RESEARCH PAPER

An overview of historical changes in the fishing gear and practices of pelagic longliners, with particular reference to Japan's Pacific fleet

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Abstract We identify changes in pelagic longline fishing gear and practices that need to be accounted for in stock assessments. Pelagic longline fishers have continuously modified their fishing gear and practices to improve fishing power and catchability, 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 increased the probability of hooking target species and landing them. Other changes increased fishing power 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 longlining operations has steadily increased since 1950. However, mean soak time did not change significantly because faster longline retrieval and deployment speeds balanced the increased hook numbers. There has been a shift from having all baits available at dawn, to having more available at dusk and at night. In the 1970s, several longline fleets began to exploit a much greater depth range, resulting in increased catchability for deep-dwelling species (e.g., bigeye tuna, *Thunnus obesus*) and reduced

catchability for epipelagic species like blue marlin (*Makaira nigricans*). Research has been mostly limited to the effects of longline depth on the catchability of target species. Recent experiments have quantified the effects of bycatch mitigation measures on fishing power and catchability. Progressive improvements in expertise and technological improvements in the gear will also affect fishing power, but are particularly difficult to quantify.

Introduction

Size data and catch rates—catch-per-unit-of-effort or ''CPUE''—from commercial longline fishing vessels are the primary source of information on the status of many fish species in the open ocean where fishery-independent methods of counting animals are impractical (Bishop 2006). However, improvements in fishing gear and practices will alter the relationship between catch rates and abundance, masking declines in fish stocks until they collapse (Cooke and Beddington 1984; Arregion-Sanchez 1996). Those variations will introduce serious flaws to time-series of abundance indices if the data are not corrected or ''standardized''. This review identifies major changes in pelagic longline gear and practices that need to be accounted for in stock assessments.

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Catchability is defined as the probability of catching an animal with a single unit of fishing effort (Paloheimo and Dickie 1964). It is a property of interactions between the gear and the animal's behaviour. By contrast, fishing power or ''fishing efficiency'' is a property of the fishing gear and practices. It has its origins in attempts to standardize fishing effort among trawlers of various sizes, horsepower and swept area (Smith 1994). Beverton and Holt (1957) defined fishing power as a vessel's effectiveness in catching animals relative to the effectiveness of a standard vessel. More generally, it is a measure of the catch taken by a unit of effort from a given density of fish in a specified time interval compared to the standard unit of effort (Gulland 1969; Smith 1994). For longline fishing gear, the number of hooks deployed is used as the unit of effort. Longline fishing power will be influenced by differences or changes in gear and practices that alter a hook's effectiveness. For example, catch rates—and thus fishing power—may vary with soak time or depth of the hook.

In examining variations in fishing power and catchability it is useful to consider why fishers modify their gear and practices. Such modifications have a financial cost that fishers accept when they expect increased financial returns or savings in other areas of their operations. Increased returns can be achieved through improvements in the size, quality or catch rates of target species. Other reasons for modifying gear or practices include a reduction in operating costs, reduced labour, improved crew safety and, more recently, regulations that limit fishing effort or interactions with species of special concern e.g., seabirds. This article reviews variations that affect catch rates because they have consequences for stock assessments.

Demersal or ''bottom'' longlines are anchored to the sea bed in Shelf or Slope waters to catch species such as sablefish (Anoplopoma fimbria) and Pacific halibut (Hippoglossus stenolepis). This review is limited to pelagic longlines, which are used to catch tuna and billfish in the mixed layer of the open ocean. They consist of a series of baited hooks, each attached to a branchline. The branchlines, which are also called snoods or gangions, are attached at 40–50 m 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. They consist of 3,000–4,000 baited hooks, which range from below the sea surface down to several hundred metres. The longlines are usually deployed and retrieved within 24 h (Ward 1996). Shorter longlines, with fewer hooks, are used by smaller vessels that land tuna and broadbill swordfish (Xiphias gladius) for fresh-chilled markets. The sparse and patchy spatial distribution of target species, diurnal cycles in their feeding activity and distance from port usually necessitate 24 h operations, regardless of catch rates or vessel size.

This review focuses on historical developments in pelagic longline gear and practices, particularly for Japan's distant-water longline fleet in the tropical Pacific Ocean. Long time-series of catch and effort data reported by this fleet are the key abundance index for assessments of most commercially important tuna and billfish species and several other pelagic species, such as blue shark (Prionace glauca), in the Pacific, Indian and Atlantic oceans.

Trends in fishing gear

Vessels

Prior to 1920, the relatively small size of vessels (<20 m), their primitive propulsion (sail) and lack of refrigeration equipment limited longlining to short trips of several days in coastal waters of Japan. Fishers navigated by the position of celestial bodies and environmental cues, such as ocean colour, surface currents and landmarks. They had no means of finding fish, other than their skills and past experience (Beverly et al. 2003).

Steam-powered, steel longliners began operating in 1914 (Miyake 2004). The introduction of diesel-powered longliners in the early 1920s (Beverly et al. 2003) further increased fishing power by increasing the ability to remain on the fishing grounds, adjust fishing practices to local conditions and to follow target species. Large factory vessels (''motherships''), with up to 30 catcher-vessels, operated around what is now Indonesia in the early 1930s. By 1939 about 70 Japanese longline vessels of 60–270 gross registered tons (GRT) were operating from several north-western Pacific ports, with additional longliners based in Japan (Beverly et al. 2003). The offshore longliners mainly fished for albacore tuna

(*Thunnus alalunga*) for canning or swordfish for domestic markets (Nakamura 1951; Wildman 1997). The area of activity contracted during the War in the Pacific and was limited by Allied Forces for the remainder of the 1940s (Nakamura 1950).

