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EMPIRICAL ESTIMATES OF HISTORICAL VARIATIONS IN THE CATCHABILITY AND FISHING POWER OF PELAGIC LONGLINE FISHING GEAR – METHODS OF ESTIMATION

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Paper prepared by

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Introduction

This paper describes methods used to estimate historical variations in the relative catchability and fishing power of pelagic longline fishing gear. Ward (submitted) presented the estimates to illustrate a method of tracking variations in catchability and fishing power. The estimates were derived from published sources and analyses of various datasets (Table 1). I used generalized linear models to estimate the effects of several variables on catchability, which were implemented in S-Plus (version 6.1) using *glm*, *glmmPQL*, and *glm.nb* from library *MASS* (Venables and Ripley 1999). Model selection was based on residual deviance and stepwise regression using Akaike's information criterion (AIC). The residual deviance measures the amount of variation in catch that is not explained by the model. The AIC is based on the model's log-likelihood and number of parameters (Venables and Ripley 1999). Model selection explored various error distributions (e.g., Gaussian, Poisson and negative binomial), combinations of variables and interaction terms, and linear, quadratic, and cubic forms of each variable. I used the *MASS* function *predict.gam* to predict catch rates of each species in each period.

Ward (submitted) describes a method of estimating relative catchability Δq from catch rates derived from experiments and other situations where abundance can be assumed to be constant:

$$\Delta q = \frac{U_{1990}}{U_{1950}}$$

where U_{1950} is the catch rate of the 1950s gear, U_{1990} is the 1990s catch rate.

The variance in relative catchability was estimated from the formula presented by Kendall and Stuart (1977):

$$\text{var}(\Delta q) = \frac{\text{var}(U_{1990})}{U_{1950}^2} + U_{1990}^2 \frac{\text{var}(U_{1950})}{U_{1950}^4}$$

where relative catchability is assumed to be independent in each period.

Area of Action and Abundance

Animal's Movement Patterns

I combined body-size – velocity relationships with size data from each period to estimate relative catchability. Simulations by Ware (1978) show that the volume of water searched is a function of the animal's swimming speed. The search volume increases in proportion to body length L raised to the power of 2.6 (Ware 1978). For each species I estimated the mean search volume V from the length of each animal reported by the Pacific Oceanic Fisheries Investigation (POFI) survey during the early 1950s and 1990s Hawaii observer data, raised by Ware's constant (Table 2):

$$V = \frac{\sum_{i=1}^{n} L_i^{2.6}}{n}$$

where *n* is the number of animals measured. Relative catchability Δq is the ratio of the search volumes in each period:

$$\Delta q = \frac{V_{1990}}{V_{1950}}$$

Depth of Gear

Ward and Myers (2005a) used a generalized linear mixed effects model to estimate the depth distribution of catchability from several longline observer datasets in the tropical Pacific Ocean. For each species, $f(D_i)$ represents the effect of depth D on relative catchability for hook number i:

$$f(D_i) = \exp(\alpha + \gamma_1 D_i + \gamma_2 {D_i}^2 + \gamma_3 {D_i}^3)$$

where α and the γ_j are parameters that Ward and Myers estimated for the species. I then inferred the daytime depth distribution of catchability for each species for longline configurations typical of each period (Table 3). The depth of each longline hook was estimated from a catenary formula (Suzuki et al. 1977) and reduced by 25% for the effects of currents (Ward and Myers 2005a). The longline configuration is almost always identical between buoys, so the number of depths that needs to be considered for each configuration is the number of hooks between buoys. The relative catchability Δq between periods is then:

$$\Delta q = \frac{\overline{f(D_{1990})}}{\overline{f(D_{1950})}}$$

where $\overline{f(D_{1950})}$ is the mean depth effect $f(D_i)$ for the 1950s and $\overline{f(D_{1990})}$ is the mean effect for the 1990s.

Fishing Master Experience

The 1990s Australian observer data included the number of years of longlining experience for 82 fishing masters responsible for 307 longlining operations. Using generalized linear models with a log-link and Poisson error distribution, I modeled the number of a species caught C in each longlining operation j as a function of experience, fishing effort, and a combination of other explanatory variables:

$$\log(C_j) = \beta_0 + \beta_1 M_j + \beta_2 A_j + \beta_3 O_j + \beta_4 S_j + \beta_5 D_j + \beta_6 D_j^2 + \beta_7 T_j + \beta_8 T_j^2 + \beta_9 X_j + \log(h_j)$$

where M_j is the month, A_j is the latitude, O_j is the longitude, S_j is the time of longline deployment, D_j is the number of hooks per buoy (a commonly used index of longline depth range), T_j is the years of experience fishing for yellowfin (*Thunnus albacares*) or bigeye tuna (*T. obesus*), X_j is the years of experience fishing for southern bluefin tuna (*T. maccoyii*), and h_j is the number of hooks deployed in each operation j. The β_k are estimated parameters.

