Population characteristics and biology of striped marlin, *Tetrapturus audax* in the New Zealand fishery

A thesis presented in partial fulfillment of the requirements for the degree of Master of Science (MSc) in Physiology at Massey University, Palmerston North, New Zealand.

R. Keller Kopf

2005

Abstract

Striped marlin (*Tetrapturus audax*) are apex predators in the pelagic ecosystem and are seasonally abundant in the off-shore waters of New Zealand during December through May. Data presented in this thesis were derived from a variety of fishing databases from New Zealand, Australia and United States as well as biological samples collected from east Northland New Zealand. This thesis may be used to help answer questions about growth and size structure, factors influencing conventional tag recoveries, and the trophic dynamics of striped marlin in the New Zealand fishery.

Results show that the average weight of striped marlin in the New Zealand recreational fishery has declined between 1925-1944 (117.9 ± 0.6 kg) and 1985-2003 (96.6 ± 0.3 kg) (Means $\pm$ S.E.). The root causes of this average size decline are unknown but appear to be related to the expansion of a surface longline fishery in the southwest Pacific Ocean during 1958. Despite the large average size (104.9 ± 0.2 kg) of striped marlin from New Zealand, parameters estimated in the von Bertalanffy growth model ($L\infty 3010$ mm, K=0.22 annual and t_0=-0.04) do not show higher growth rates compared to Hawaii or Mexico.

During their residency in the New Zealand Exclusive Economic Zone (EEZ) the condition Wr (relative weight) of striped marlin improves from 95.1 ± 1.2 to 109.4 ± 3.4 and average weight increases from 98.1 ± 2.0 kg to 114.6 ± 0.4 kg. These data imply that striped marlin migrate to New Zealand in order to take advantage of the abundant food resources and to improve condition after spawning in warmer waters to the north. Arrow squid (*Nototodarus* spp.), jack mackerel (*Trachurus murphyi*) and saury (*Scomberesox saurus*) comprised a large portion of the diet from (n=20) striped marlin stomachs during March of 2004. Additionally, with a consumption rate of 0.962 to 1.28 kg of prey per day, striped marlin may consume the equivalent of 2.8-3.5% of New Zealand's current commercial catch of arrow squid and jack mackerel respectively.

With concerns about declining pelagic fish stocks, tag-and-recovery programmes have become increasingly popular and over 50% of recreationally captured marlin in New Zealand are tagged and released annually. However, low tag recovery rates (<1.0%) have hindered progress in understanding growth, stock structure and migration patterns important for managing this species. Data from this study suggests that tag returns from striped marlin would increase if more fish were captured and released in less than 39 min and a greater number of small (< 89 kg) individuals were released. Tag recoveries and presumably post-release survivorship of striped marlin was reduced by increasing capture time and fish size. Rates of injury were lowest during capture times ranging from 20-29 min and in fish weighing 60-89 kg.

Preface

Billfishes (marlins, sailfishes, spearfishes, and swordfish) are large, aggressive, relatively rare, highly migratory and inhabit an expansive pelagic environment. These characteristics make management and scientific study difficult and are the root causes for the paucity of biological information about these fishes. The large gap in our knowledge of billfishes fosters a high level of uncertainty about the sustainability of current fishing practices and demands immediate attention.

The 1972, 1988, and 2001 Billfish Symposia are the most significant works published about management and scientific study of these fishes (Shomura & Williams 1974; Stroud 1989; JMFR 2003). Related works by Bromhead et al. (2004); Hinton & Maunder (2003); Hinton & Bayliff (2002) and; Nakamura (1985) are specific to striped marlin biology and fisheries. As the need for international cooperation in billfish management and research persists, more information will be disseminated during the Fourth International Billfish Symposium held in Avalon, Santa Catalina Island, California, in 2005. Research presented in this thesis attempts to address some of the fundamental questions about billfish biology and fisheries which were posed in the previously cited symposia and literature.

In order to provide a more robust investigation, new data presented in this report were supplemented with data sets from the Bay of Islands Swordfish Club and from three of the world's largest Conventional Cooperative Billfish Tagging Programmes. The goals of this thesis were to review and consolidate the scientific literature on striped marlin (Chapter 1); provide information about growth and size structure (Chapter 2); determine factors influencing conventional tag recoveries (Chapter 3); and describe the diet of striped marlin while in the New Zealand fishery (Chapter 4). Chapter 5 provides an overall discussion of the results and summarises the main findings from Chapters 1-4.

Recently, there has been considerable debate about the animal welfare implications associated with fishing and recreational game fishing has been the focus of much attention in New Zealand. At the present time, very little information exists informing anglers on how to improve the welfare of fish which they catch. Anglers may be forced to change their methods of capture and it is up to the scientific community to provide objective evaluations to inform the procedures on how to improve the treatment of fish during capture. Appendix D is a manuscript submitted to the Journal of Fish Biology which addresses this issue by evaluating some of the behavioural and physiological impacts of capture by hook-and-line.

Acknowledgements

Table of Contents

Chapter 1:

Review of striped marlin biology, ecology and fisheries

Chapter 2:

Size trends and growth of striped marlin in the New Zealand recreational fishery

Chapter 3:

Impacts of capture time, body mass and injury on conventional tag recoveries from striped marlin

Chapter 4:

Diet and feeding ecology of striped marlin off the coast of New Zealand

Chapter 5:

General discussion and summary

List of Tables

Chapter 2

Chapter 3

Chapter 4

List of Figures

Chapter 1

Chapter 2

Chapter 3

Chapter 4

List of Appendices

Chapter 1

Review of striped marlin biology, ecology and fisheries

1.1 Systematics

The striped marlin, *Tetrapturus audax* (Philippi, 1887) is one of eight billfishes in the family Istiophoridae, which encompasses marlins (*Tetrapturus* spp. and *Makaira* spp.), sailfishes (*Istiophorus* spp.) and spearfishes (*Tetrapturus* spp.) (Bromhead et al. 2004). The total number of Istiophorid billfishes is unclear because there is considerable uncertainty about recognition several species of spearfish and differentiating Atlantic and Indo-Pacific blue marlin and sailfish (Graves & McDowell 1995; Graves & McDowell 2003). In contrasts to popular beliefs, molecular evidence suggests that Istiophorids are not in the same suborder as tunas and mackerels (Scombrodei), rather they are members of the suborder Xiphioidei (Finnerty & Block 1995). The suborder Xiphioidei includes marlins, sailfishes, spearfishes and broadbill swordfish (*Xiphias gladius*).

All five of the Istiophorid species that occur in the Pacific and Indian Oceans have been recorded in New Zealand waters but striped marlin are most common. Of the billfishes occurring in the Pacific and Indian Oceans, striped marlin are most closely related to shortbill spearfish (*T. angustirostris*) and share classification at the genus level (Nakamura 1985). Mitochondrial DNA research indicates that white marlin (*T. albidus*) in the Atlantic Ocean and striped marlin are separated by nearly the same level of genetic diversity as blue marlin species of the Atlantic and Pacific Oceans. However, white marlin and striped marlin are separate lineages (Graves & McDowell 2003).

1.2 Identification

Striped marlin have two dorsal (first is 37-42 rays, second is 5-6 rays) and anal fins (first anal fin is 13-18 second 5-6 rays). The second dorsal fin is positioned slightly behind the second anal fin and there is a pair of notched lateral keels on the caudal peduncle. Pectoral fins are long (18-22 rays) and can be pressed against the body and are similar in length to ventral (single spine) pelvic fins. The upper jaw (bill) extends nearly twice the length of the lower jaw and is round in cross section with small sand paper like teeth (Preceding paragraph from Nakamura 1985; Figure 1.1).
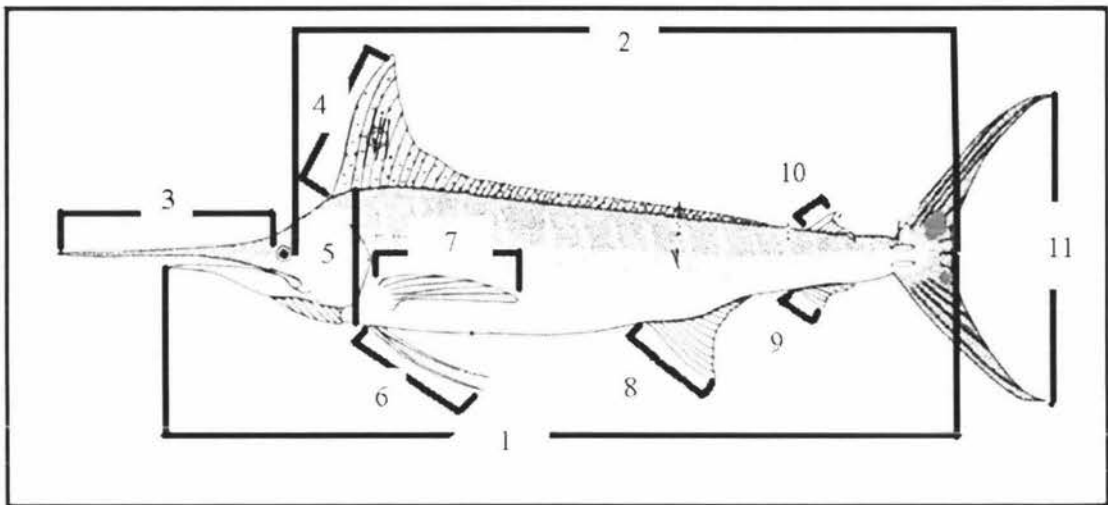
Figure 1.1 External features of striped marlin showing common morphological measurements cited throughout text. 1) Lower jaw-fork length; 2) Eye-fork length; 3) Bill length; 4) First dorsal fin height; 5) Body depth; 6) Pelvic fin length; 7) Pectoral fin length; 8) First anal fin height; 9) Second anal fin height; 10) Second dorsal fin height; 11) Caudal spread.