In the early 1950s, Allied Forces permitted mothership operations in an area of the equatorial western Pacific (Yamaguchi 1989). Subsequent relaxation of those restrictions and the introduction of large, freezer longliners in the mid 1950s facilitated the geographical expansion of longlining into distant waters. Within ten years the fleet had expanded across the Pacific and into the Indian and Atlantic oceans to cover all the tuna resources known today. In the late 1960s, distant-water longliners installed super-cold freezers (−40°C or lower) that allowed extended fishing trips of 12 months or longer, yet landing sashimi-quality tuna and billfish in Japan (Sakagawa et al. 1987). Trans-shipment, when practiced, also increased fishing power by allowing longliners to remain on fishing grounds for extended periods.

Longline materials

Longliners improved catchability through progressive refinements to longline materials. Initially they used natural fibres, such as hemp (Beverly et al. 2003). More durable synthetic materials, such as kuralon, were first used for mainlines and branchlines in the 1960s. However, they were not widely used until the early 1980s (Yamaguchi 1989).

At first, longline leaders or ''traces'' were also made from natural fibres. The Japanese have used wire leaders since the 1920s to reduce the loss of hooked animals from line-breaks and bite-offs (Shimada 1951; Yamaguchi 1989). They began using nylon monofilament leaders in the mid 1980s (Mr. Peter Miyake pers. commun. 18 April 2006), which would increase catchability through their low refractive index and high tensile strength (more than 250 kg for a 2.5 mm line). Branstetter and Musick (1993) reported that catch rates of pelagic sharks on wire leaders were much higher than those on nylon monofilament leaders. On the other hand, the introduction of monofilament may have increased loss rates for several species with abrasive teeth (e.g., wahoo, *Acanthocybium solandri*), skin (e.g., sharks) or gill plates (e.g., yellowfin tuna, *Thunnus albacares*). Since the early 1980s, several fleets have used luminescent lightsticks to increase swordfish (Berkeley et al. 1981) and bigeye tuna catchability.

Early longliners used iron hooks, which sometimes broke or bent under stress and corroded, thereby reducing the hook's sharpness. The use of tin-plated, tempered iron hooks in the 1950s and galvanized high-carbon steel and stainless steel hooks in the 1980s increased fishing power (Otsu 1954; Yamaguchi 1989). Similar changes to wire leaders reduced corrosion.

Hook design has also evolved, with the Japanese tuna hook replacing ''J'' hooks by the early 1970s (Shimada 1972). Some fleets initially used large ''shark hooks'' or ''big-game'' hooks (Hoey et al. 1998). In the 2000s, circle hooks were adopted by several fisheries to mitigate sea turtle bycatch (Fig. 1). Field trials indicate that circle hooks do not significantly affect the catchability of tuna and sharks, but they may reduce the catchability of swordfish (Watson et al. 2005).

Communications

Communication is essential to finding fish in the open ocean. The Japanese began using radio telegraph in 1908 for ship-to-shore communication (TBMIAC 2006). By 1927, 120 Japanese fishing vessels had installed wireless communication equipment (Yamaguchi 1989). In 1959, all Japanese vessels over 100 GRT were required to carry radio transceivers (Kodaira 1959). Distant-water longliners had a dedicated radio operator among their crew, highlighting the importance of radio communication. Since the
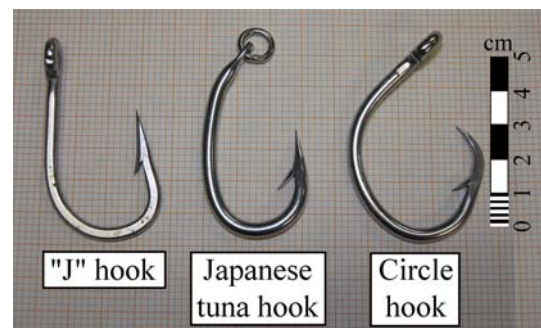

Fig. 1 Examples of the three types of hooks used by pelagic longliners: ''J'' hook (manufactured by Forman Tech Co. Ltd.), Japanese tuna hook (Kabuto) and circle hook (Maruto). In recent years, US longliners have used much larger circle hooks (≥16/0) to reduce sea turtle bycatch

early 1980s, weather facsimiles (''weather fax'') have provided longliners with weather maps annotated with information on sea surface temperature, the position of other longliners and areas of current and past catches (Yamaguchi 1989; Whitelaw and Baron 1995). Since the 1980s, satellite-based communication systems (e.g., Inmarsat-C and satellite telephones) have provided more reliable and secure, global communication (Inmarsat 2006).

Navigation

Satellite navigation (SatNav) and Global Positioning Systems (GPS) have provided longliners with frequent, very accurate fixes on their positions since the late 1970s. This allows fishers to locate bathymetric features, such as underwater seamounts. When related to satellite imagery, it allows fishers to find oceanographic features where target species are known to aggregate, e.g., temperature fronts.

