Effort creep in tuna fishery stock assessments: preliminary investigation.

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Abstract

This paper provides an incomplete, draft investigation of how effort creep may affect the indices of abundance used in IOTC stock assessments. This is an important issue for stock assessment outcomes and fishery management, and the draft paper provides an opportunity for discussion. The paper begins with an overview of effort creep, differentiating between effort creep and hyperstability, and outlining factors that can contribute to increases in catchability through time. It considers methods for estimating effort creep, such as statistical analyses that compare catch rates between vessels with different characteristics, leading on to syntheses of analyses across multiple fisheries. For the particular case of tuna longline CPUE, it examines previous work to explore factors that may affect catchability. Purse seine, pole and line, and acoustic FAD CPUE will be considered in a later update. Syntheses of numerous effort creep studies indicate that technology creep should be assumed in all analyses involving time series of fishing effort, particularly if they exceed one decade of temporal coverage. Although index-specific estimates are often unavailable, where catchability increases are likely, ignoring effort creep is likely to result in overly optimistic stock status estimates. Stock assessments should consider a range of scenarios regarding long-term catchability trends, from low to high but noting that 0% is rarely plausible.

1. Introduction

Increases in catch efficiency, or fishing power, have played a critical role in the history of fisheries (Gabriel et al., 2005; Scherrer and Galbraith, 2020; Squires and Vestergaard, 2013).

In the context of stock assessment, effort creep can be defined as an unquantified increase in fishing power over time due to the adoption of a series of adjustments in fishing practices. These adjustments result in higher catch rates than would have occurred without the adjustments. Changes in catchability over time can substantially affect the outcomes of stock assessments, through their influence on CPUE indices.

The term ‘fishing power’ describes the efficiency with which vessels catch fish, defined by Beverton and Holt (1957) as a vessel’s effectiveness in catching animals relative to the effectiveness of a standard vessel.

Effort creep is important for stock assessment because of the assumed relationship between catch rates (CPUE) and stock abundance. This relationship is based on the catch equation, which relates the number of fish in the catch, C, fishing effort, E, and the average fish population density, D, on the fishing grounds:

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$$C = qED$$

where q is a fixed constant of proportionality known as the catchability coefficient and is related to the efficiency of the fishing gear (i.e., the proportion of the stock removed by one unit of effort). Effort creep progressively changes the value of q.

The concept of 'hyperstability' is sometimes linked with effort creep (e.g., Ward, 2008) since they can both cause CPUE to remain high when abundance declines. Hyperstability is best defined as a lack of proportionality between CPUE and abundance, such that $CPUE = \alpha N^{\beta}$, where β is less than 1 (Hilborn and Walters, 1992). In this context, α and β are time-invariant, and hyperstability effects are independent of changes in catchability through time. The form of a hyperstable relationship between abundance and CPUE depends on the distributions of fish and fishing effort in space and time, and the nature and definition of effort (Erisman et al., 2011; Harley et al., 2001; Ward et al., 2013). However, in this paper we focus solely on effort creep.

Effort creep can be affected by how the unit of effort is defined (Scherrer and Galbraith, 2020). For example, if the unit of effort is fishing day, a vessel that increases the number of sets per day will increase its catchability, whereas that will not be the case if the effort unit is the set.

1.1. The nature of effort creep

Industrial fisheries experience strong incentives to increase production, which are the ultimate drivers of effort creep. However, these incentives are more complex than simply a drive to increase CPUE. In economic terms they can be summarized as incentives to increase the surplus in outputs, after subtracting inputs. Productivity is an index of output divided by an index of total input usage (Grosskopf, 1993). For our purposes, the relevant output is the value of the catch, and the relevant inputs are the total costs associated with fishing.

Economic incentives to increase productivity are therefore associated with more than just the CPUE. They are also linked to the abundance of the species caught, the values of those species, and costs of inputs such as fuel, crew, and interest payments.

For example, despite technological advances and expansion of fishing throughout the world's oceans, and partly as a consequence of stock reduction, global production efficiency in terms of the tonnage of wild marine catch per watt days of fishing effort, was less in 2012 than in 1950 (Bell et al., 2017).