Striped marlin can most easily be distinguished from blue and black marlin (*M. nigricans* and *indica*) by the height of the first dorsal fin. The 1st and possibly 2nd or 3rd dorsal fin spine in striped marlin is nearly equal to or greater in height than straight line body depth. The height of the first dorsal fin in blue and black marlin is distinctly less than body depth (Figure 1.1). Blue and black marlin have more robust bodies and steeply sloped foreheads compared to striped marlin. The ability of striped marlin to fold pectoral fins against the body also differentiates it from the black

marlin (Ueyanagi & Wares 1975). The pectoral fins of the black marlin are locked in an outward position away from the body. Colour during life is metallic blue with 10-15 prominent vertical stripes that remain present several hours after death. Metallic stripes in blue marlin usually fade soon after death (Paul 2000).

1.3 Distribution and Habitat Preferences

Striped marlin are widely distributed throughout pelagic ecosystems, inhabiting tropical and temperate waters throughout the Pacific and Indian Oceans. Commercial longline catch rates show a horseshoe shaped distribution pattern in the Pacific and a latitudinal range of 45° N to 45 ° S in the Indian and Pacific Oceans (Nakamura 1985; Figure 1.2)
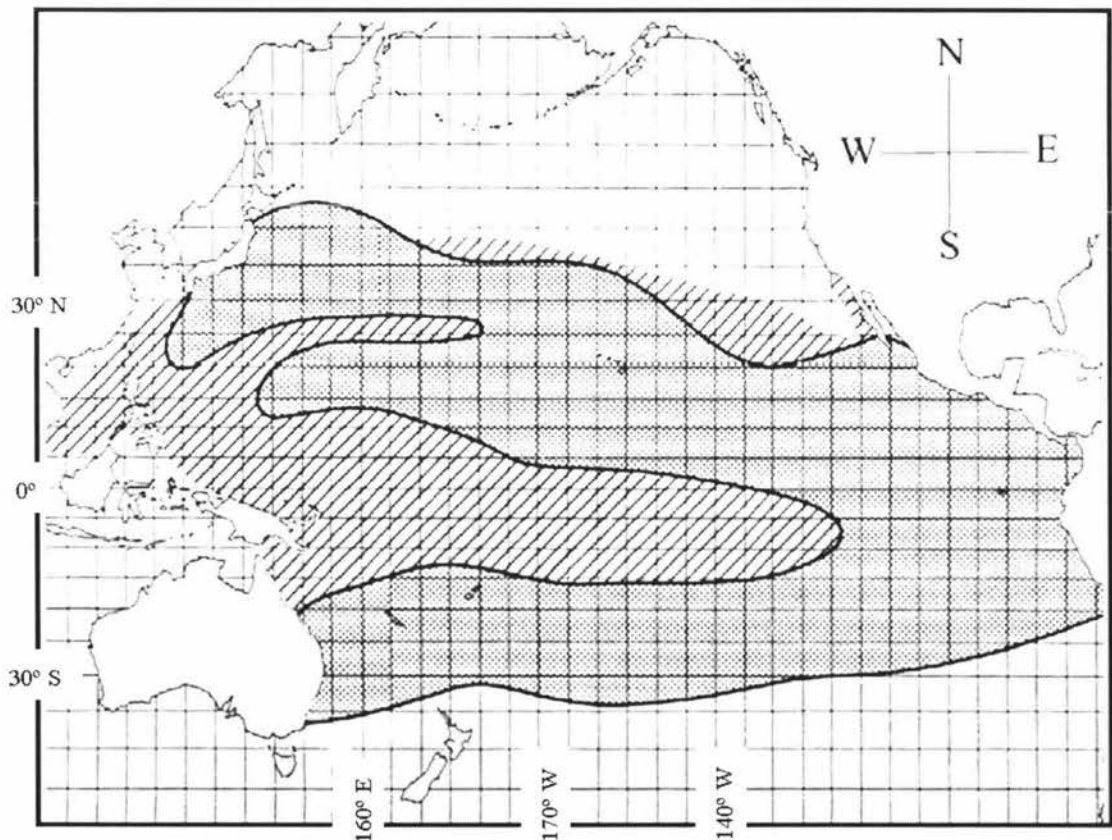
Figure 1.2 Distribution of striped marlin in the Pacific Ocean gathered from Japanese longline records (1964-69). Shaded areas indicate moderate to high catch rates. Cross hatched areas represent lower catch rates. * Striped marlin also occur approximately 10° north and south of shaded areas and in the Indian Ocean. Reproduced from Squire & Suzuki (1990).

Striped marlin occur in the widest range (15.2 ° - 30.5 ° C) of sea surface temperatures of all Istiophorid species (Bromhead et al. 2004). Catch rates show that juveniles are more abundant in warmer equatorial waters while adults frequently penetrate higher latitudes and cooler waters during the summer months in both hemispheres. Squire (1974) found that striped marlin were most frequently captured in the eastern Pacific at water temperatures ranging from 16.1° to 22.8 °C and Bromhead et al. (2004) cite that 97% of striped marlin near Australia are caught at sea surface temperatures ranging from 18 ° to 27 ° C. The absolute water temperatures in which striped marlin can survive is unknown but there appears to be is a limiting rate of water temperature change that influences the ability for deep dives ($\approx$ 8-10 °C) (Holts & Bedford 1990; Sippel et al. unpublished).

Satellite and acoustic tags have shown that striped marlin regularly make short dives to depths exceeding 100 m but most time is spent in the upper 10 m of the water column (Holts & Bedford 1990; Domeier et al. 2003). The deepest dive recorded for striped marlin is 180 m and longlines rarely catch striped marlin deeper than 150 m (Boggs 1992; Brill et al. 1993). However, in a satellite tagging study from New Zealand, Sippel et al. (unpublished) recorded a striped marlin dive of 310 m. At night striped marlin spend approximately 78% of their time in the upper 5 m of the water column and during the day spend they spend 65% of their time in the upper 5 m (Sippel et al. unpublished).

1.4 Migration and Stock Structure

Fine scale seasonal movements of striped marlin are unclear but appear to be driven by changes in water temperature, food availability and reproduction. Tag recoveries from conventional tagging programmes reveal that striped marlin a capable of long distance migrations and the longest straightline distance recorded is 6713 km (Ortiz et al. 2003; *see* Chapter 3). Satellite tags have recorded a striped marlin which traveled an average of 58 km per day for 33 days migrating from the King Bank off the coast of New Zealand to Vanuatu, 2140 km north (Sippel et al. unpublished). Despite their extensive movements, striped marlin appear to be less migratory than the blue and black marlin, which have both had tag recoveries with net displacements exceeding 14,000 km (Ortiz et al. 2003).

Currently, striped marlin in the Pacific are considered a single stock but investigations into Mitochondrial DNA suggest significant heterogeneity between samples from Australia, Hawaii, Ecuador and Mexico (Graves & McDowell 1994). Interestingly, other highly migratory and pelagic fish species such as yellowfin tuna (*Thunnus albacares*) and black marlin show no heterogeneity in genotype samples from the same areas in which striped marlin were sampled (Graves & McDowell 1994). Population structuring of striped marlin may be facilitated by multiple spawning areas throughout the Pacific Ocean, while black marlin who exhibit no Pacific wide heterogeneity are known to spawn only in one region which is near the Great Barrier Reef (Graves & McDowell 1994). However, the two most likely theories regarding stock structure of striped marlin are: 1) Single unit-stock or 2) Two stocks, one in the north and south Pacific, roughly divided by the equator (Hinton & Bayliff 2002).