Fish-finding

Since the early 1960s, Japanese longliners have used echo-sounders to detect the deep-scattering layer (concentrations of plankton and forage species), tuna

schools and variations in current direction and velocity (Tominaga et al. 1963). Longliners also use echo-sounders to locate seamounts (Mr. Peter Miyake pers. commun. 15 April 2006). Multi-directional sonar has been used by longliners to locate and target aggregations of fish, or to identify individual fish since the mid 1980s. Soon after, Doppler current profilers were introduced to determine the velocity and direction of currents at various depths. With knowledge of subsurface currents, fishers can also adjust the depth and direction of longline deployment to reduce mainline breaks and tangles and thereby maximize the availability of baited hooks to target species.

Longliners use remotely sensed images to locate oceanographic features where target species may be abundant, thereby reducing searching time and increasing fishing power. They have used sea surface temperature imagery since the 1970s to locate temperature fronts (Mr. Johnny Aoki pers. commun. 10 October 2006). Ocean colour and sea surface height imagery has been available since 1990 for identifying biologically rich areas of upwelling and current sheer. Lyne et al. (2000) found that longline catch rates of several species were significantly correlated with ocean colour, sea surface temperature
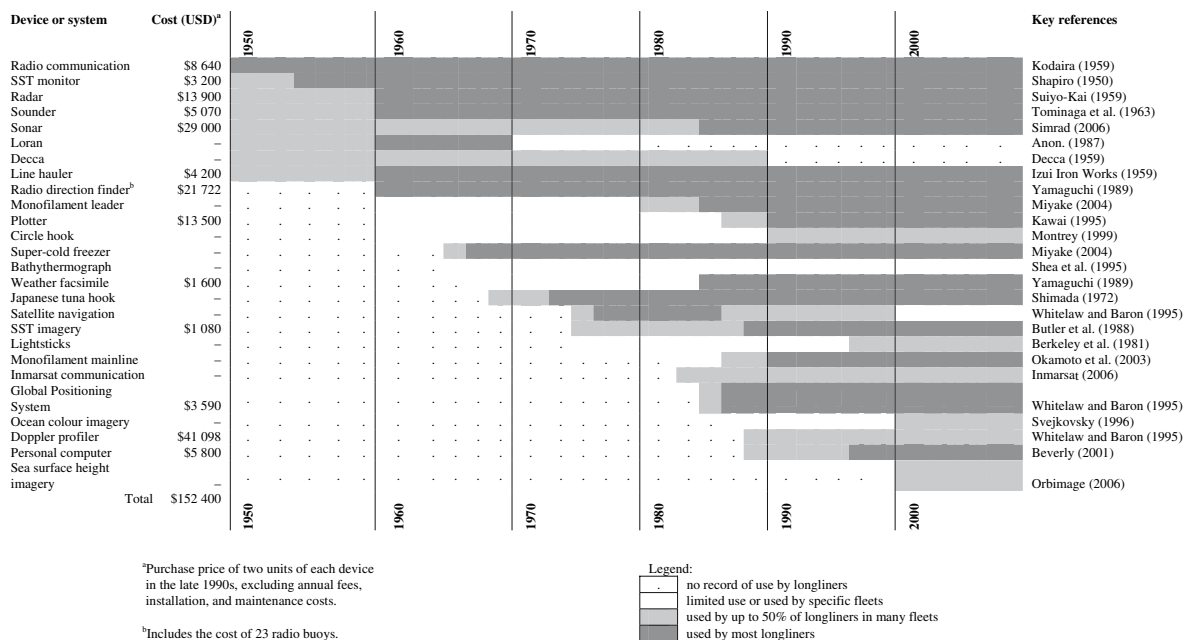

Device or system	Cost (USD)[a]	Key references
Radio communication	$8 640	Kodaira (1959)
SST monitor	$3 200	Shapiro (1950)
Radar	$13 900	Suiyo-Kai (1959)
Sounder	$5 070	Tominaga et al. (1963)
Sonar	$29 000	Simrad (2006)
Loran	–	Anon. (1987)
Decca	–	Decca (1959)
Line hauler	$4 200	Izui Iron Works (1959)
Radio direction finder[b]	$21 722	Yamaguchi (1989)
Monofilament leader	–	Miyake (2004)
Plotter	$13 500	Kawai (1995)
Circle hook	–	Montrey (1999)
Super-cold freezer	–	Miyake (2004)
Bathythermograph	–	Shea et al. (1995)
Weather facsimile	$1 600	Yamaguchi (1989)
Japanese tuna hook	–	Shimada (1972)
Satellite navigation	–	Whitelaw and Baron (1995)
SST imagery	$1 080	Butler et al. (1988)
Lightsticks	–	Berkeley et al. (1981)
Monofilament mainline	–	Okamoto et al. (2003)
Inmarsat communication	–	Inmarsat (2006)
Global Positioning System	$3 590	Whitelaw and Baron (1995)
Ocean colour imagery	–	Svejkovsky (1996)
Doppler profiler	$41 098	Whitelaw and Baron (1995)
Personal computer	$5 800	Beverly (2001)
Sea surface height imagery	–	Orbimage (2006)
Total	$152 400	

[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 up to 50% of longliners in many fleets
- used by most longliners

Fig. 2 Time-line of the uptake of gear and electronic devices by pelagic longliners. Indicative purchase price is shown for equipment used on a typical distant-water longliner in the 1990s

and proximity to temperature fronts. 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 that include the location of recent catches.