I used the model to predict catch rates for each species in the 1950s and the 1990s, with only the years of experience modified between periods (Table 4). The estimate of the average years of experience (two years) of 1950s fishing masters was highly uncertain. I did not locate any reports of Japan’s longliners operating in the study area before the 1950s. On the other hand, longliners operated in south-eastern Asia and the north-western Pacific Ocean in the 1920s and 1930s and around Japan since the early 1900s (Nakamura 1950). I restricted the analyses to fishing master experience in longlining for tunas, ignoring their experience in other fisheries.

Operation Time

Ward et al. (2004) used mixed effects models to analyze observer records of longline catches in relation to the periods when hooks were available. I used their model to predict the catch rates for the dawn and dusk exposure of hooks of a typical longline in each period (Ward and Hindmarsh 2007). For each species, relative catchability was estimated as the catch rate predicted for a typical 1990s operation divided by the mean catch rate predicted for 1950s operations.

Availability of Baited Hooks

Bait Loss

I used the generalized estimating equations of Ward and Myers (2007) to estimate the change in fishing power due to variations in bait loss between the 1950s and 1990s. Loss rates were predicted for operational details (e.g., location, soak time, hook depth, and bait species) that were typical of Japan's longliners operating in the study area in each period.

Gear Saturation

For each period, I estimated the catch rate U_{0i} of each species i in the absence of all other species (Rothschild 1967):

$$U_{0i} = 1 - Q_0^{\frac{Q_i}{1-Q_0}}$$

where Q_0 is the proportion of hooks that were vacant at the time of longline retrieval and Q_i is the proportion of hooks occupied by species i. For each period I estimated relative catchability q_i:

$$q_i = \frac{Q_i}{U_{0i}}$$

and estimated the relative catchability Δq between periods due to saturation:

$$\Delta q = \frac{q_{i,1990}}{q_{i,1950}}$$

The proportions of vacant and occupied hooks were from Japanese five-degree data (Table 5). For each species I derived the proportion of occupied hooks from the mean catch rate over all five-degree – month – year cells. I adjusted that number for losses predicted by the bait loss model (Ward and Myers 2007). The proportion of vacant hooks Q_0 was from the mean catch rate of all species over all cells.

The 1950s data were available for nine species of tunas and billfishes, but they did not include sharks and other non-commercial species. Therefore, I divided the total catch by 0.67, which was the proportion of tunas and billfishes in the total catch of the 1950s POFI survey. To estimate catches of shortfin mako shark (*Isurus oxyrinchus*), which were not reported by Japan's longliners, I multiplied the proportion of mako shark in the POFI survey (0.004) by the total number of all species estimated for each cell.

For the 1990s I estimated the other species catch as the marlin (Istiophoridae), broadbill swordfish (*Xiphias gladius*), and tuna catch divided by 0.75, which was the proportion of those species reported in the 1990s Japanese survey data. To estimate catches of skipjack tuna (*Katsuwonus pelamis*) and mako shark, which were not reported by Japan's longliners, I multiplied the proportion of skipjack tuna (0.035) and the proportion of mako shark (0.009) in the surveys by the total number of all species estimated for each cell.

Detection

Detection of Gear

I estimated the effect of branchline material on catchability from the results of an experiment by Stone and Dixon (2001). They did not estimate an effect for bigeye tuna, skipjack tuna, or blue marlin (*Makaira nigricans*; Table 6). I used their white marlin (*Tetrapturus albidus*) estimate for blue marlin because those two species inhabit similar ecological niches. I applied those estimates to the proportion of monofilament branchlines deployed in the tropical Pacific in the 1950s (0%; Shimada 1951) and the 1990s Australian observer data (85%).

Attraction to Bait

Hunger

Stillwell and Kohler (1982) estimated that the daily food ration for mako shark was about 27.9 g kg^{-1} d^{-1} for routine metabolism. To compensate for energy expended during active metabolism (e.g., foraging and migration), they predicted that daily ration would increase by at least 25–50% (3.47–4.27% of body weight). To obtain an index of feeding motivation for mako shark, I multiplied the midpoint of the daily ration (3.88%) by individual body-mass in the 1950s POFI survey and 1990s Hawaii observer data. The relative catchability was then the mean 1990s index divided by the 1950s mean (Table 7). I used estimates of daily ration presented by Menard et al. (2000) for skipjack tuna, bigeye tuna, and large (>90 cm) yellowfin tuna from free-swimming schools. I used estimates from Junior et al. (2004) for blue marlin.

Competition among Gears

I estimated the distance between hooks from the catenary formula (Suzuki et al. 1977) and the dimensions reported for longlines in each period. I also used the POFI survey data to compare catch rates of distal hooks with those from the next closest buoy. Distal and nearby hooks will have almost identical soak times, depth ranges, and local abundance of animals. A Fisher exact test indicated that there was no significant difference in the catch rates of distal hooks and those of those of nearby hooks (Table 8).