Productivity growth can be separated into technical change and efficiency change (Grosskopf, 1993), and the same considerations can be applied to fishing power change. Efficiency represents how far an observation is from the frontier of technical possibility, while technical change shifts the production frontier. A new technology such as bird radar or monofilament mainlines may shift the production frontier of potential catch rates, but a period of learning is required for individuals to apply the technology to full effect – i.e., for fishing efficiency to increase. For example, Robins et al. (1997) found that, in the Australian northern prawn fishery, "installation of a GPS without a plotter led to an increase of 4% in relative fishing power (over boats without a GPS). During the fisher's first year of using a plotter, fishing power increased by 7% over trawlers without a GPS or plotter; an additional year of experience with a plotter increased it to 9%; and a third year increased it to 12%."

One effect of this learning process is, to some extent, to smooth the rate of effort creep and make it less episodic than it might otherwise be, given the intermittent nature of technology change.

Technologies are often trialled by part of the fleet before being taken up more broadly. For example, in 1995 in the Japanese southern bluefin longline tuna fishery, a small number of vessels were trialling the use of monofilament mainline material (Whitelaw and Baron, 1995), but their use soon spread to the whole fleet.

Regulation is an important factor that can prevent technological change in fishing practices. For example, a study of the Dutch herring fisheries of the sixteenth to nineteenth centuries found almost no technological innovation for more than 300 years. Technical change was prevented by law (Poulsen, 2008).

2. Drivers of effort creep

The effectiveness of a unit of effort in catching fish can change over time due to the adoption of new technologies, gear modifications, fisher skill, enhanced communication / networking among skippers and/or access to other information such as oceanographic data that helps locate fish (Hamer and Teears, 2023). These factors vary by fishery.

Examples include the installation of GPS systems, provision of increasingly informative environmental data from satellites and models, upgraded communication technology to share information between vessels and with fishing companies, and scientific progress in understanding the factors that affect fish distribution, which may derive from public research or from fishers' interrogation of their own stored catch and effort data.

Squires (1992) found that the most important sources of technical progress in the Pacific coast trawl fishery were electronics and the application of scientific (rather than craft) principles to vessel and equipment design and to harvesting methods.

3. Methods for estimating effort creep.

One difficulty in estimating rates of fishing power change is obtaining the necessary data (Scherrer and Galbraith, 2020). The details of the equipment on a vessel are often unavailable to analysts.

3.1. Syntheses, and estimates of individual components.

Nevertheless, in a number of cases data have been available for equipment potentially affecting fishing power. Technological creep is observed in almost all analyses involving time series of fishing effort, particularly if the period of coverage exceeds ten years (Palomares and Pauly, 2019).

Eigaard et al. (2014) estimated a mean rate of increase of 3.2% per year across a range of studies. Palomares and Pauly (2019) reviewed 51 estimates of trends in fishing power over time, with most in the range of 2-4% per year. They noted a negative relationship between the period of the study and the estimated rate of change: annual creep rate = 13.8 x (period in years)$^{-0.511}$. They suggest that this trend occurs because "creep factors are usually estimated and published to correct for the introduction of an effective new technology over a short period of time". The estimated relationship implies an expected rate of 1.3% per year for studies that cover a 100-year period. However, this is likely to be an underestimate because the decline with time is likely also affected by negative biases in long-term estimates (Scherrer and Galbraith, 2020). These tend to omit some types of technological progress, particularly changes adding to existing vessels, or accumulation of knowledge.

Wilberg et al. (2009) noted that time-varying catchability is common in most fisheries, and can be caused by environmental, biological, and management processes as well as technological factors.

3.2. Vessel effects

In the absence of data on equipment, catchability change associated with vessel turnover can be accounted for by including a vessel identifier (e.g., the callsign) in the model. The contribution of this component of catchability change can be estimated by comparing the trends with and without the vessel id in the model (e.g., Hoyle, 2009). Vessel turnover can affect fishing power because new vessels tend to have recent technology, and because vessels may be more likely to leave a fishery if they have lower catch rates. However, this method tends to underestimate effort creep because it omits the catchability change associated with changes on a vessel, such as installing new technology or learning to use it effectively. In tuna fisheries targeting multiple species, effort creep estimates using this method can also be positively or negatively biased by the targeting behaviours of individual vessels.

3.3. Measurement against a baseline:

The notes here are incomplete. I will further consider calibration by comparing CPUE indices with survey estimates, and comparisons among gear types within a stock assessment.

4. Relevance for tuna fisheries

4.1. Longline

Indices of abundance based on longline CPUE are the key indices used in stock assessments for bigeye, yellowfin, albacore, and bluefin tunas, in all oceans. Trends in these indices are among the most important influences on stock assessment outcomes (Hoyle et al., 2024), and catchability changes associated with effort creep have the potential to change those outcomes. Indices used in stock assessment generally start in 1952 at the earliest, so I will focus on potential catchability changes during the period 1952 to 2023.