Fishers on large longliners have quickly adopted the new technology, partly because the cost of such equipment represents a small proportion of their total operating budget (Fig. 2). For a typical large longliner in the late 1990s, for example, the purchase price of electronic devices was about $US 150,000 (Fig. 2). Over the lifetime of those devices, this amounts to a small proportion of the value of the vessel's annual operating costs (about $US 2.850 million per year; Reid et al. 2003).

Trends in fishing practices

Bait

Bait species and type (e.g., frozen, fresh, live) affects catchability and fishing power through its ability to attract animals and to remain on the hook. Japanese longliners initially used pilchard (*Sardinops sagax*) and saury (*Cololabis saira*) (Shapiro 1950; Ego and Otsu 1952). They mostly deployed frozen saury during the 1960s and 1970s in the tropical central Pacific Ocean. Other species (e.g., mackerel, *Scomber* spp.) gradually replaced saury in the late 1970s (Fig. 3). Observers reported that Japanese longliners off eastern Australia in 1985–95 mostly used frozen mackerel (43% of baits), pilchards (23%) and squid (23%). In other areas, squid has been the most popular bait since about 1970 (Mr. Johnny Aoki pers. commun. 10 October 2006). It increases the catchability of bigeye tuna and swordfish and is less likely

to be removed from hooks by scavengers or by turbulence (Murphy 1960; Ward and Myers, accepted). Recent increases in squid prices have resulted in several fleets reverting to fish bait, although the Japanese distant-water fleet has continued to use squid (Mr. Peter Miyake pers. commun. 15 August 2006). Various artificial baits have been tested, but they tend to have lower catch rates than natural bait (Tsurudome 1970).

Locally based longliners used live milkfish (*Chanos chanos*) in the equatorial Pacific in the mid 1990s, which elevated yellowfin tuna catch rates (Fitzgerald 1996). Live bait continues to be used by longliners in the Gulf of Mexico and off south-eastern Australia where it improves the catchability of yellowfin tuna and billfish, e.g., blue marlin (Scott et al. 2000)

Number of hooks

In using the number of hooks as the measure of fishing effort, it is assumed that adjacent baits do not compete for catches. The number of hooks deployed in each operation by Japan's longliners increased from about 1,200 hooks in the 1950s to well over 3,000 by the late 1990s (Campbell 1997). Locally based longliners deploy fewer hooks, typically ranging from 500 to 1,500 hooks per operation. Hindmarsh and Ward (in press) show that the distance between hooks ($\sim$45 m) along longlines has not changed significantly since the early 1950s. Polacheck (1991) found no statistically significant effect of hooks per operation on catch rates of bigeye or yellowfin tuna in the tropical western Pacific. Nevertheless, particular features where target species are found, such as temperature fronts or seamounts, may be smaller than the distance covered by the longline. Hooks that are deployed in less suitable areas will

Fig. 3 Variations in the species of bait used by Japanese longliners in the tropical central Pacific Ocean (Fisheries Agency of Japan 1962–80). Observer data suggests that the category ''other'' is likely to be mostly pilchards and mackerel
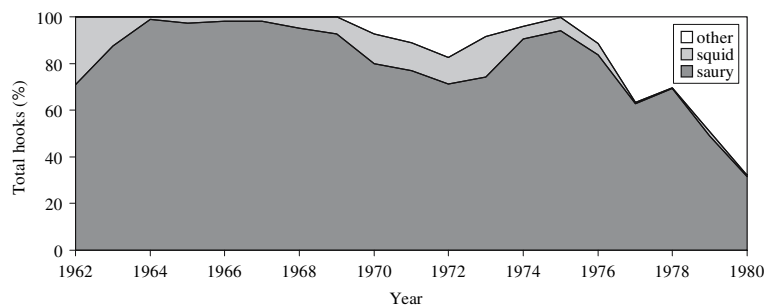
have lower catch rates on average. Therefore, an increase in the distance covered by the longline may reduce overall fishing power. This may be why small, locally-based longliners often report higher catch rates than larger longliners fishing nearby.

Soak time

The increased number of hooks per operation might be expected to result in longer soak times. However, the increases in hook numbers were accompanied by increased retrieval and deployment speeds and reduced time between the completion of deployment and commencement of retrieval (Fig. 4). Branchline coilers and line-haulers resulted in increased retrieval

speeds. Line-shooters or ''line-throwers'' increased setting speeds. Consequently, the average soak time of longline hooks decreased, from about 11.5 h in the 1950s to 10.0 h in the 1990s. Ward et al. (2004) estimated an expected catch rate for swordfish of 0.94 per 1,000 hooks for a soak time of 11.5 h compared to 0.82 per 1,000 hooks for 10.0 h.