Catch rates, tag recoveries and modal shifts in size classes show there are several regions in the Pacific where striped marlin make cyclic annual migrations but there is also significant population mixing throughout the ocean (Squire & Suzuki 1990). In the southwest Pacific, striped marlin migrate south to New Zealand during the austral summer and are most abundant in January through April (Figure 1.3). In May or June, striped marlin migrate north, away from New Zealand to a wide variety of locations in the tropics and then many migrate to the Coral Sea of Australia where spawning is known to take place during September-December (Hanamoto 1977; Figure 1.3). In December or January striped marlin migrate south and return once again to New Zealand waters. However, conventional tag recoveries span a wide spread throughout the southwest Pacific and indicate potential population mixing with other regions (Figure 1.4).

In the eastern Pacific, evidence suggests that there is transequatorial exchange from South America (Ecuador) to Mexico and southern California (Ortiz et al. 2003). However, striped marlin off the coast of South America are also known to migrate northwest toward the central Pacific during the winter and return with warmer waters during the summer (Squire & Suzuki 1990). The region surrounding Hawaii also appears to be a central location for striped marlin migrating from northeast and northwest Pacific during cooler seasons of the year and is also in close proximity to known spawning grounds.
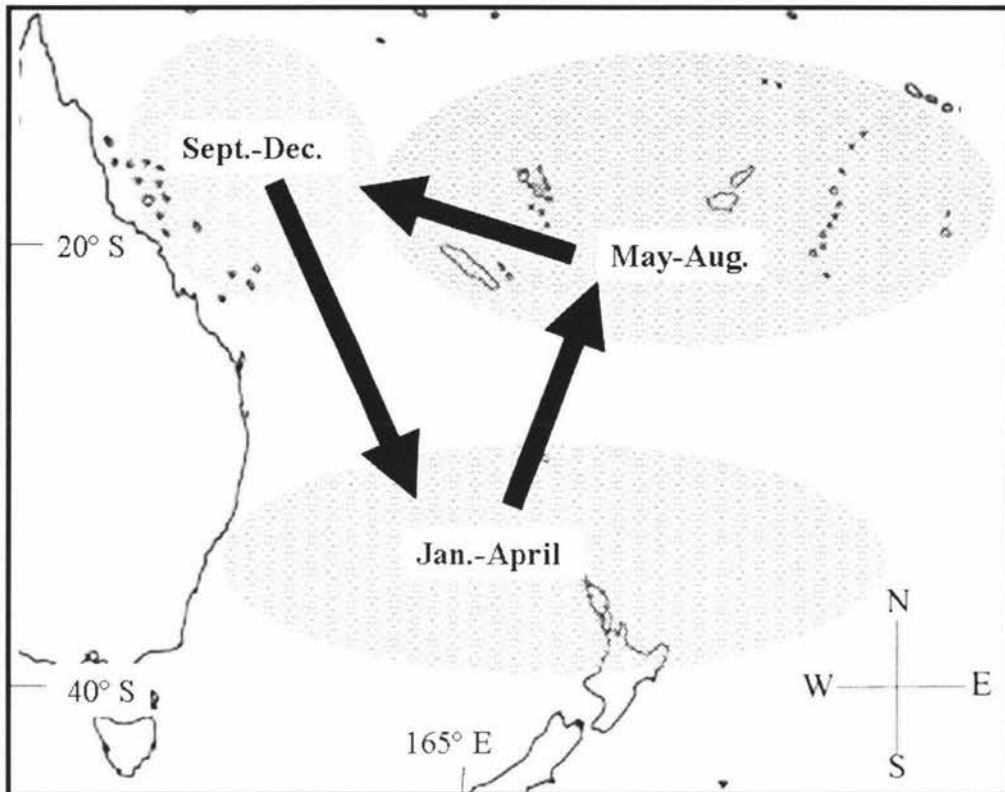
Figure 1.3 General movement patterns of striped marlin in the southwest Pacific Ocean derived from longline catch records adapted from Hanamoto (1977) and Squire & Suzuki (1990).
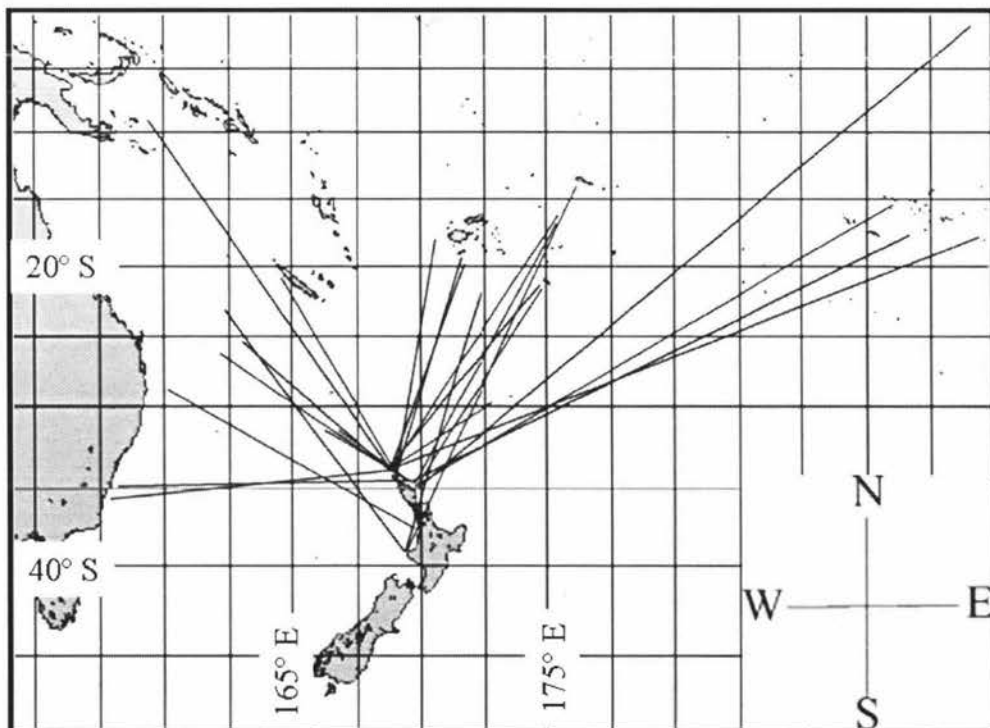
Figure 1.4 Displacement of conventional tag recoveries of striped marlin tagged in New Zealand from Holdsworth & Saul (2004).

1.5 Reproduction

Striped marlin are oviparous and spawn in the open ocean (Nakamura 1985). The pelagic ecosystem provides little protection for eggs, larvae, and juvenile fish, which likely results in low survival rates. Striped marlin overcome this challenge by using a high fecundity reproductive strategy that can yield over 20 million eggs per female, but fecundity is highly dependent on female size (Eldridge &Wares 1974). Fertilisation is external and eggs are approximately 1-1.5 mm diameter. There is no parental care and survival of young is dependent upon on current, predators, and food supply.

Spawning behaviour is not well documented but striped marlin have been observed swimming in close pairs during known spawning periods and may remain together even when one fish is hooked (Eldrige & Wares 1974). Literature suggests that spawning occurs once annually but recent research on white marlin indicates that spawning may occur several times per year (Bromhead et al. 2004). Striped marlin exhibit a low degree of sexual dimorphism but females are generally larger than males but not to the same extent as blue marlin and black marlin (*see* Chapter 2).

Water temperature may influence the location of spawning grounds as most larvae are collected in sea surface temperatures $\geq 24^{\circ}C$ (Ueyanagi & Wares 1975). The majority of larvae recoveries occur in off shore waters between 25 and $27^{\circ}C$ and during the summer in both hemispheres (Gonzalez-Armas et al. 1999). However, Gonzalez-Armas et al. (1999) recovered striped marlin larvae in the coastal waters of the mouth of the Gulf of California and Leis et al. (1987) collected istiophorid larvae from inshore waters near reefs in the Coral Sea region of Australia. Larvae are usually collected in the upper 5 m of the water column but distribution changes

between night and day and ontogenetic development (Leis et al. 1987; Ueyanagi 1974).

Spawning areas have been identified in the southwest Pacific (Hanamoto 1977); west-central Pacific (Ueyanagi 1974); eastern Pacific (Kume & Joseph 1969 and Gonzalez-Armas et al. 1999); and through out the Indian Ocean (Nakamura 1985). The contribution of individual spawning grounds to the total population unclear but the abundance of juveniles in the north-central to western Pacific suggests this is a major spawning ground (Squire & Suzuki 1990). There is no evidence of striped marlin reproduction near mainland New Zealand. However, one of the closest recorded striped marlin spawning grounds to New Zealand occurs in the Coral Sea near Australia. Female ovaries start to mature in this region during late September or early October (Hanamoto 1977). Spawning peaks in November and December as 60-70% of fish are mature.