The data used to develop longline CPUE indices come from large distant water tuna longline vessels. Longlines consist of a mainline carrying a series of branchlines (also called snoods or gangions) attached at 40–50 m intervals. Each branchline carries a baited hook. The mainline is suspended from buoys floating at the sea surface and carries 3000-4000 baited hooks. Longline effort is usually defined in terms of hooks set, so while increasing the number of hooks set is likely to increase catch per day, it will not itself affect the catch per hook. There may be some reduction in CPUE if only part of the longline occurs within a targeted feature, or if hook saturation occurs, but these are not thought to be important factors for tuna longline catch rates (Polacheck, 1991). The number of hooks set can also be associated with confounding factors such as targeting (Hoyle and Okamoto, 2013).

Ward and Hindmarsh (2007) noted that “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”. Technology advances include electronic devices to help navigate, communicate, and find target species. Synthetic materials allowed fishers to improve hooks and lines which increased probabilities of both hooking and landing. Satellite imagery improved search efficiency. Freezers increased the proportion of time spent on fishing grounds. Equipment for faster longline retrieval increased hooks set without affecting soak time.

Table 1 of Ward and Hindmarsh (2007) summarises published studies that have measured variation in the catchability of longline fishing gear. Ward (2007) provides, in a WCPFC information paper, estimates of historical variation in the relative catchability and fishing power of pelagic longline fishing gear, applied mostly to bigeye and yellowfin tunas and blue marlin, but also considering mako shark, skipjack tuna, and some other species. He considers the following factors: body size (via animal movement), depth of gear, fishing master experience, period of hook availability, bait loss, gear saturation, gear detectability (branchline material), hunger, gear competition, bait type, bite off, and fish-finding equipment. The peer-reviewed version of this research (Ward, 2008) notes that although the effects on catchability of many of these factors appear large, they are also very uncertain. While this uncertainty may make it difficult to use the estimates directly to adjust CPUE trends, it also (and perhaps appropriately) reduces confidence in CPUE indices based on standardizing longline CPUE.

The views of Australian Fishing Zone observers working on Japanese longline vessels were canvassed via questionnaires and a series of discussions (Whitelaw and Baron, 1995), to help identify changes in equipment and fishing techniques from the 1970s to the 1990s. They investigated changes in fishing gear (lines, hooks, sinkers, bait throwers, radio beacons, baits), location finding techniques (electronics, visual observations), vessel and fleet structure (cooperation, crew, vessel design), and fishing practices (setting, hauling). These observations for the Japanese southern bluefin tuna longline fishery are also relevant for other Japanese tuna longline fisheries, in the Indian Ocean and elsewhere.

4.1.1. Materials

Initially used natural fibres such as hemp. Synthetic materials such as kuralon introduced for mainlines and branchlines in the 1960s, and began to be widely used in the 1980s (Ward and Hindmarsh, 2007). Fishers began using monofilament branchlines in the mid-1980s, which have lower visibility to tunas than wire branchlines (Nakamura et al., 1999), and were said to increase catchability due to their low refractive index and high tensile strength (Kasuga, 1990; Ward and Hindmarsh, 2007). Monofilament mainlines largely replaced kuralon during in the 1990s, accompanied by a shift to higher numbers of hooks between floats (HBF). Kuralon mainlines (diameter 7.9 mm) were too heavy to be sustained by a normal float when operating with more than 17 HBF. The rapid increase of HBF which started around 1992 in the Indian Ocean seems to derive from the introduction of the new material (Okamoto et al., 2004).

The introduction of stainless-steel hooks in the 1980s increased fishing power by reducing breakage. Wire branchlines also changed to stainless-steel, reducing breakage and rates of replacement. In the early 1970s, Japanese tuna hooks replaced J hooks. Circle hooks were introduced in some fisheries in the 2000s.

Stone and Dixon (2001) found substantially higher catchability of multiple pelagic fish species for branchlines of monofilament nylon compared to tarred multifilament nylon. This was a small (10 sets) study with alternating branchline types, but other studies have obtained similar results suggesting that branchline visibility (monofilament versus multifilament or wire) affects catchability (e.g., Afonso et al., 2012; Kasuga, 1990; Vega and Licandeo, 2009; Ward et al., 2008). Lin et al. (1997) obtained higher catch rates with mainlines of monofilament versus kuralon.