On a broader scale, I inferred the effects of gear competition on catchability from the difference between catch predictions of a cubic model and a linear model. My cubic model was a generalized linear model with a log-link and Poisson error distribution, with the number of bigeye tuna caught C in each cell j of the global five-degree data modeled as a function of fishing effort and other explanatory variables:

$$C_j = \beta_0 + \beta_1 Y_j + \beta_2 M_j + \beta_3 A_j + \beta_4 O_j + \beta_5 N_j + \beta_6 D_j + \beta_7 D_j^2 + \beta_8 D_j^3 + \beta_9 H_j + \beta_{10} H_j^2 + \beta_{11} H_j^3$$

where Y_j is the year, M_j is the month, A_j is the latitude, O_j is the longitude, D_j is the number of hooks per buoy, and H_j is the number of hooks deployed in each cell j in the study area. I developed a time-series of the number of hooks per buoy from published and unpublished reports. Monthly population abundance N_j is the number of bigeye tuna predicted by an age-structured stock assessment model (Hampton et al. 2005a) for the region that approximates the study area. The β_k are estimated parameters.

The linear model was identical to the cubic model, but it did not include the quadratic H_j^2 and cubic H_j^3 terms and it excluded cells where fishing effort exceeded the effort corresponding to the maximum catch predicted by the cubic model. Relative catchability was the ratio of catches predicted by the linear model C_{linear} and the cubic model C_{cubic} at the mean monthly 1990s level of fishing effort (213 527 hooks per cell; Figure 1):

$$\Delta q = \frac{C_{cubic}}{C_{linear}}$$

I applied the same method to estimate the effect of gear competition on yellowfin tuna and blue marlin catchability (Table 9). At intermediate levels of fishing effort the linear model often predicts lower catches than the cubic model. This is probably an artefact of model structure because residual plots indicate that the cubic model overestimates catches at intermediate levels in attempting to fit catch declines at high effort levels. The effects of competition were not estimated for mako shark or skipjack because abundance estimates were not available for those species.

Bait Type

The 1950s longliners deployed South American pilchard (*Sardinops sagax*) or Pacific saury (*Colalabis saira*) bait almost exclusively (Shapiro 1950; Ego and Otsu 1952). I used 1990s Australia observer data to estimate the effect of bait type on catchability. Those data consist of various combinations of bait, including mackerels (34% of all bait), squid (21%), pilchards (20%), scad (3%) and milkfish (2%). Using generalized linear models with a log-link and Poisson error distribution, the number caught C in each longlining operation j was modeled as a function of bait type, fishing effort, and a combination of other variables that influence catches:

$$\log(C_j) = \beta_0 + \beta_1 A_j + \beta_2 O_j + \beta_3 M_j + \beta_4 S_j + \beta_5 T_j + \beta_6 D_j + \beta_7 K_j + \beta_8 P_j + \beta_9 S_j + \beta_{10} Q_j + \beta_{11} I_j + \log(h_j)$$

where A_j is the latitude, O_j is the longitude, M_j is the month, S_j is the time of longline deployment, T_j is the maximum soak time (minutes elapsing between the commencement of deployment and completion of retrieval), D_j is the number of hooks per buoy, and h_j is the number of hooks deployed in each operation j. The model included the proportion of hooks with the five most frequently used baits: mackerel (K_j), squid (Q_j), pilchard (P_j), scad (S_j), and milkfish (I_j). I fitted the models separately to the data for each species and predicted catch rates for the 1950s combination of bait (all pilchard) and the various combinations of bait types deployed in each operation in the 1990s (Table 10).

Landing

Bite-off

I predicted loss rates associated with the switch from wire to nylon monofilament leaders from results of an experiment that compared catch rates on the two leaders deployed by Australian longliners (Ward et al. accepted). Japan's longliners used wire leaders almost exclusively until the early1980s when they began to use nylon leaders (Ward and Hindmarsh 2007). However, many longliners continued to use wire leaders, and Australian observers reported that 72% of the leaders deployed by Japan's longliners were nylon in the 1990s.

Other Estimates

Fish-finding Equipment

I estimated the effects of electronic fish-finding equipment on catchability by calculating the proportional increase in catch rates required to cover the annual cost of electronic equipment. I estimated the annual cost of electronic equipment for a typical longliner (Table 11), then calculated the proportional increase in catch rates required to cover those costs (Table 12). The value of the catch of each species i is the product of its catch rate U_i (number per 1000 hooks), mean weight w_i (kg), market price P_i (USD/kg), and the total number of hooks deployed each year H (878 802 hooks; Reid et al. 2003). The longliner's operating profit R is then the summation of the market value of all species minus total costs C:

$$R = \left[\sum_{i=1}^{6} U_i H w_i P_i \right] - C$$

Catch rates must increase by Δq to cover the additional costs of electronic equipment E:

$$R + E = \left[\sum_{i=1}^{6} \Delta q U_i H w_i P_i \right] - C$$

The estimates suggest that a 0.01 increase in catchability was required to offset the annual cost of the equipment, which was not statistically significant (Table 13). This result was not presented in the published paper because it is likely to underestimate the effects of electronic equipment on catchability. First, estimation depends on the outlay that owners need to recoup each year. Based on advice from Australian longline fishers, I fixed the equipment's life span at seven years. Catchability must increase by 0.07 to cover the outlay if the life span is set to one year.