The minimum size of mature fish recorded in the Coral Sea is estimated at 1430 mm (eye-fork length) or approximately 1700 mm (lower jaw-fork length) and 36 kg. Ueyanagi & Wares (1975) estimate maturity in the central Pacific Ocean at approximately 1600 mm (lower jaw-fork length). The striped marlin fishing season in New Zealand begins in December and coincides with the end of recorded spawning time in the Coral Sea near. Striped marlin captured in New Zealand are rarely less than 2000 mm (lower jaw-fork length) suggesting that these fish are mature. Age at maturity is unclear but by applying age at length data to size at maturity data it is probable that fish become reproductively active between ages 2 and 4 (Davie & Hall 1990; Skillman & Yong 1976; Ueyanagi & Wares 1975).

1.6 Growth, Size and Age

Striped marlin grow to a larger size than shortbill spearfish but are the smallest and most slender of the three species of marlin occurring in the Pacific and Indian Oceans. Few studies on striped marlin recognize significant sexual dimorphism but some suggest that females may grow to a larger size than males (Pillai & Ueyanagi 1978). Sexual dimorphism for weight and length is apparent in New Zealand's recreational fishery as females are on average 10% longer and 16% heavier than males. Females in New Zealand averaged 106 kg and 2399 mm LJFL in length while males averaged 90 kg and 2305 mm LJFL (*see* Chapter 2). New Zealand is renown for large striped marlin and average weight (104 kg) is significantly greater than commercial and recreational catches from Hawaii (31.9 kg), Mexico (54.7 kg), the Indian Ocean (65.0 kg) and southern California (68 kg) (Squire 1983; van der Elst 1990; Dalzell & Boggs 2003; Ortega-Garcia et al. 2003). The world record striped marlin was caught in New Zealand and weighed 224 kg (IGFA 2004). However, a positively identified striped marlin weighing 243 kg was also weighed in New Zealand but the method of recreational capture did not meet the International Game Fish Association (IGFA) rules and thus was disqualified.

Conventional tagging programs have provided insight on age and growth of many pelagic fishes but striped marlin have one of the lowest recovery rates of all billfishes (Ortiz et al. 2003; *see* Chapter 3). Age estimates have been made using growth rings in spines and otoliths or statistical modeling of length frequencies but these methods are not validated. Davie and Hall (1990) estimated the age of striped marlin in New Zealand using dorsal spine growth rings and found between 2 and 8 bands (ages). Melo-Barrera et al. (2003) identified between 2 and 11 bands (ages) in Mexico and Skillman & Yong (1976) classified up to 12 age groups in Hawaii. von

Bertalanffy growth models predict that striped marlin may grow up to 45% of their total length in the first year of life and weigh 100 kg by age 4 or 5 (Skillman & Yong 1976; Melo-Barrera et al. 2003; *see* Chapter 2).

1.7 Diet

Striped marlin frequently forage on schools of pelagic and epipelagic organisms ranging from squid and nautilus to mackerel and saury (Baker 1966; Morrow 1953; Saul 1983; *see* Chapter 4). Longline commercial fishing vessels have significantly higher catch rates of striped marlin at depths < 150 m, which suggests that feeding occurs most often in the upper level of the water column (Boggs 1992). Although striped marlin are primarily epipelagic predators, benthic and demersal prey items such as rays (Batoidea spp.) are occasionally consumed (Abitia-Cardenas et al. 1997; Baker 1966). Little research has been conducted on the behaviour of striped marlin during feeding but they are believed to be highly visual and solitary predators but have been observed feeding in small groups. Crystalline deposits in iridophores cause an iridescent "lighting up" in the lateral stripes of striped marlin during feeding and may work to disorient prey (Davie 1990).

Striped marlin are opportunistic feeders that rely on food availability rather than on specific prey items. The opportunistic nature of striped marlin is exhibited in stomach contents analysis from New Zealand, which record over 28 fish and 4 cephalopod species. Off the coast of New Zealand the most frequent prey items of striped marlin are saury (*Scomberesox saurus*) and arrow squid (*Nototodarus spp.*) followed by jack mackerel (*Trachurus murphyi*) (Baker 1966; Morrow 1953; Saul 1984). Saul (1983) found a small variety of prey species in individual striped marlin stomachs from New Zealand, 73% of 147 stomachs contained one or two prey

species. This data suggests that feeding occurs during short intense events rather than continuously through out the day and that digestion is rapid. Specific feeding times have not been identified but catch rates from Australian longline vessels indicate a tendency for daytime feeding (Bromhead et al. 2004).

1.8 Anatomy and Physiology

Striped marlin are large, highly athletic predators which migrate thousands of kilometers each year and their anatomy and physiology have unique attributes which support this demanding life style. Marlin body mass is made up of 57-65 % muscle which is supplied with blood from a four chambered heart consisting of a sinus venosus, atrium, ventricle and bulbus arteriousus (Davie 1990). Striped marlin use ram ventilation to oxygenate their gills which means that water is propelled through the gills as the fish as it swims forward (rather than using the gills to pump water) (Davie 1990). They are designed for fast efficient swimming whereby propulsive thrusts of the axial musculature and caudal fin can propel some Istiophorids as fast as 75 kph (Walters 1962).

Despite the faith of many anglers there exists a large debate on weather or not billfish see colour. Fritsches (2004) identified three visual pigments in striped marlin that provide the "hardware" for colour vision. However, without the ability to study live specimens the question remains unanswered. Striped marlin spend the majority of their time in the light rich pelagic ecosystem and for this reason it is reasonable to assume that striped marlin can see colour. Another intriguing aspect of the eyes of marlin is the presence of a heater organ. The heater organ is also present in the brain of marlin and is made up of highly modified muscle cells that produce heat by ATP hydrolysis (Block 1986). The function of the eye and brain heaters are not fully

understood but probably allow marlin to occupy regions of cooler water and exploit prey items that do not possess such physiological attributes.

The gastrointestinal tract of striped marlin is similar to that of most top predators and can be described by a large capacity stomach and short intestine (Davie 1990). Large capacity stomachs allow striped marlin to take advantage of patchy feeding opportunities in the pelagic ecosystem. Occasionally, marlin that undergo rapid changes in depth from deep to shallow water will evert their stomach because of an expansion in the swim bladder. The ability of marlin to evert their stomach may be an adaptation to expel unwanted items such as squid beaks (Davie 1990).

Another area of interest in marlin anatomy is the bill and its use during feeding. Reports of marlin moving their head and bill from side to side in a slashing motion are more common than accounts of prey being speared (Baker 1966). However, large prey items such as mako sharks and tuna have exhibited signs of being speared (Saul 1983). Numerous researchers have documented marlin with broken bills and none has identified fish as being in less than average condition (Morrow 1951). These findings suggest that the bill may occasionally facilitate prey capture but marlin are not dependent on it for feeding.

1.9 Commercial Fisheries

Striped marlin are commercially fished throughout most of their distribution but commercial fishing for marlin has been prohibited in New Zealand since 1987 (Holdsworth et al. 2003). Striped marlin are caught as bycatch in New Zealand but all must be released dead or alive. Surface longlining is the primary method of capture but purse seining and gill netting account for a small proportion of catch (Bromhead et al. 2004). Striped marlin are regularly targeted by Japanese, Korean and Taiwanese

fleets mainly in the east central and northwest Pacific Ocean (Bromhead et al. 2004) However, countries like the United States, Belize, South Africa and Australia have also developed longline fisheries for tuna and swordfish in which striped marlin are caught.

Striped marlin is more valuable than blue or black marlin in the sashimi markets of Japan but yields a lower price than other fish such as the southern bluefin tuna (*Thunnus maccoyii*). The global catch of striped marlin peaked during the late 1960's at over 20,000 metric tonnes but has decreased to around 12,000 metric tonnes per annum since 1990 (FAO 2004). Underreporting of catch and grouping all billfish into one catch statistic has created a great deal of concern about the validity of information provided by commercial fishers. The uncertainty about catch statistics also causes concern about the status of the population and at present time the sustainability of the Pacific Ocean fishery is unknown.