4.1.2. Bait effects

Bait species and type can substantially affect catchability. Target species vary in their affinity for different baits. Japanese longliners initially used pilchard and saury, switched to frozen saury in the 1960s and 1970s, then other species such as mackerel in the late 1970. Squid bait has been widely used in many areas since the 1970s. Bait use has varied between areas, presumably due to a combination of availability and targeting.

Squid bait is believed to increase the catchability of bigeye tuna and swordfish. In the mid-1990s, some equatorial Taiwanese longliners used live milkfish, which increased catch rates of yellowfin tuna (Fitzgerald, 1996).

Loss rates vary among bait types, with higher loss rates for soft-bodied mackerel species compared to firmer squid, which are less likely to be removed from hooks (Ward and Myers, 2007). Bait loss also increases with soak time.

Tori lines and bait casting machines reduced bait loss to birds in some fisheries, and bait casting may also reduce tangles during setting (Whitelaw and Baron, 1995).

Changes in bait loss between the 1950s and 1990s have been estimated to multiply fishing power by up to 3 times, for all target species (Ward, 2008; Ward and Myers, 2007). Changes in the types of bait used by Japanese longliners may have approximately doubled bigeye catchability, while halving yellowfin tuna catchability (Ward, 2007).

4.1.3. Communication

Communication is an essential tool for fishing vessels. Important for safety, but also for sharing information a) between vessels, b) from shore to vessel, c) from remote sensing tools to vessel. Information sharing is potentially very powerful for increasing catch rates. All Japanese vessels have been required to carry radio transceivers since 1959 (Ward and Hindmarsh, 2007). Weather data have been faxed to vessels since the early 1980s, with information on sea surface temperatures (SST), positions of other longliners, and areas of current and past catches (Ward and Hindmarsh, 2007; Yamaguchi, 1989). Since the 1980s, there has been increasing availability and use of satellite-based communication with a range of improvements in technology and cost reductions. Communication networks have also increase search power – vessels can search cooperatively and share information.

4.1.4. Navigation

Since the late 1970s, precise location fixes, initially from SatNav and subsequently from GPS, have allowed longliners to precisely locate bathymetric features such as seamounts (Ward and Hindmarsh, 2007), where catch rates can be higher (Morato et al., 2010a; Morato et al., 2010b). More generally, they also allow vessels to return to areas of historic and/or recent high catch rates. When combined with satellite imagery, they allow longliners to find promising oceanographic features. When combined with communication devices, they allow vessels to inform each other about where to fish, and where not to fish.

Whitelaw and Baron (1995) suggest that GPS had a major impact when introduced to the southern bluefin tuna fishery.

4.1.5. Fish finding

Japanese longliners have used echo-sounders since the early 1960s to detect the deep-scattering layer, tuna schools, current variation, and seamounts (Ward and Hindmarsh, 2007). Multi-directional sonar has been used since the mid-1980s to locate fish aggregations. Doppler current profiles have been used since the late 1980s to determine currents at various depths, which helps to optimise longline deployment. Remote sensing has been used to locate promising oceanographic features, including SST imagery since the 1970s, ocean colour and sea surface height imagery to identify areas of upwelling and current shear. These technologies have also changed through time with likely improvements.

Over many decades there has been considerable public investment in understanding oceanography (Schwing, 2023), which has accelerated with the need to understand and predict climate change. Consequently, there is currently an explosion of new data about the ocean (Lubchenco and Haugan, 2023). Large-scale oceanographic models provide publicly available information about ocean dynamics at increasingly fine spatial and temporal scales. Catch rates of swordfish, yellowfin and bigeye can be significantly correlated with fine-scale ocean colour, sea surface temperature and distance from temperature fronts (Lyne et al., 2000). The skill and specialised knowledge of experienced fishermen is also an important factor contributing to fish finding.

4.1.6. Set time

Japanese longliners changed strategy from having all baits available at dawn, to having more available at dusk and at night (Ward and Hindmarsh, 2007). Expected catch rate for bigeye tuna for bait that is available at dawn and dusk is approximately twice that for bait available at dawn only (Ward et al., 2004).