Second, the estimate is sensitive to the price differential between catches and equipment costs. The price of tuna was static after 1970, whereas the cost of electronic equipment declined substantially (Campbell and McIlgorm 1997; FFA 1998). Catchability must increase by 0.02 to cover equipment costs if estimates are based on pre-1980 equipment costs.

The third reason why this method is likely to underestimate increases in catchability is that an owner would not purchase and install a device unless they were convinced that it would contribute to profit, let alone cover the outlay. Many of the devices will increase profits well beyond the equipment’s initial cost. A sea surface temperature (SST) monitor, for example, is indispensable in the location of oceanic fronts. It would return far more than the USD733 outlay.

References

Campbell, H.F., and McIlgorm, A. 1997. Comparative advantage and distant water fishing fleets: the Australian East Coast Tuna Longline Fishery. Marine Policy **21**: 493-499.

Ego, K., and Otsu, T. 1952. Japanese mothership-type expeditions in the western equatorial Pacific, June 1950 to June 1951. U.S. Fish and Wildlife Service. Commercial Fisheries Review **14**: 1-19.

FFA 1998. Development opportunities in selected tuna fisheries for Pacific island countries. Forum Fisheries Agency, Honiara, Solomon Islands.

Hampton, J., Kleiber, P., Langley, A., Takeuchi, Y., and Ichinokawa, M. 2005. Stock assessment of yellowfin tuna in the western and central Pacific Ocean. In Working paper SA WP-1 presented at the first meeting of the Scientific Committee of the Western and Central Pacific Fisheries Commission (WCPFC-SC1), pp. 77. WCPFC, Pohnpei, Federated States of Micronesia, 8-19 August 2005, Nouméa, New Caledonia.

Junior, T.V., Maria Vooren, C., and Paula Lessa, R. 2004. Feeding habits of four species of Istiophoridae (Pisces: Perciformes) from northeastern Brazil. Environmnetal Biology of Fishes **70**: 293-304.

Kendall, M., and Stuart, A. 1977. The advanced theory of statistics. Volume 1: Distribution theory. MacMillan Publishing, New York.

Menard, F., Stequert, B., Rubin, A., Herrera, M., and Marchal, E. 2000. Food consumption of tuna in the Equatorial Atlantic Ocean: FAD-associated versus unassociated schools. Aquatic living resources **13**: 233-240.

Murphy, G.I., and Shomura, R.S. 1972. Pre-exploitation abundance of tunas in the equatorial central Pacific. Fish. Bull. **70**: 875-913.

Nakamura, H. 1950. The Japanese long-line fishery for tunas. U.S. Fish and Wildlife Service. Commercial Fisheries Review **12**: 1-26.

Nakano, H., Okazaki, M., and Okamoto, H. 1997. Analysis of catch depth by species for tuna longline fishery based on catch by branch lines. Bulletin of the National Research Insititute of Far Seas Fisheries **34**: 43-62.

Reid, C., Vakurepe, R., and Campbell, H. 2003. Tuna prices and fishing costs for bioeconomic modelling of the western and central Pacific tuna fisheries, Rep. No. ACIAR Project No. ASEM/2001/036 Maximising the Economic Benefits to Pacific Island Nations from Management of Migratory Tuna Stocks Technical Paper No. 1. Australian Centre for International Agricultural Research, Canberra.

Rothschild, B.J. 1967. Competition for gear in a multi-species fishery. ICES Journal of Marine Science **31**: 102-110.

Sabatini, P. 2003. Tuna commodity update. Globefish, Food and Agriculture Organization of the United Nations, Rome.

Shapiro, S. 1950. The Japanese longline fishery for tunas. U.S. Fish and Wildlife Service. Commercial Fisheries Review **12**: 1-26.

Shimada, B.M. 1951. Japanese tuna-mothership operations in the western equatorial Pacific Ocean. U.S. Fish and Wildlife Service, Fishery Leaflet No. 284 **13**: 1-26.

Shomura, R.S. 1955. A comparative study of longline baits. U.S. Fish and Wildlife Service. Special Scientific Report: Fisheries, Washington.

Stillwell, C.E., and Kohler, N.E. 1982. Food, feeding, habits, and estimates of daily ration of the shortfin mako (*Isurus oxyrinchus*) in the northwest Atlantic. Canadian Journal of Fisheries and Aquatic Sciences **39**: 407-414.

Stone, H.H., and Dixon, L.K. 2001. A comparison of catches of swordfish, *Xiphias gladius*, and other pelagic species from Canadian longline gear with alternating monofilament and multifilament nylon gangions. Fish. Bull. **99**: 210-216.

Suzuki, Z., Warashina, Y., and Kishida, M. 1977. The comparison of catches by regular and deep tuna longline gears in the western and central equatorial Pacific. Bulletin of the Far Seas Fisheries Research Laboratory **15**: 51-89.