Commercial longlining began in the southwest Pacific around 1952 as Japanese fleets targeted albacore (*T. alalunga*) and yellowfin tuna (*T. albacares*). Fleets soon moved south targeting bluefin and bigeye tuna (*T. obesus*) and the first record of longlining in New Zealand's present day exclusive economic zone (EEZ) was 1955. Fishing effort for striped marlin in the southwest Pacific Ocean approached 30 million hooks per year by 1960 and nearly 175 million hooks per year by 2001 (Figure 1.5). The catch per unit effort (CPUE) in the southwest Pacific, however shows a declining trend from 3-6 striped marlin per 1000 hooks in the 1950's down to less than 0.5 during the 1990's until present (Figure 1.6). CPUE and overall effort in New Zealand's EEZ show a similar declining trend but there is more variability between years (Figure 1.7; 1.8). The variability may due to differences in striped marlin abundance but are likely also related to their seasonal availability.
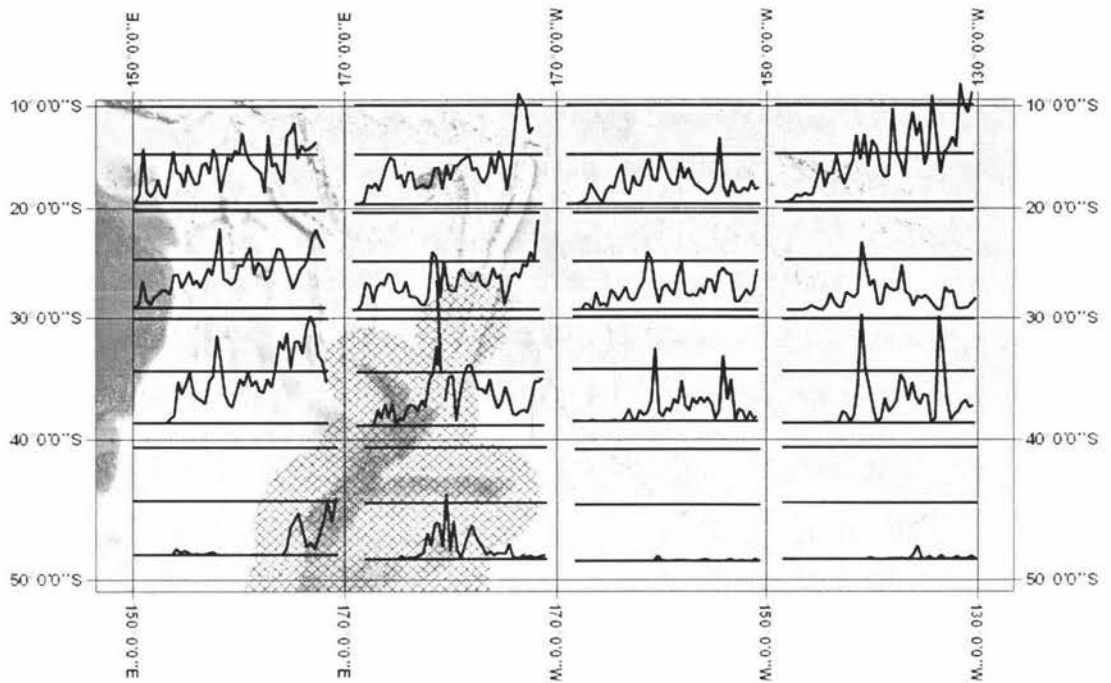
Figure 1.5 Number of longline hooks set for striped marlin by year in the southwest Pacific Ocean for 10 ° latitude and 20° longitude blocks (years 1952-2001, X axis of each block), (grid lines at 10 and 20 million hooks, Y axis of each block). Hatched represents the New Zealand EEZ. Data collected from the Ocean Fisheries Programme (OFP) of the Secretariat of the Pacific Community (SPC).
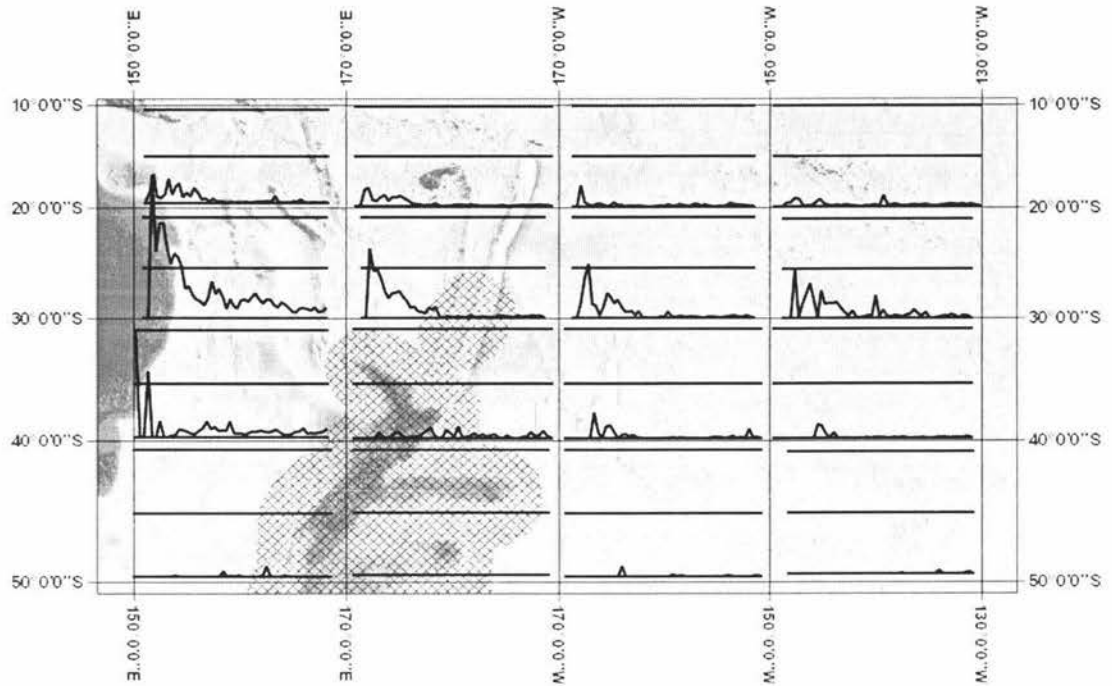
Figure 1.6 Striped marlin longline catch per unit effort (CPUE) in the southwest Pacific Ocean for 10 ° latitude and 20 ° longitude blocks (years 1952-2001, X axis of each block), (grid lines at 3 and 6 per fish per 1000 hooks, Y axis of each block). Hatched area represents the New Zealand EEZ. Data collected from the Ocean Fisheries Programme (OFP) of the Secretariat of the Pacific Community (SPC).
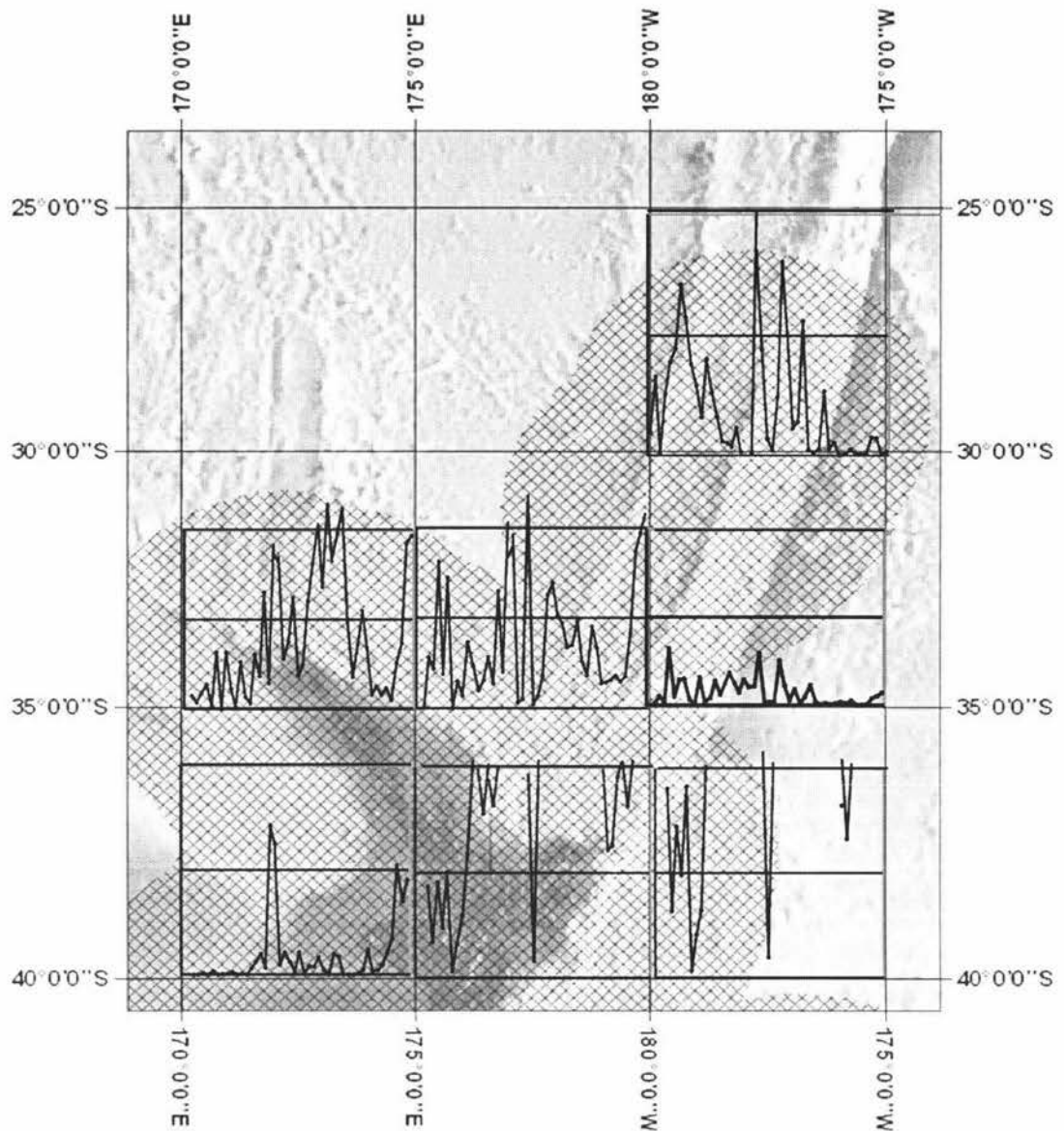
Figure 1.7 Number of longline hooks set for striped marlin by year in the New Zealand EEZ for 5 ° latitude and 5° longitude blocks (years 1952-2001, X axis of each block), (grid lines at 1 and 2 million hooks, Y axis of each block). Hatched area represents the New Zealand EEZ. Data collected from the Ocean Fisheries Programme (OFP) of the Secretariat of the Pacific Community (SPC).
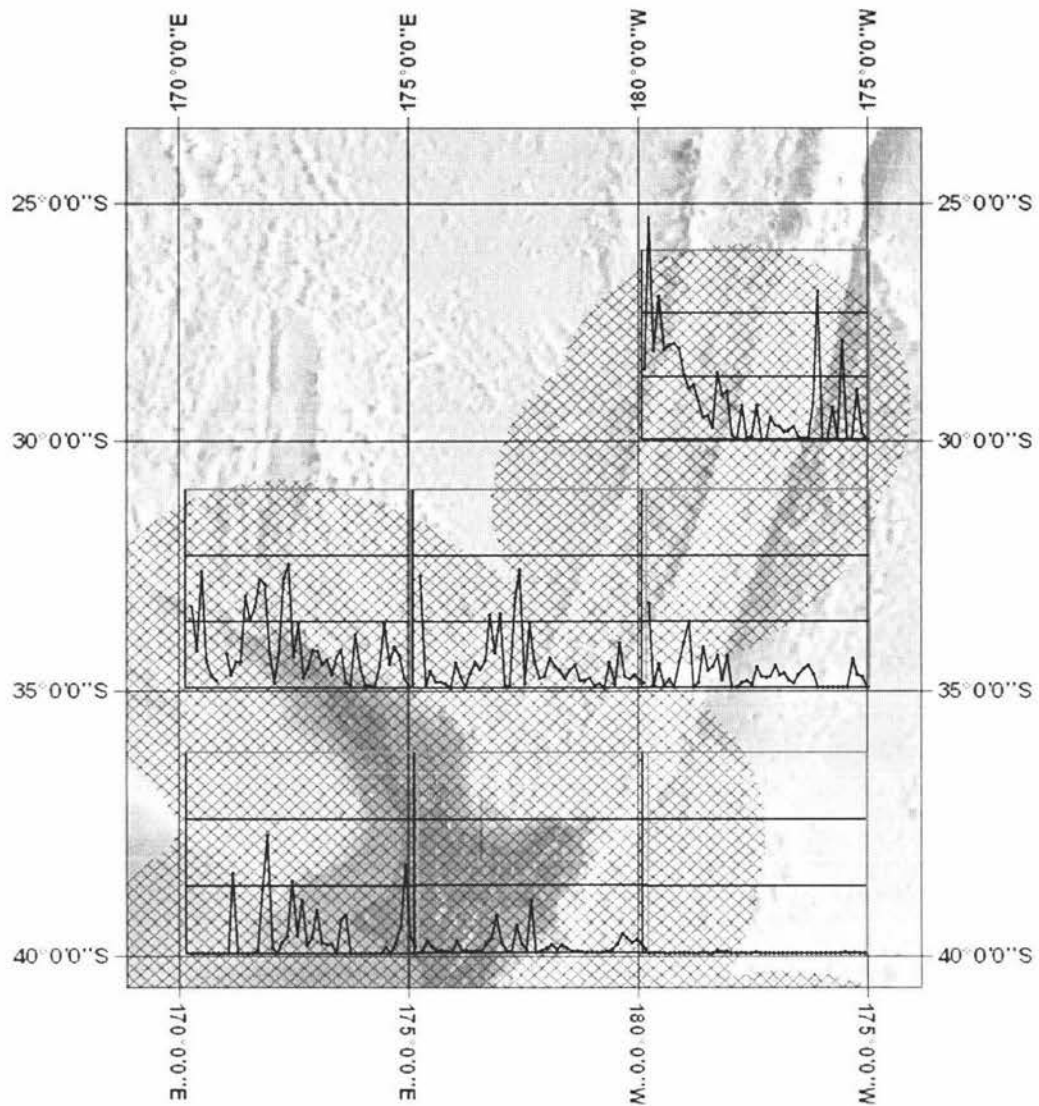
Figure 1.8   Striped marlin longline catch per unit effort (CPUE) in the New Zealand EEZ for 5° latitude and 5 ° longitude blocks (years 1952-2001, X axis of each block), (grid lines at 1, 2 and 3 fish, Y axis of each block). Hatched area represents the New Zealand EEZ.   Data collected from the Ocean Fisheries Programme (OFP) of the Secretariat of the Pacific Community (SPC).