4.1.7. Set depth

Before the 1970s, Japanese sets were relatively shallow (25-170m), but depths increased (25-300m) in the early 1970s in both the Pacific and Indian oceans (Suzuki et al., 1977) in order to target bigeye tunas. The number of hooks per basket (aka hooks between floats) can be an indicator of set depth but other factors are also important, both in characteristics of the gear (mainline tension, weights on lines, and branchline and mainline material), and the environment (wind and current shear) (Rice et al., 2007). Catchability is affected by the overlap between stock and gear distribution (Boggs, 1992). These relationships have been explored in CPUE standardization (e.g., Forrestal et al., 2019; Goodyear, 2016; Hinton and Nakano, 1996) but the data available to analysts are insufficient to reliably estimate it for individual sets (Maunder et al., 2006).

The depth distribution of bigeye tuna is affected by body size (Schaefer and Fuller, 2010), but it is not clear how much this pattern affects the size selectivity of different fishing gear configurations.

Based on a mixed model fitted to observer data, Ward and Myers (2005) inferred substantial (39%) increase in bigeye catchability from 1950 to 1990 based on increased set depth, and a non-significant (1%) increase for yellowfin tuna. It is unclear how successfully CPUE analyses account for these changes by including HBF in the analysis, given that HBF is an inconsistent proxy for set depth.

4.1.8. Fisher skill

In every area of human activity there is considerable skill variation between individuals, with contributions from factors like local knowledge, better use of available information, and stronger communication networks (Hilborn, 1985; Hilborn and Ledbetter, 1985).

Local knowledge and skill increase with time spent in an activity. Therefore, technological improvements that allow vessels to spend longer on the fishing grounds may have been important for improving catchability, by increasing fisher experience. Examples of such improvements include super cold freezers and transshipment.

User skill also affects the benefits obtained from each technological improvement, with greater skill improving efficiency, i.e., moving fishing power closer to the frontier of technical possibility (Grosskopf, 1993). This is likely to be particularly important for complex activities such as using remotely sensed data and developing collaborative arrangements between vessels.

Economic incentives can also reduce fisher skill through time which may reduce catch rates. If labour costs can be reduced by more than the value of the consequent loss of catch, skilled crew may be replaced by cheaper crew with less experience and training. In the early 1990s, fish price declines led vessel owners to reduce costs by replacing Japanese fishing crews with foreign crews (mostly Indonesians) who were considered to be less skilled (Miyake et al., 2010). Taiwanese distant water fleets rely largely on low-cost migrant labour, with the majority of workers from Indonesia, the Philippines, and Vietnam (Hung et al., 2022).

4.2. Purse seine CPUE

Tidd et al. (2016) estimated an average increase in fishing power from 1993-2010 of 3.8% per year across the USA, Korean, Taiwanese, and Japanese purse seine fleets fishing in the Western and Central

Pacific Ocean (WCPO). Estimates of between 3% and 6% per year were obtained for PNA EEZs in the WCPO, for the period 2006-2018 (Vidal et al., 2021).

4.2.1. Associated

4.2.2. Acoustic FADs

Echosounders were found to increase catch per set by an average of about 10% in a study of French purse seiners in the period 2012-2017 (Wain et al., 2021).

4.2.3. Unassociated

4.3. Pole and line

5. Stock assessment

5.1. Previous sensitivity analyses and effects on outcomes

Sensitivity analyses for tuna stock assessments:

- WCPO albacore tuna (Davies et al., 2009), 0.5% p.a.
- WCPO bigeye tuna (Hoyle et al., 2008), 0.5% p.a. 1952-1985, 2% p.a. 1985-2007
- WCPO yellowfin tuna (Harley et al., 2009) 0.5% p.a. 1952-1990, 2% p.a. 1990--2008
- Indian Ocean albacore tuna (Hoyle et al., 2014), 1% p.a. 1980-2012

5.2. Issues

These will include time variation, uncertainty, and stakeholder concerns.

5.3. By species

6. Recommendations for stock assessment

Where catchability increases are considered likely but estimates are unavailable, ignoring them will positively bias stock status estimates (e.g., Han et al., 2023; Ye and Dennis, 2009). Wilberg et al. (2009) recommend a default assumption that catchability varies over time. They recommend that multiple methods of including time-varying catchability should be applied.

Scherrer and Galbraith (2020) recommend that inclusion of technological creep in fisheries management is essential for long-term sustainability, since underestimating its long-term value will lead to underestimating fisheries impacts. Similarly, Palomares and Pauly (2019) state that technology creep must be included in all analyses involving time series of fishing effort, particularly if they exceed one decade of temporal coverage. Hoyle et al. (2024) recommend that, to allow for uncertainty about fishing power, stock assessments (particularly for target species) should consider a range of scenarios regarding long-term catchability trends, from low to high but noting that 0% is rarely plausible.

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