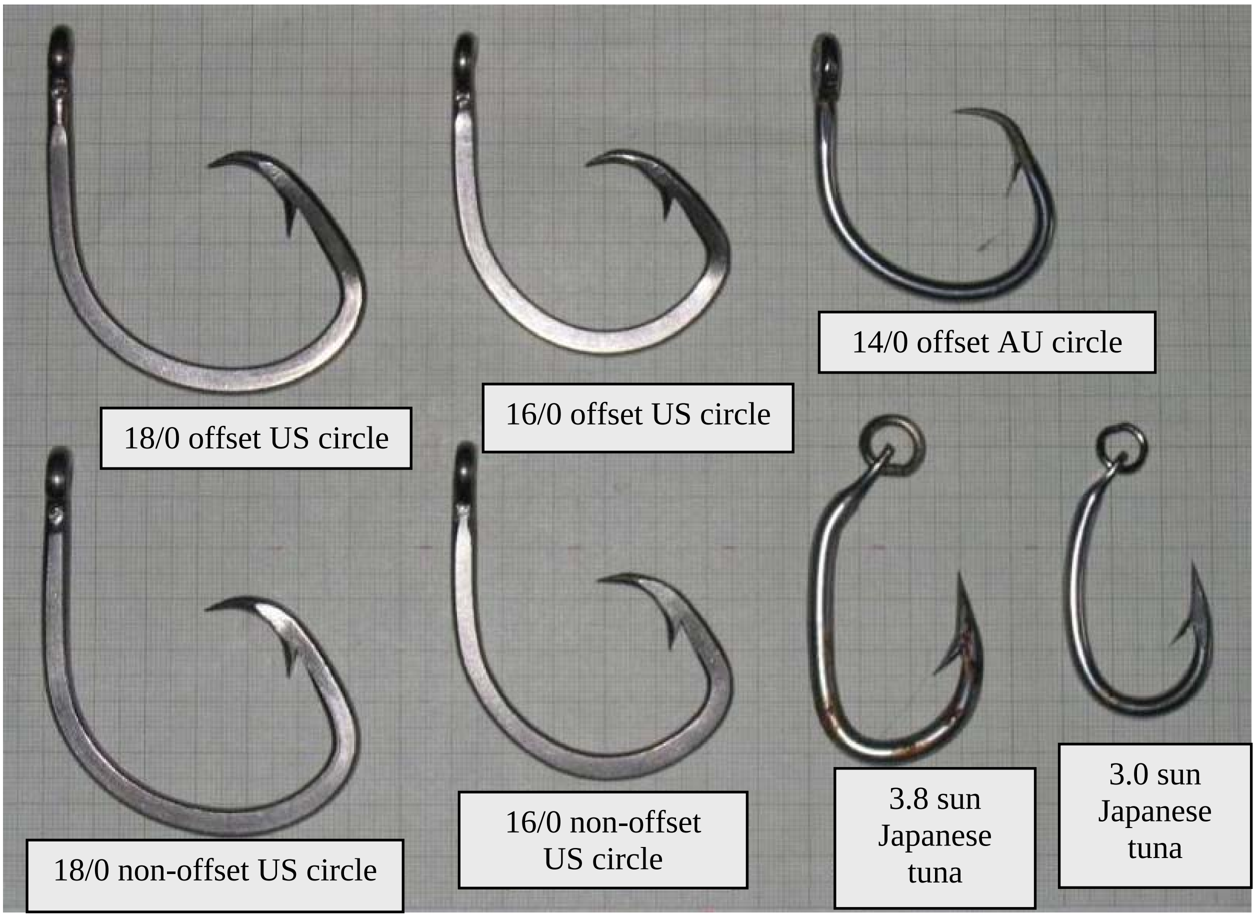
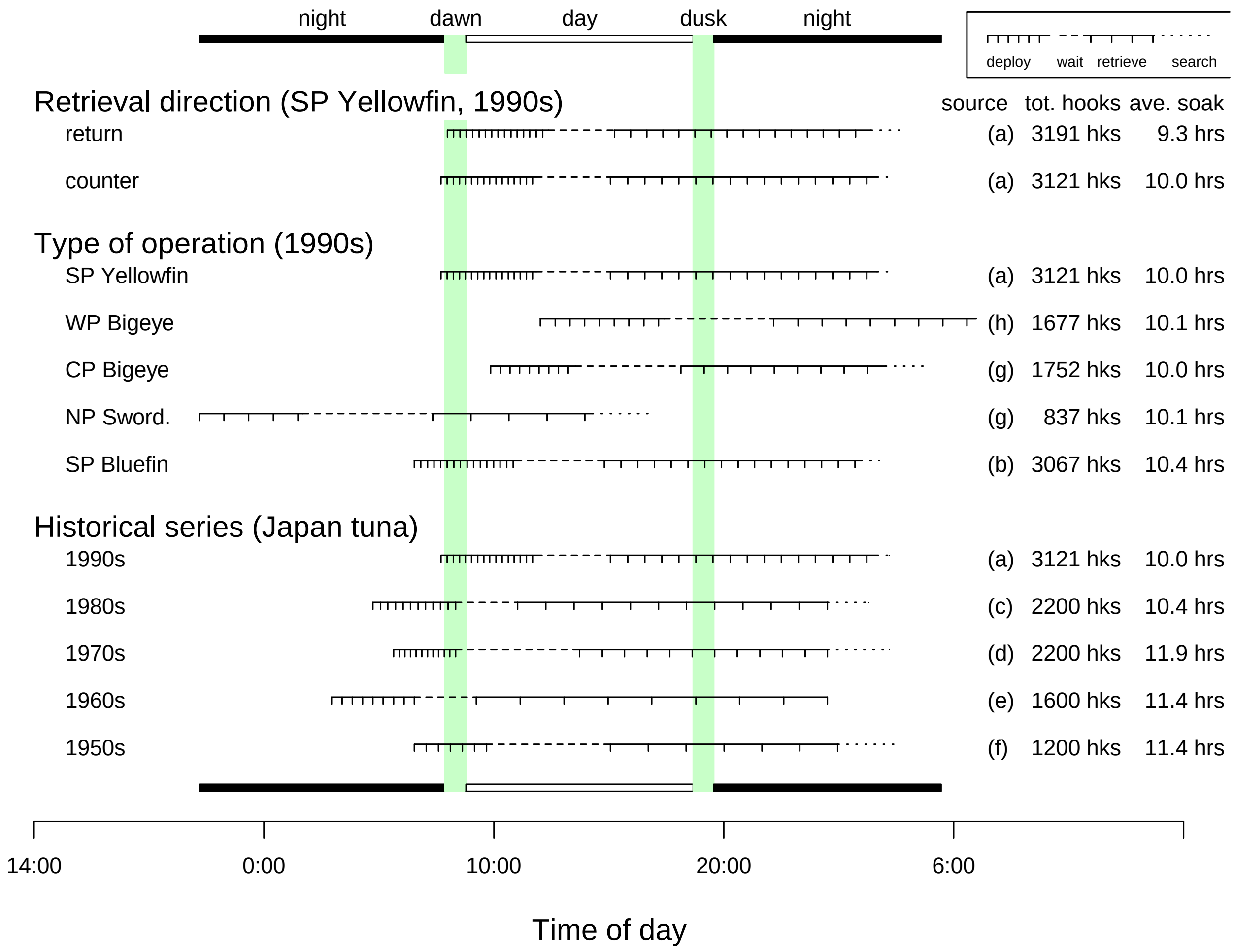

14/0 offset AU circle
18/0 offset US circle
16/0 offset US circle
18/0 non-offset US circle
16/0 non-offset US circle
3.8 sun Japanese tuna
3.0 sun Japanese tuna

Figure 3


night
dawn
day
dusk
night
deploy
wait
retrieve
search
Retrieval direction (SP Yellowfin, 1990s)
source
tot. hooks
ave. soak
return
(a) 3191 hks 9.3 hrs
counter
(a) 3121 hks 10.0 hrs
Type of operation (1990s)
SP Yellowfin
(a) 3121 hks 10.0 hrs
WP Bigeye
(h) 1677 hks 10.1 hrs
CP Bigeye
(g) 1752 hks 10.0 hrs
NP Sword.
(g) 837 hks 10.1 hrs
SP Bluefin
(b) 3067 hks 10.4 hrs
Historical series (Japan tuna)
1990s
(a) 3121 hks 10.0 hrs
1980s
(c) 2200 hks 10.4 hrs
1970s
(d) 2200 hks 11.9 hrs
1960s
(e) 1600 hks 11.4 hrs
1950s
(f) 1200 hks 11.4 hrs
14:00
0:00
10:00
20:00
6:00
Time of day