There are occasional reports of longliners during the 1950s and locally based vessels patrolling their longlines. This involved hauling branchlines that had already caught an animal, then rebaiting the hooks and returning them to the water. This increases fishing power by adding to the number of effective hooks. The increased number of hooks deployed since the 1950s and subsequent contraction in the
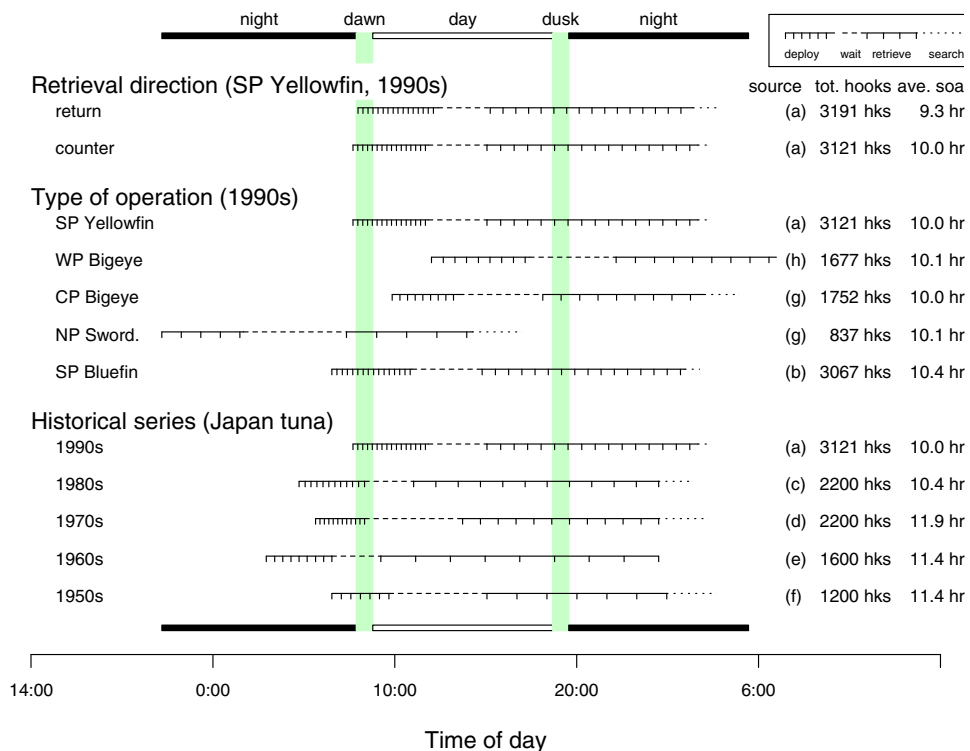

Fig. 4 Schematic representation of the duration of various types of longline operations. Also shown is the average number of hooks deployed per operation and the average soak time for all hooks in each type of operation. Each tick mark represents 200 hooks so that the density of ticks reflects deployment and retrieval speeds. Longlines are usually countered-retrieved (retrieval begins with the last buoy deployed), 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 for yellowfin and bigeye tuna in the tropical

Pacific Ocean. Sources: (a) Australian Fisheries Management Authority observer data (South Pacific yellowfin fishery, 1992–1997) (b) Australian Fisheries Management Authority observer data (South Pacific bluefin fishery, 1992–1997); (c) Yamaguchi (1989); (d) Au (1985) (e) Sivasubramaniam (1961) and Maéda (1967) (f) Shapiro (1950) and Shimada (1951); (g) US National Marine Fisheries Service observer data (1994–1999); (h) Secretariat of the Pacific Community observer data (1990–1999). Abbreviations of fishery names: NP North Pacific; CP Central Pacific; WP Western Pacific; SP South Pacific; Sword. Swordfish; Bluefin Southern bluefin tuna (*Thunnus maccoyii*)

period between deployment and retrieval has precluded large longliners patrolling their longlines (Mr. Johnny Aoki pers. commun. 10 October 2006).

Time of day

Longline catchability is closely linked to the availability of baited hooks at 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. Longlines are deployed at dawn and retrieved in the late afternoon and evening to catch tuna (Ward and Elscot 2000). Japan's longliners initially commenced deployment after midnight so that most 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 (Fig. 4). Analyses presented by Ward et al. (2004) show that those differences 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 (with other factors, such as depth, location and soak time, held constant).

Lunar cycle

Fishers have long been aware of the influence of the lunar cycle on catchability through its effects on tides, currents, light levels and animal behaviour, including 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). Locally-based longliners often time their trips to coincide with full moons to maximize their catch rates of swordfish. Observers also report that Japanese longliners sometimes targeted swordfish around full moons with shallow longlines deployed at night over seamounts off eastern Australia (Ward and Elscot 2000).

Depth

The vertical distribution of many pelagic animals depends on their behavioural responses to physical and biological conditions that are depth-dependent,

e.g., ambient temperature, oxygen concentration, light levels, 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 by varying the vessel's speed, the mainline's tension and the distance between floats. They may also increase depth range by adding weights to the mainline or branchlines and by increasing the lengths of floatlines or branchlines. Line-shooters are used in most fleets to slacken the mainline by pulling the line from the reel or bin at a rate faster than the vessel's speed. This reduces tension on the mainline, allowing it to settle at greater depths.

The number of branchlines 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 has received close attention in assessments (Suzuki et al. 1977; Hinton and Nakano 1996; Bigelow et al. 2002). Before the mid 1970s the Japanese deployed their longlines at relatively shallow depths (25–170 m) by maintaining tension on the mainline and having a long distance between floats relative to the length of the mainline (about 4–6 hooks-per-basket). The Koreans were the first to use deep longlines (Koido 1985), followed by the Japanese 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 25–300 m or deeper. They continue to be used by Japanese longliners in tropical waters and by other fleets that target bigeye tuna where the thermocline and oxycline are deep, e.g., Hawaii, Fiji, Korea and, more recently, Taiwan.