1.10 Recreational Fisheries

Striped marlin are one of the worlds most sought after big game fishes and are targeted by sport fishers throughout the Pacific and in several locations of the Indian Ocean (van der Elst 1990; Whitelaw 2003; Kopf et al. unpublished). Major recreational fisheries exist in northern New Zealand; Cabo San Lucas, Mexico; Hawaii, United States; southern California, United States and New South Wales, Australia. Most fisheries are seasonal with peak catches occurring during the summer in both hemispheres. The New Zealand striped marlin fishery is unique because it is a recreational fishery only as commercial catch of marlin has been prohibited since 1987, and all commercial fishers must release marlin dead or alive within the EEZ.

The New Zealand fishery generally extends 25 km offshore while most fishing occurs within 16 km of the coast (Saul 1983). The first recorded striped marlin catch by rod and reel in New Zealand occurred in 1915 and by 1924 a marlin fishing club (The Bay of Islands Swordfish and Mako Shark Club) was established (Saul 1983). The fishery gained worldwide recognition by visits from the American author and fisherman, Zane Grey who deemed New Zealand the "Anglers Eldorado". This fishery consistently produces some of the worlds largest striped marlin and is the location of 16 of the 22 line class world records (IGFA 2004; *see* Chapter 2).

Until the late 1970's the primary method of capture was drifting or trolling baits but has subsequently changed to trolling surface lures at speeds of 4 to 10 knots (Holdsworth & Saul 2004). Tag-and-release programmes in which fishers tag, release and most importantly recover striped marlin have been adopted by most major recreational fisheries including New Zealand. However, recovery rates of striped marlin are among the lowest of all pelagic fishes and are less than 1% (183/25,555) (*see* Chapter 3). The New Zealand tagging programme has been in place since 1974

and approximately 68 striped marlin have been recovered while 12, 418 have been released. In 2004, 1019 striped marlin were tagged and released which accounts for approximately 65% of the recreational catch (Holdsworth & Saul 2004).

The New Zealand recreational fishing season begins in December and persists through until May. The number of reported striped marlin catches in New Zealand's recreational fishery generally ranges from 1200 to 2000 per annum but has a high seasonal variability. The catch rate in New Zealand's recreational fishery ranges from 0.053 to 0.269 striped marlin per charter boat day (Holdsworth et al. 2003). The exact number of private boats which fish for marlin is unknown but there are approximately 100 professionally licensed vessels between 11 and 18 metres in length (Kingett-Mitchell 2002). This fishery generated an estimated $17 million NZD in gross output during the year 2000-2001 in which spending was negatively affected by poor weather (Kingett-Mitchell 2002).

Chapter 2

Size trends and growth of striped marlin in the New Zealand recreational fishery from 1925 to 2003

2.1 ABSTRACT

Size trends and growth of striped marlin landed in the New Zealand recreational fishery were evaluated using club records from the Bay of Islands Swordfish Club (BOISC) from 1925 to 2003 (n = 15,114) and biological samples from northern New Zealand collected from 1985 to 1994 (n = 684). Average weight (kg) ± S.E. of striped marlin from the BOISC declined 6 - 9 kg every 20 years between 1925 (124.2 ± 1.0 kg) and 2003 (100.1 kg ± 0.4). Weight (kg) (P = 0.011) and condition (Wr) (P < 0.001) increased throughout the recreational fishing season (December - May). No differences were observed in the Lower Jaw- Fork Length (LJFL, mm) – weight (kg) (L-W) relationship between sexes (P = 0.074) but average weight of females (106.2 ± 1.1 kg) was significantly greater than males (90.2 ± 1.2 kg) (P < 0.001). Negative allometric growth (W = 2E -08 LJFL^ 2.88) was recorded for all striped marlin. Individual growth was modeled by fitting backcalculated LJFL to 8 age classes derived from dorsal spine measurements (n = 94) using the von Bertalanffy growth equation (r^2 = 0.96). The parameters estimated in the von Bertalanffy growth model were: L∞=3010 mm, K=0.22 annual and t_0= -0.04.