Uozumi, Y., and Matsumoto, T. 2002. Some investigations on the status of logbook reporting for billfishes by the Japanese longline vessels operated in the Atlantic Ocean. In SCRS/2002/059 Col. Vol. Sci. Pap., Vol. 55, pp. 480-483. International Commission for the Conservation of Atlantic Tunas, Madrid.

Van Campen, W.G. 1952. Japanese mothership-type tuna fishing operations in the western equatorial Pacific, June - October 1951 (Report of the seventh, eighth and ninth expeditions). U.S. Fish and Wildlife Service. Commercial Fisheries Review **14**: 1-9.

Vannuccini, S. 1999. Shark utilization, marketing and trade, Rep. No. FAO Fisheries Technical Papers - T389. Food and Agriculture Organization of the United Nations, Rome.

Vaske, Jr. T., Vooren, C.M. and Lessa, R.P. 2004. Feeding of four species of Istiophorid (Pisces: Perciformes) from northeastern Brazil. Environmental Biology of Fishes 70:293–304.

Venables, W.N., and Ripley, B.D. 1999. Modern applied statistics with S-Plus, Third edn. Springer, New York.

Ward, P. (submitted) Empirical estimates of historical variations in the fishing power and catchability of pelagic longline fishing gear. Reviews in Fish Biology and Fisheries

Ward, P. and Myers, R.A. 2007. Bait loss and its potential effects on fishing power in pelagic longline fisheries. Fisheries Research **86**: 69–76.

Ward, P., and Myers, R.A. 2005a. A method for inferring the depth distribution of catchability for pelagic fishes and correcting for variations in the depth of longline fishing gear. Canadian Journal of Fisheries and Aquatic Sciences **62**: 1130-1142.

Ward, P., and Myers, R.A. 2005b. Shifts in open ocean fish communities coinciding with the commencement of commercial fishing. Ecology **86**: 835-847.

Ward, P., Myers, R.A., and Blanchard, W. 2004. Fish lost at sea: The effect of soak time and timing on pelagic longline catches. Fish. Bull. **102**: 179-195.

Ward, P.J.1996. Japanese longlining in eastern Australian waters, 1962-90. Bureau of Resource Sciences, Canberra.

Ward, P., Lawrence, E., Darbyshire, R., and Hindmarsh, S. (accepted) Large-scale experiment shows that banning wire leaders helps pelagic sharks and longline fishers. Fisheries Research.

Ward, P. and Hindmarsh, S. (2007) An overview of historical changes in the fishing gear and practices of pelagic longliners, with particular reference to Japan's Pacific fleet.. Reviews in Fish Biology and Fisheries.

Ware, D.M. 1978. Bioenergetics of pelagic fish: theoretical change in swimming speed and relation with body size. J. Fish. Res. Board Can. **35**: 220-228.

Zar, J.H. 1984. Biostatistical analysis. Second Edition., 2 edn. Prentice-Hall International, New Jersey.

Table 1. Datasets used to estimate relative catchability. Unless otherwise indicated, analyses were limited to data from the tropical Pacific Ocean study area (20°S–20°N and 140°E–140°W) for the 1950s (1951–55) or 1990s (1995–99).

Dataset name	Period	Target species	Characteristics	Data features	No. of ops	Source	Key reference(s)
POFI survey	1950s	yellowfin tuna	26–200 m, daytime, Japanese rope gear with wire leaders	gear details, hook-level catch, effort, operational data, individual lengths, weights, damage	880	Pacific Oceanic Fisheries Investigations (US National Marine Fisheries Service)	Murphy and Shomura (1972)
POFI bait status	1950s	yellowfin tuna	[as above]	[as above], details of the status of each hook	208	entered by author from original POFI data sheets	Shomura (1955)
Hawaii observer	1990s	bigeye, yellowfin tuna	27–600 m , daytime, monofilament gear with wire leaders,	gear details, hook-level catch, effort, operational data, individual lengths and damage	505	US National Marine Fisheries Service	http://swr.nmfs.noaa.gov/pir/qreports/qreports.htm
Australian observer	1990s	bigeye, yellowfin tuna	20–200 m , daytime, monofilament branchlines, one-third with wire leaders, eastern Australian fishing zone (10–40°S, 140–175°E)	gear details, catch, effort, operational data, individual lengths, weights, damage, fishing master experience	307	Australian Fisheries Management Authority	Ward (1996)
Japanese surveys	1992, 1995	[scientific surveys]	70–290 m , daytime, monofilament branchlines	catch, effort, operational summaries for three trips, including east of Hawaii	108	Table 3 of Nakano et al. (1997)	Nakano et al. (1997)
Japanese five-degree	1950s, 1990s	bigeye, yellowfin tuna	20–500 m, night and day , monofilament branchlines, some wire leaders	monthly catch and effort summaries for each 5° cell	39 485 month 5°cells	Japan's National Research Institute of Far Seas Fisheries	Shimada (1951), Ego and Otsu (1952), Van Campen (1952), Suzuki et al. (1977)

Dataset name	Period	Target species	Characteristics	Data features	No. of ops	Source	Key reference(s)
Global five-degree	1950s, 1990s	bigeye, yellowfin tuna	20–500 m, night and day , monofilament branchlines, some wire leaders	monthly catch and effort summaries for each 5° cell (all flags combined)	51 069 month – 5-degree cells	Secretariat of the Pacific Community	http://www.spc.int/oceanfish/html/SCTB/Data/index.asp

Table 2. Variations in mean body length *L* (m; Ward and Myers 2005b), mean volume of water searched per second $L^{2.6}$ (m^3; Ware 1978), and relative catchability for five species in the study area (standard deviation in parentheses).