Depths obtained from depth sensors often differ from depths predicted by the catenary formula. Wind and current sheer may cause hooks to rise towards the surface or "shoal". Bigelow et al. (2006), for example, estimate that the hooks adjacent to the floats on longlines with 13 hooks-per-basket shoaled by about 20% when subjected to a current velocity of 0.4 m s^{-1}. Observers report that fishers minimize shoaling by deploying their longline in the same direction as currents, as determined with Doppler current profilers.

Bycatch mitigation

Several fishery management agencies have legislated the use of weighted swivels to reduce seabird bycatch, e.g., Australia since 2005. Other mitigation measures include bird-scaring lines (''tori lines''), night-deployment of gear, complete thawing of bait, sub-surface setting chutes, side-setting, circle hooks (to reduce turtle bycatch) and the banning of wire leaders (to reduce shark bycatch). These measures will also increase fishing power by reducing bait loss and may affect the catchability of target and non-target species (see review by Bull 2007).

Measuring fishing power and catchability

Commercial enterprises rarely report systematic analyses of the comparative performance of fishing gear; and there are few published studies on the effects of particular innovations on fishing power or catchability. Large companies and fleets that freely share information might gain some insights into the performance of new gear and practices. However, it is extremely difficult for individual fishers to quantitatively compare the performance of new and old gear because of the variability in the temporal and spatial distribution, abundance and availability of target species in the open ocean.

Several methods are available for estimating the effects of fishery changes. Effort standardization involves fitting models—such as generalized linear models—to data on catch, effort and covariates that might affect fishing power or catchability, such as area of activity and longline depth (Maunder and Punt 2004; Bishop 2006). However, uptake of innovations is often very rapid, reducing the overlap between the use of old and new gear and practices and thereby reducing the statistical power of analyses. Such models require large data sets, such as historical time-series of commercial longline data. Where information is not available, it may be possible to develop synthetic data series of covariates. Lee et al. (2005), for example, use species composition data to categorize the depth range of pre-1995 longline operations. Bishop (2006) highlights the need to develop estimation models for extrapolating from commercial catch and effort datasets that quantify bias in parameter estimates, rather than relying on prediction models that are subject to confounding among variables.

Empirical experiments are another way of estimating variations in fishing power or catchability. The effects of hook design on catchability, for example, can be reliably estimated by alternating the different hook types (e.g., circle and ''J'' hooks) along the same longline, with details recorded on the species caught on each hook. Each hook pair can be treated as a separate experiment in a conditional logistic regression. At a broader level, it is possible to gain insights into variations in fishing power by comparing the performance of two or more vessels using different gear or practices. Robins et al. (1998), for example, examined the impact of GPS and plotters on fishing power in an Australian prawn fishery. They found that vessels using GPS had 4% greater power than vessels without GPS. The addition of a plotter increased power by 7% over vessels without this equipment. Power increased by 12% when both pieces of equipment were used for at least three years (Robins et al. 1998). In one of the few studies of longliner fishing power, Lin et al. (1997) compared the performance of longliners using contemporary and traditional longline systems. For 27 pairs of longlines within about 12 km of each other, the contemporary system's catch rates of target species were up to 1.67 times higher than those of the traditional system. Lin et al. (1997) attributed the difference to increased deployment and retrieval speeds (resulting in longer soak times) and the deeper depths reached by the contemporary system.

Gulland (1969) shows how estimates of fishing power can be combined by the summing of each unit's fishing power multiplied by its fishing time, which is equivalent to the product of the gear's swept area and the proportion of animals in that area that is retained by the gear. Statistically robust methods need to be developed to allow overall changes in catchability to be derived from several different experiments, e.g., the results of hook design experiments combined with bait and leader material experiments conducted in a different fishery.

Our review identifies many studies that have quantified the effects of hook depth on catchability (Table 1). In the 1950s several studies demonstrated the effects of bait species on catchability. Since then, however, few bait studies have been published, despite considerable variations in the bait species

Table 1 Summary of published studies that have measured variations in the fishing power or catchability of pelagic longline fishing gear