2.2 INTRODUCTION

Striped marlin are distributed throughout temperate and tropical regions of the Pacific and Indian Oceans and are frequently targeted by recreational fishers because of their size, speed, and athletic abilities (Davie 1990). Striped marlin are the most widely distributed of all billfish and make up 96% of billfish catch in the New Zealand East Northland recreational fishery (Nakamura 1985; Holdsworth et al. 2003; Figure 2.1).
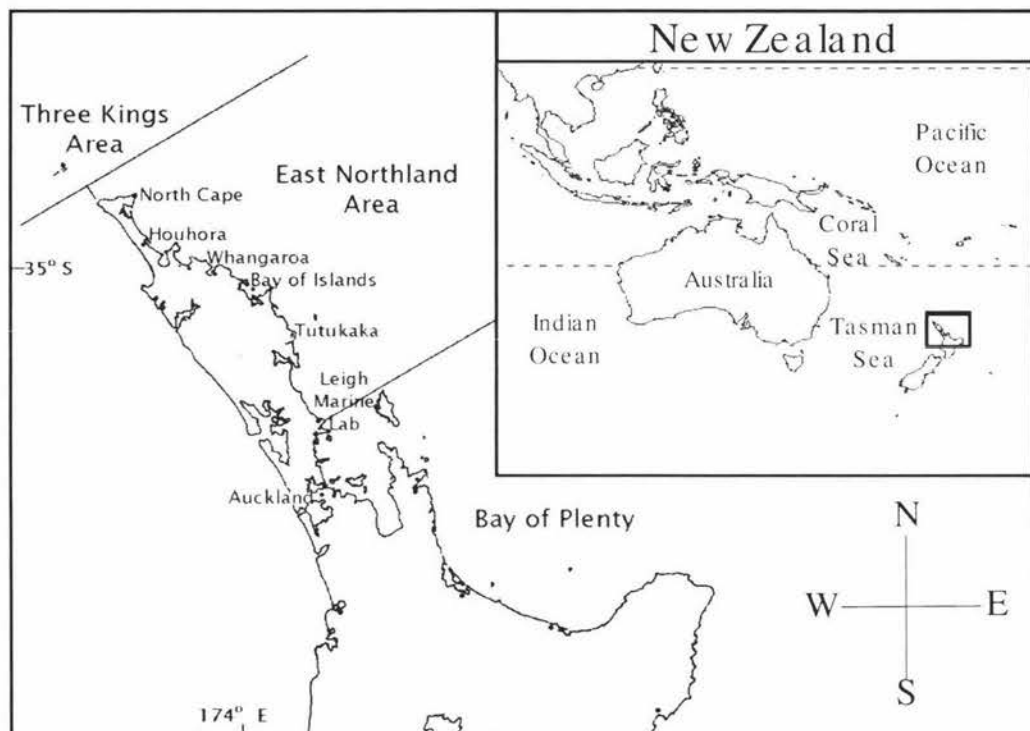
Figure 2.1 Marlin fishing regions of New Zealand and relation to the wider Pacific and Indian Oceans.

This recreational fishery is renowned for large striped marlin and is the location of 16 of the 22 line class world records, including the all-tackle record of 224.1 kg (IGFA 2004). The economic contribution of the billfishery is important to the local tourist industry in Northland and Bay of Plenty regions by generating an estimated $17 million NZD from a total expenditure of $65 million annually (Kingett-Mitchell 2002). New Zealand has a non-commercial striped marlin fishery as

commercial landing of all billfish except for swordfish has been prohibited since 1987.

Recent attempts to identify stock structure of striped marlin in the Pacific Ocean have focused on molecular science or standardisation of Catch Per Unit Effort (CPUE) data and some have revealed contrasting results from the single Pacific-wide stock theory (Skillman 1990; Graves & McDowell 1994; Graves & McDowell 2003). Mitochondrial DNA of striped marlin indicates spatial partitioning and shallow but statistically significant population structure within the Pacific Ocean (Graves & McDowell 2003). More traditional morphological studies have also revealed differences in striped marlin between regions of the Pacific Ocean. Using a morphological character index, Morrow (1957) was able to effectively separate 73% of striped marlin between Peru and New Zealand/Australia. However, the two most likely theories regarding stock structure of striped marlin are: 1) Single unit-stock or 2) Two stocks, one in the north and south Pacific, roughly divided by the equator (Hinton & Bayliff 2002). If variations in genetic makeup and CPUE are significant enough to warrant stock separation there may also be differences in ages, growth rates, length frequencies, and condition factors of striped marlin between stocks. These are not new methods for population assessment but are vital parameters, which are little studied in New Zealand and the wider southwest Pacific Ocean (*see* Boggs 1990).

There is a growing body of untapped information gathered by recreational billfishing clubs that is a valuable source of biological data, particularly in well established fisheries such Kailua-Kona (Hawaii, U.S.A.), Bimini (Bahamas), Cairns (Australia), and the Bay of Islands (New Zealand) (Farman 1990). The Bay of Island Swordfish Club (BOISC) in New Zealand has kept records beginning in 1925 of each

striped marlin caught by members and non-members fishing out of this port. Records were not kept only during the Great Depression and World War II. The BOISC database may be one of the world's oldest and most comprehensive recreational fishing databases for striped marlin which has 15,114 records of date and weight from 1925 to 2003. The first objective of this study was to analyze the temporal variation in weight and size distribution of striped marlin from the BOISC database.

The second objective of this study was to identify the Lower Jaw-Fork Length (LJFL, mm) – weight (kg) (L-W) relationship, condition (Wr) and individual growth of striped marlin from biological samples collected in New Zealand from 1985 to 1994. Assessment of L-W relationship, condition, and growth of striped marlin have been reported in several other studies but few have been conducted in the south or west Pacific Ocean (Kume & Joseph 1969; Merrett 1971; Pillai & Ueyanagi 1978; Ponce Diaz et al. 1991; Torres & Pauly 1991). Skillman & Yong (1976) used cohort analysis to model progression in age classes and used the von Bertalanffy growth model to describe growth of striped marlin in Hawaii. Melo-Barrera et al. (2003) were the first to model individual striped marlin growth based on hard structures (dorsal spines) but did so in Mexico. Davie and Hall (1990) estimated ages of striped marlin in New Zealand but did not model growth. Research on size and growth of striped marlin in the southwest Pacific Ocean was conducted in the 1930's and 1950's with substantially smaller sample sizes compared to the present study (Gregory & Conrad 1939; Morrow 1952(A); Morrow 1957). This study provides several vital statistics and historical size changes of striped marlin in the New Zealand recreational fishery.

2.3 METHODS

2.3.1 Bay of Islands Swordfish Club (BOISC) Weights

Striped marlin (n = 15,114) were captured by members and non-members of the BOISC in New Zealand from 1925 to 2003 and weight (total weight, ± 0.5 kg) was recorded. Starting in 1976, weight estimates made at the time of tag and release (n = 4454) were included the database. Tag and release was encouraged by the New Zealand Big Game Fishing Council who introduced a voluntary minimum size limit of 90 kg in 1988.

2.3.2 Length-Weight Relationship and Condition

Measurements (n = 684) of weight (total weight, ± 0.5 kg), Lower Jaw-Fork Length (LJFL, ± 10 mm) and sex of striped marlin captured by anglers fishing from the Bay of Islands, Whangaroa, and Tutukaka were recorded between 1985 and 1994 (Figure 1). Average size by sex was calculated from data pooled across years. L-W relationships were estimated only from lengths ranging 2000-2830 mm (LJFL) and weights (kg), which were fitted to the power function described in Ricker (1975). The b value represents the slope of the L-W relationship and is the isometry coefficient. The isometry coefficient b = 3 indicates isometric growth, b > 3 positive allometric growth, and b < 3 negative allometric growth (Ricker 1975). Change in b values may occur annually, between sexes, or locations and can be used to compare general condition within a fish species (Ricker 1975).

$$(W = aL^b)$$

W = Weight; **L** = Lower Jaw-Fork Length; **a** = Regression coefficient; **b** = Isometry coefficient

Monthly condition of individual striped marlin was evaluated using a relative weight (Wr) index (Wege & Anderson 1978). Striped marlin (n = 449) measured in the L-W relationship during January through April were used to develop equations. Other months were not used as result of insufficient sample sizes and because December through May is the usual length of the recreational fishing season. Wr values of 100 are equal to weight predicted by the regression analysis. Wr values greater than 100 indicate weight is greater than what is predicted by the regression and conversely for values less than 100.