Common name	1950s			1990s			Relative catchability	
	no.	L	$L^{2.6}$	no.	L	$L^{2.6}$	estimate	p-value
Mako shark	6	1.82	5.15	80	1.46	3.04	0.59	0.78
		(0.41)	(2.46)		(0.37)	(2.13)	(1.43)	
Blue marlin	38	2.13	7.86	421	1.65	3.87	0.49	0.73
		(0.47)	(4.42)		(0.25)	(1.72)	(1.46)	
Bigeye tuna	253	1.52	3.12	2 652	1.27	1.98	0.64	0.66
		(0.22)	(1.04)		(0.22)	(0.79)	(0.82)	
Yellowfin tuna	1 536	1.41	2.49	6 333	1.13	1.45	0.58	0.63
		(0.15)	(0.73)		(0.19)	(0.60)	(0.87)	
Skipjack tuna	135	0.76	0.49	1 168	0.70	0.41	0.83	0.68
		(0.07)	(0.10)		(0.08)	(0.11)	(0.41)	

Table 3. Longline dimensions that were used to estimate the depth of each hook. Dimensions for the 1950s are from Shapiro (1950) and Shimada (1951). The 1990s dimensions are means derived from 721 day-operations during 1994–2003 (P. Williams, pers. comm.). Depth estimates were derived from a catenary formula (Suzuki et al. 1977) and reduced by 25% for the effects of currents.

Period	1950s	1990s
Number of hooks between buoys	6	18
Buoyline length (m)	20.0	21.7
Branchline length (m)	30.0	24.1
Mainline between buoys (m)	280	726
Distance between buoys (m)	180	502
Minimum depth (m)	66	61
Maximum depth (m)	111	231

Table 4. Estimates of the effects of fishing master experience on relative catchability. I used generalized linear models to estimate the effect of experience on catch rates of each species from 1990s Australia observer data. I then used the models to predict catch rates of each species for the mean years of experience in the 1990s (15 years) and that assumed for the 1950s (2 years). Catch rates are the mean number predicted per 1000 hooks (standard deviation in parentheses).

Common name	Number modeled	Model residual deviance	AIC	Predicted catch rate (no./1000 hooks)		Relative catchability	
				1950s	1990s	estimate	p-value
Mako shark	487	297	435	1.92	0.60	0.31	0.00
				(0.61)	(0.04)	(0.01)	
Blue marlin	41	297	162	0.02	0.04	1.52	0.78
				(0.03)	(0.01)	(3.33)	
Bigeye tuna	1 900	297	1 760	0.89	2.28	2.55	0.15
				(0.37)	(0.17)	(1.15)	
Yellowfin tuna	6 896	297	4 004	3.21	6.76	2.11	0.17
				(1.20)	(0.53)	(0.65)	
Skipjack tuna	442	297	689	0.29	0.42	1.44	0.59
				(0.16)	(0.04)	(0.65)	

Table 5. Estimates of the effect of gear saturation on catchability. I used the formula of Rothschild (1967) to correct the reported fishing effort and catch rate of each species for the bait made unavailable through known catches. Reported catch rates (mean number per 1000 hooks) are from Japan's longliners in the study area during 1995–99 (1384 million hooks) and 1952–55 (123 million hooks), supplemented with species composition data from the 1950s POFI and 1990s Japanese surveys. The number of hooks was adjusted for bait loss predicted by the GEE model. Relative catchability is the corrected catch rate divided by reported catch rate. The relative catchability is the 1950s saturation adjustment divided by that in the 1990s.

Common name	1950s			1990s			Catchability change	
	reported	corrected	relative	reported	corrected	relative	estimate	p-value
	catch rate	catch rate	catchability	catch rate	catch rate	catchability		
Mako shark	0.80	0.93	1.16	0.23	0.23	1.01	1.15	0.98
	(0.36)	(0.51)	(0.61)	(0.15)	(0.16)	(0.92)	(1.45)	
Blue marlin	15.92	17.88	1.12	0.54	0.54	1.01	1.11	0.99
	(12.22)	(13.94)	(0.97)	(0.80)	(0.82)	(2.09)	(6.18)	
Bigeye tuna	28.79	31.04	1.08	5.18	5.23	1.01	1.07	1.00
	(31.81)	(33.67)	(1.44)	(4.47)	(4.52)	(1.21)	(3.66)	
Yellowfin tuna	65.25	71.38	1.09	6.18	6.25	1.01	1.08	1.00
	(57.22)	(63.60)	(1.14)	(7.76)	(7.91)	(1.77)	(4.85)	
Skipjack tuna	0.82	0.95	1.15	0.87	0.88	1.01	1.13	1.00
	(2.75)	(3.15)	(4.10)	(0.59)	(0.62)	(0.96)	(17.56)	

Table 6. Comparison of nylon monofilament and multifilament catchability. This table is reproduced from Stone and Dixon (2001) who deployed longlines with alternate mono- and multifilament branchlines, in ten longline operations of 1440 hooks each. Relative catchability is the number caught on monofilament divided by the number on multifilament. The p-values are for a chi-square test that Stone and Dixon used to determine whether catchability differed from parity.