Variable	Region	Data source[a]	Analytical methods[b]	Key conclusions on fishing power or catchability	Author(s)
Gear saturation	Tropical Central Pacific	Experiment	Arithmetic mean	Increasing the density of hooks by 38% resulted in a 34% reduction in yellowfin tuna catch rates.	Murphy and Elliot (1954)
	Tropical Pacific	Survey	ANOVA, runs test, deterministic model	Longlines encounter tuna aggregations or schools, which may result in gear saturation.	Murphy and Shomura (1955), Maéda (1967)
	New Zealand	Observer	NND	Longlines encounter aggregations or schools of tuna and striped marlin.	Kirby et al. (2003)
	Tropical Central Pacific	Logbook	Deterministic model	Gear saturation unlikely to significantly affect fishing power at the catch levels encountered by pelagic longliners.	Murphy (1960), Rothschild (1967)
Bait loss	Tropical Central Pacific	Survey	ANOVA, GEE	Loss rates increased with soak time and the local abundance of tuna, but declined with hook depth.	Shomura (1955), Ward and Myers (accepted)
Bait species	Tropical Central Pacific	Observer	ANOVA	No difference in tuna or marlin catch rates between saury and sardine baits.	Murphy and Otsu (1954)
	Tropical Pacific and Indian Ocean	Experiment	Arithmetic mean,	Differences in catch rates between most bait species for most tuna and billfish species.	Anonymous (1952), Shomura (1955), Shimada and Tsurudome (1971), Shimada (1972)
	South Pacific	Experiment	ANOVA, Scheffé's test	Certain mixes of bait species (e.g., herring, sardine) increased catch rates.	Bach et al. (2000)
	Equatorial Indian Ocean	Experiment	–	Catch rates of tuna and billfish on plastic flying fish were lower than those on saury.	Tsurudome (1970)
Bait status	Various	Survey, experiment, observer	ANOVA	No differences in tuna catch rates with bait status (fresh, frozen, etc). Reduced bait loss from seabirds when bait is fully thawed. Effect of blue-dyed bait varied.	Shomura (1955), Brothers et al. (1995), Duckworth (1995), McNamara et al. (1999), Boggs (2001), Gilman et al. (2003)
Bait status	Gulf of Mexico	Observer, logbook	GLM	Catch rates of billfish are higher on live bait than on dead bait.	Scott et al. (2000)
Bait size	Tropical Pacific and Indian oceans	Experiment	–	Marlin catch rates were higher on large baits (e.g., mackerel). Tuna catch rates were higher on small saury.	Shimada and Tsurudome (1971)
Soak time	Tropical Pacific and Indian Ocean	Survey	ANOVA	Bigeye catch rates increased with soak time, whereas yellowfin catch rates were highest at intermediate soak times.	Sivasubramaniam (1961)
	Pacific Ocean	Observer	GLMM	Catch rates of sharks and billfish increased with soak time, but declined for small species, perhaps because of depredation.	Ward et al. (2004)

Table 1 continued

Variable	Region	Data source[a]	Analytical methods[b]	Key conclusions on fishing power or catchability	Author(s)
Depth	Tropical Oceans	Survey	ANOVA, paired *t*-test, multiple regression	Catch rates of epipelagic[c] species were higher on shallow hooks, whereas catch rates of mesopelagic[c] species were higher on deep hooks. Catch rates of mesopelagic species increased on shallow hooks at night.	Rey and Munoz-Chapuli (1991), Boggs (1992), Higashi and Yuwaki (1993), Nakano et al. (1997), Matsumoto et al. (2000), Musyl et al. (2003), Yokawa and Saito (2004)
	Tropical Oceans	Logbook	Arithmetic mean, LM	As above.	Suzuki et al. (1977), Suzuki and Kume (1981), Koido (1985), Gong et al. (1989), Rey and Munoz-Chapuli (1991), Yokawa and Saito (2004)
	Tropical Central Pacific	Observer	GLMM	As above. Parameters for day and night depth-dependent catchability estimated for 37 pelagic species.	Ward and Myers (2005)
Leader material	Western Atlantic	Experiment	*t*-test	Catch rates of offshore sharks on wire leaders higher than those on nylon monofilament leaders.	Branstetter and Musick (1993)
	North-western Atlantic	Experiment	Chi-square goodness of fit	Catch rates of most species on nylon monofilament leaders significantly higher than that on multifilament leaders.	Stone and Dixon (2001)
Bird-scaring (''tori'') line	High latitudes	Observer	–	Bird-scaring lines reduced catch rates of seabirds and increased fishing power through reduced bait loss.	Imber (1994), Duckworth (1995), Keith (1998)
Weighted swivels	High latitudes	Observer	–	Weighted swivels reduced catch rates of seabirds and increased fishing power through reduced bait loss.	Brothers et al. (2001), Baker and Robertson (2004)
Lightsticks	Eastern Australia	Experiment	Arithmetic mean	Lightsticks increased swordfish and yellowfin catch rates. Hooks with lightsticks may attract animals away from nearby hooks without lightsticks.	Williams (1993)
	North Pacific	Logbook	GAM	Swordfish and blue shark catch rates increased significantly with lightsticks.	Bigelow et al. (1999)
Vessel	Equatorial Western Pacific	Experiment	Chi-square	Total and target species catch rates on monofilament mainlines were significantly higher than those on kuralon mainlines.	Lin et al. (1997)
	Western Atlantic	Logbook	Arithmetic mean	Swordfish catch rates of US longliners were significantly higher than those of Spanish longliners.	Hoey et al. (1998)
	Western Atlantic	Logbook	GLM	Vessel identity significantly affected blue shark catch rates.	Campana et al. (2006)

Table 1 continued

Variable	Region	Data source[a]	Analytical methods[b]	Key conclusions on fishing power or catchability	Author(s)
Lunar cycle	North Pacific	Logbook	GAM	Swordfish catch rates increased significantly with lunar index.	Bigelow et al. (1999)
	Eastern Australia	Survey	GAM, GLM	Swordfish, bigeye and yellowfin catch rates increased significantly with lunar index.	Lyne et al. (2000)
Hook shape	Various	Experiment	χ^2 analysis, GLM, paired t-test, ANOVA	Effects of circle, "J", and tuna hooks on catch rates vary among species and among fisheries. Swordfish catch rates are sometimes lower on circle hooks.	Falterman and Graves (2002), Poulsen (2004), Bolten and Bjorndal (2005), Watson et al. (2005), Kerstetter and Graves (2006), Yokota et al. (2006)
Hook size	Various	Experiment	Paired t-test, Friedman χ^2	Hook size does not affect the catchability of large predators, but will limit the minimum size of animals with a small gape, e.g., sea turtles.	Watson et al. (2004), Bolten and Bjorndal (2005)
Time of day	Various Pacific fisheries	Observer	GLMM	Catch rates of most tuna and sharks species increased during crepuscular periods, particularly at dusk.	Ward et al. (2004)
Satellite imagery	North Atlantic	Logbook	GLM	Catch rates of swordfish were significantly correlated with distance from temperature fronts.	Podesta et al. (1993)
	Eastern Australia	Survey	GLMM, GAM	Catch rates of swordfish, yellowfin and bigeye were significantly correlated with fine-scale ocean colour, sea surface temperature and distance from temperature fronts.	Lyne et al. (2000)

Note: The variables listed here are not necessarily mutually exclusive, e.g., bait type, soak time and depth may all affect the rate of bait loss. Where there is no published study, variables are not listed, e.g., fish-finding equipment. Studies that have investigated the short-term effects of environmental variables (e.g., temperature and season) on species' availability are not included in this table

[a] Estimates of longline fishing power and catchability have been obtained from experiments that tested the effects of two or more variables on longline catches; research surveys that used standard fishing gear and practices; or from catch, effort, and gear data reported by fishers in logbooks or by observers on commercial longliners

[b] Analytical methods include analysis of variance (ANOVA), chi-square (χ^2), nearest neighbour distance analysis (NND), linear regression or linear models (LMs), generalized linear models (GLMs), generalized linear mixed models (GLMMs), generalized additive models (GAMs) and generalized estimating equations (GEEs)

[c] Epipelagic species (e.g., blue marlin, *Makaira nigricans* and mahi mahi, *Coryphaena hippurus*) remain in the mixed layer of the open ocean, e.g., within about 200 m of the sea surface in the tropical western Pacific. Mesopelagic species (e.g., bigeye tuna, *Thunnus obesus*, and swordfish, *Xiphias gladius*) inhabit deeper depths (>200 m), but migrate towards the sea surface at night

used by longliners. Concerns over bycatch have recently led to many experiments with mitigation measures. These have also provided estimates of the effects of those measures on fishing power and the catchability of target and other non-target species. For example, several studies have estimated the effects of bird-scaring lines on the number of baits removed by seabirds during longline deployment (Bull 2007). Very few studies have investigated the effects of line materials (e.g., wire leaders) or electronic devices that assist in navigation, communication or fish-finding. Our literature search was mainly limited to publications in English. There are likely to be other studies on variables affecting fishing power and catchability that have been published in other languages, e.g., the Japanese were particularly active in this area since 1930. There is also extensive research on factors affecting the fishing power and catchability of demersal longlines (Løkkeborg 1994; Stoner 2004). Those studies have been used to design standardized research surveys that are routinely used to estimate the abundance of groundfish. They may also be useful in identifying areas of future research on pelagic longline fishing.

Further work

Technologies that have had the greatest effect on fishing power and catchability need to be identified and then methods for monitoring and quantifying those effects need to be developed. In addition to fishing gear and practices, there are other areas where pelagic fishers have improved their fishing power. These include the development of communication networks that enhance searching and improvements to existing equipment, such as the range and precision of sonar. There is also considerable variation in skill among fishers (Hilborn and Ledbetter 1985; Squires and Kirkley 1999). Over time, fishers will develop expertise in operating fish-finding devices and interpreting the outputs of those devices. A particular device might significantly affect fishing power for one vessel, whereas it might be used incorrectly or not used at all on other vessels. Therefore, empirical comparisons of performance when new gear and practices are first introduced are likely to underestimate their true effects on fishing power and catchability.

Conclusions

The many developments in gear and practices are likely to have increased fishing power and the catchability of target species (and any non-target species that are closely associated with those target species). By the 1990s, many longliners had installed a sophisticated array of electronic communication, navigation and fish-finding equipment. The introduction of technology based on computer-chips and satellites in the 1980s was essential for those improvements. Variations in bait, hooks, lightsticks and leader materials are likely to have changed catchability by affecting the probability of an animal attacking bait, being hooked and being landed. Other innovations have increased the availability of baited hooks (e.g., deeper longlines), improved searching efficiency (e.g., satellite imagery) and increased time on fishing grounds (e.g., freezers), providing fishers with opportunities to adapt to local conditions and to follow the fish. The establishment of major fishing companies in Japan during the 1950s provided logistical support for longliners and networks for sharing information.

Research surveys or surveys utilizing commercial fishing vessels should be considered for estimating the abundance of pelagic fish in the open ocean because of the problems in measuring fishing power and catchability in commercial longline fisheries. Assessments of several major groundfish fisheries use abundance indices derived from regular research surveys that use standard demersal fishing gear and practices at predetermined stations (Sullivan and Rebert 1998). Surveys have rarely been attempted in the open ocean apparently because of the high cost of obtaining representative samples from a system that features vast distances and high spatial and temporal variability (Bishop 2006). It will be essential to estimate variations in fishing power through surveys and experiments that compare the performance of past and current longline gear and practices if surveys or other fishery-independent methods do not prove to be feasible for estimating the abundance of pelagic fish in the open ocean.

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