Common name	Latin binomial	Number caught		Relative	p-value
		multifilament	monofilament	catchability	
Swordfish	*Xiphias gladius*	128	260	2.03	0.000
Yellowfin tuna	*Thunnus albacares*	1	9	9.00	0.011
Mako shark	*Isurus oxyrinchus*	39	58	1.49	0.054
Blue shark	*Prionace glauca*	116	225	1.94	0.000
White marlin	*Tetrapturus albidus*	13	47	3.62	0.000
Mahi mahi	*Coryphaena hippurus*	10	27	2.70	0.005
Pelagic stingray	*Daysatis violacea*	31	63	2.03	0.001
Loggerhead turtle	*Caretta caretta*	26	40	1.54	0.085
Total	–	364	729	2.00	0.000

Table 7. Historical variations in mean body-mass (1950s POFI survey and 1990s Hawaii observer data) and mean daily ration. Relative catchability is the ratio of mean daily ration between periods (standard deviation in parentheses).

Common name	Daily ration		1950s			1990s			Relative catchability	
	constant (kg.day^{-1}.mass^{-1})	source	N	mean mass (kg)	daily ration (kg.day^{-1})	N	mean mass (kg)	daily ration (kg.day^{-1})	estimate	p-value
Mako shark	0.0388	Stillwell (1982)	6	74	2.9	80	40	1.6	0.54	0.81
				(40)	(1.6)		(35)	(1.4)	(1.89)	
Blue marlin	0.0125	Vaske (2004)	38	100	1.3	421	43	0.5	0.42	0.78
				(67)	(0.8)		(24)	(0.3)	(2.05)	
Bigeye tuna	0.0482	Menard (2000)	253	76	3.7	2652	45	2.2	0.60	0.68
				(28)	(1.3)		(20)	(1.0)	(0.96)	
Yellowfin tuna	0.0259	Menard (2000)	1536	52	1.3	6333	28	0.7	0.55	0.67
				(18)	(0.5)		(13)	(0.3)	(1.05)	
Skipjack tuna	0.0551	Menard (2000)	135	10	0.5	1168	8	0.4	0.80	0.70
				(2)	(0.1)		(3)	(0.1)	(0.52)	

Table 8. Comparison of catch rates on distal hooks and hooks at the next nearest buoy (POFI survey data). Also shown is the p-value for an approximation to the Fisher exact test (Zar 1984) that tests whether the proportions of hooks with a catch are the same.

Statistic	Distal hooks	Nearby hooks
Vacant (no.)	379	386
Catch (no.)	37	30
Catch (%)	10	8
p-value	0.1461	

Table 9. The effects of competition among longlines on relative catchability. Relative catchability was estimated as the ratio of catches predicted by a model that included cubic terms for fishing effort C_{cubic} and a linear model C_{linear} for the number of hooks corresponding to the mean monthly – five-degree catch in the 1990s. Standard errors are in parentheses.

Common name	Predicted catch (no.)		Relative catchability	
	C_{cubic}	C_{linear}	estimate	p-value
Blue marlin	30	30	0.98	0.999
	(2.06)	(2.01)	(0.01)	
Bigeye tuna	930	886	0.95	0.000
	(4.25)	(4.05)	(0.00)	
Yellowfin tuna	935	890	0.95	0.000
	(4.11)	(4.31)	(0.00)	

Table 10. Estimates of the effects of bait type on relative catchability. I used generalized linear models to estimate the effect of bait type on catch rates of each species from 1990s Australia observer data. I then used the models to predict catch rates of each species for bait combinations in the 1950s (all pilchards) and the mean proportion of each bait type reported for the 1990s. Catch rates are the mean number predicted per 1000 hooks (standard deviation in parentheses).

Common name	Number modeled	Model residual deviance	AIC	Predicted catch rate (no./1000 hooks)		Relative catchability	
				1950s	1990s	estimate	p-value
Mako shark	545	434	458	0.66	0.62	0.94	0.79
				(0.15)	(0.04)	(0.22)	
Blue marlin	46	130	154	0.01	0.03	4.66	0.43
				(0.00)	(0.01)	(4.61)	
Bigeye tuna	2 340	1 825	1 849	1.24	2.41	1.94	0.14
				(0.40)	(0.18)	(0.63)	
Yellowfin tuna	8 811	3 982	4 006	15.47	7.36	0.48	0.00
				(3.66)	(0.51)	(0.12)	
Skipjack tuna	580	745	769	0.92	0.60	0.65	0.12
				(0.31)	(0.06)	(0.22)	

Table 11. Estimates of the annual cost of electronic navigation, communication, and fish-finding equipment used by a typical Japanese longliner off eastern Australia, 1995–97 (Mr. Steve Beverley, Secretariat of the Pacific Community). Purchasing and installation costs were estimated as a fixed percentage (20%) of the purchase price. The cost of maintenance was estimated as 5% of the purchase price. To estimate annual costs, I depreciated total costs by 14% per year.

Device	Model	Purchase price (USD)	Purchasing and installation (USD)	Depreciated cost (USD)	Annual maintenance cost (USD)	No. of units	Annual cost (USD)
Global position system	Furuno GP-70	1 795	359	308	90	2	795
Radio-direction finder	Taiyo RDF TD-L110	2 995	599	513	150	2	1 326
Radio beacons	PR-30	684	137	117	34	23	3 484
Echo sounder	Furuno FCV-271	2 535	507	435	127	2	1 123
Radar	JRC-JMA 527	6 950	1 390	1 191	348	2	3 078
Colour plotter	JRC-NWU-51	6 750	1 350	1 157	338	2	2 989
SST monitor	Furuno T-2000	695	139	119	35	2	308
Doppler current meter	JRC JLN-616	20 549	4 110	3 523	1 027	2	9 100
NOAA satellite receiver	Garmin GDL 30	540	108	93	27	2	239
High frequency radio	Simrad RS86F	2 160	432	370	108	2	957
Weather facsimile	JRC JAX-79	1 400	280	240	70	2	620
						Total	24 018

Table 12. Estimates of the additional catch required to meet the annual cost of electronic equipment (USD24 018) installed on Japan's longliners during the 1990s. Equipment costs are itemized in Table 10. Annual catches are based on catch rates multiplied by the mean number of hooks per operation (2949 hooks) and the mean number of operations per year (298 operations; Reid et al. 2003). Catch rates are from data reported by Japan’s longliners in the study area, except for mako shark and other species, which are from the 1990s Japanese surveys. Mean weights were estimated from 1990s Hawaii observer data. Prices are from Vannuccini (1999) for mako shark, Uozumi and Matsumoto (2002) for blue marlin, FFA (1998) for bigeye and yellowfin tuna, and Sabatini (2003) for skipjack tuna. The value for other species was arbitrarily set at 5% of the total value of those five species.

Common	Market	Mean	Without electronics				With electronics			
name	price	wt.	catch rate	annual catch		total value	catch rate	annual catch		total value
	(USD/kg)	(kg)	(no./1000 hks)	(no.)	(t)	('000 USD)	(no./1000 hks)	(no.)	(t)	('000 USD)
Mako shark	1.96	18.9	0.20	178	3.4	7	0.21	180	3.4	7
Blue marlin	1.89	51.9	0.48	419	21.8	41	0.48	424	22.0	42
Bigeye tuna	10.10	36.4	4.64	4 076	148.2	1 497	4.68	4 116	149.7	1 512
Yellowfin tuna	5.40	28.7	5.48	4 819	138.3	747	5.54	4 866	139.7	754
Skipjack tuna	1.04	6.7	0.77	680	4.6	5	0.78	687	4.6	5
Other species	1.11	12.4	9.48	8 331	103.5	115	9.57	8 413	104.5	116
					total	2 411			total	2 435

Table 13. Financial analysis of annual income and expenditure of a Japanese longliner during the 1990s. All estimates are based on FFA (1998), except for income from sale of catch, which is based on the catch rates and prices presented in my Table 11. The estimated annual cost of electronic equipment (USD24 018) is included in vessel maintenance in the "With electronics" column.

Component		Item	Without electronics (USD 000s)	With electronics (USD 000s)
Income				
	Sale of catch			
		Mako shark	7	7
		Blue marlin	41	42
		Bigeye tuna	1 497	1 509
		Yellowfin tuna	747	753
		Skipjack tuna	5	5
		Other species	609	614
		total income	2 905	2 929
Expenditure				
	Variable costs			
		crew expenses	1 145	1 145
		fuel and oil	358	358
		bait	288	288
		other	132	132
		total variable costs	1 922	1 922
	Fixed costs			
		vessel maintenance	169	193
		fishing gear maintenance	83	83
		support and management	178	178
		total fixed costs	430	454
		Total costs	2 353	2 376
		Operating profit	553	553
		Depreciation	400	400

Component	Item	Without electronics (USD 000s)	With electronics (USD 000s)
	Net profit	153	153
	Replacement cost	5 000	5 000
	Net return to investment	3%	3%

Figure Captions

Figure 1. Effect of gear competition on catch rates. Using the global five-degree data, I inferred relative catchability of bigeye tuna as the difference between catch predictions of a generalized linear model that included quadratic and cubic terms for fishing effort (the cubic model) and one that did not include those terms (the linear model).