$$(Wr = W/Ws *100)$$

Wr = Relative weight; **W** =Individual weight; **Ws** = Length specific weight standard predicted by regression

2.3.3 Growth

Using age estimates and measurements of cross sections (n=94) from the third dorsal spine collected by Davie & Hall (1990) a relationship between L and R (R, grouped in 0.5 mm categories) was calculated (Melo-Barrera et al. 2003). Spines that exhibited vascular erosion of the core were excluded from the present analysis, which resulted in a significant relationship between LJFL and spine radius.

$$L = aR^b$$

L = Lower Jaw-Fork Length; **R** = Spine radius; **a** and **b** = Fit parameters of model

Length at age was backcalculated from dorsal spine measurements using an equation described in Ehrhardt (1992) designed to compensate for lengths in underrepresented age groups. This backcalculation technique is suitable for pelagic

game fishes where sampling (recreational fishing) captures a large proportion of old or large individuals.

$$\text{Log } Li = [\log Ri\, (\log L - \log a)/\log R] + \log a$$

Li = Lower Jaw-Fork Length at age; **Ri** = Spine radius at age; **L** = Lower Jaw-Fork Length; **a** = Y axis intercept of (L-R) relationship; **R** = Spine radius

Individual growth was modeled by fitting backcalculated lengths at age to the von Bertalanffy growth equation.

$$Lt = L\infty\,[1 - e^{-k(t-to)}]$$

Lt = Lower Jaw-Fork Length at age t; **L∞** = Asymptotic length; **k** = Annual growth rate; **t** = Age (years); **to** = Age (years) at hypothetical length 0

2.3.4 Statistical analysis

All statistical comparisons were based on 0.05% level of significance. A two-way ANOVA was used to compare temporal differences in mean weights and relative weights. Slope and intercept of L - W relationship between sexes, months and years were evaluated using an ANCOVA. A simple regression analysis was used to determine the L - R (L, Lower Jaw-Fork, mm and R, Spine Radius, mm) relationship (Davie & Hall 1990). Parameters of the von Bertalanffy growth model were estimated using the Gauss-Newton, NLIN procedure in SAS, Version 8.2.

2.4 RESULTS

2.4.1 Weight

Table 2.1 summarises striped marlin weights in the BOISC from 1925 to 2003 (*see*

Appendices A and B for weight frequency distributions).

Table 2.1 Total, monthly and 20 year summary of striped marlin body weight (kg) from the Bay of Islands Sword Fishing Club (BOISC) from 1925 to 2003 with modal age (years) classes predicted by the von Bertalanffy growth model. Means ± S.E. June-November (n=102) not included.

		n	Body Weight (kg)	Range Weight (kg)	Mode Age (Years)
All		15114	104.9 ± 0.2	32.0 – 243.6	7
Month	December	160	98.1 ± 2.0	40.0 – 182.1	6
	January	2048	99.6 ± 0.5	32.0 – 189.6	7
	February	4442	102.1 ± 0.3	33.4 – 243.6	7
	March	4607	105.2 ± 0.3	35.0 – 207.9	7
	April	2806	109.2 ± 0.4	40.0 – 198.0	7
	May	940	114.6 ± 0.4	53.1 – 195.0	8
Year	1925-44	1150	117.9 ± 0.6	58.1 – 193.2	8
	1945-64	4483	112.1 ± 0.3	40.9 – 194.3	7
	1965-84	3530	105.5 ± 0.4	32.0 – 207.9	7
	1985-03	5951	96.6 ± 0.3	33.4 – 243.6	6

All means are cited ± S.E. Average weight of striped marlin progressively declined 6 - 9 kg every 20 years from 1925 to 2003 and was most significant comparing the periods 1925 - 1944 and 1985 - 2003 ($P < 0.001$; Figure 2.2). Significant differences in average weight were also observed comparing the periods from 1925 - 1944 with 1965 - 1984 ($P < 0.001$). The largest positively identified striped marlin was captured in February 1995 and weighed 243.6 kg which would have surpassed the current IGFA world record by nearly 20 kg but was disqualified because of the method of capture.
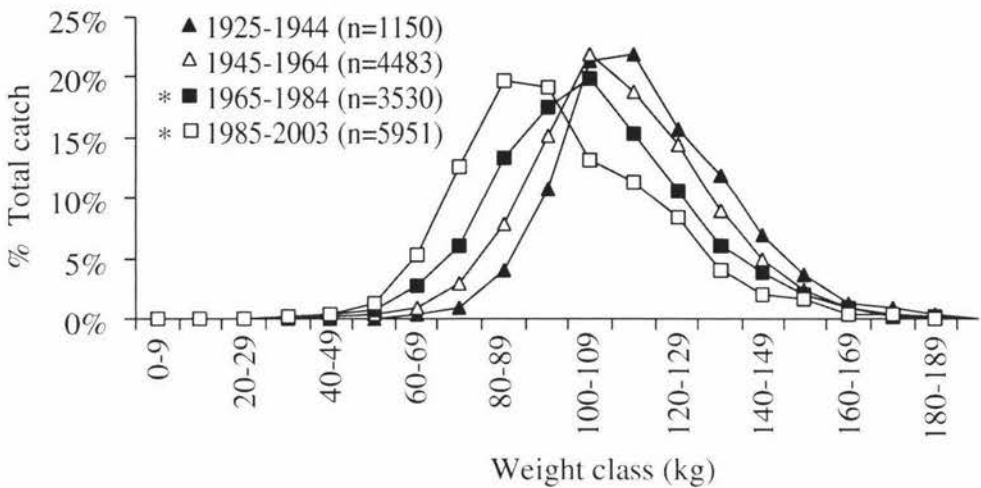
Figure 2.2 Twenty year period weight (kg) distributions of striped marlin from the Bay of Islands Swordfish Club (BOISC) New Zealand from 1925 to 2003 (n = 15, 114). * indicates significant difference (P < 0.05) compared to the period 1925 - 1944.
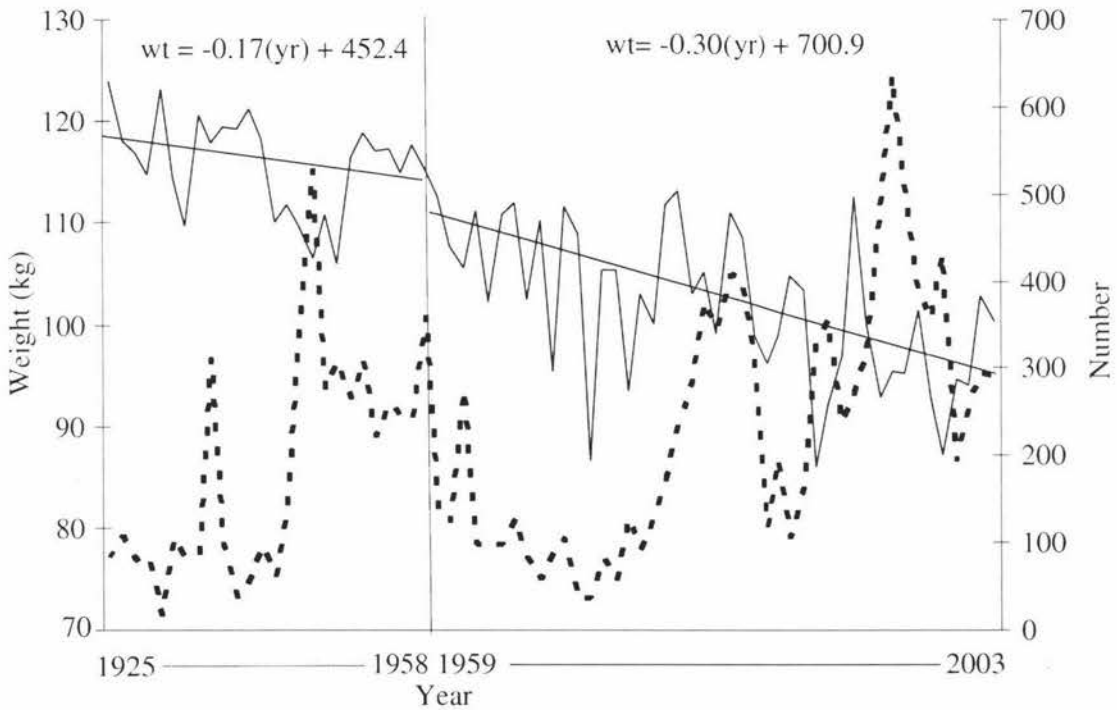
Figure 2.3 Mean annual weights (kg) (—) and number (▬▬▬) of striped marlin from the Bay of Islands Swordfishing Club 1925 to 2003 (n = 15, 114) and trend lines comparing before surface longlining 1925 – 1958 (n = 4805) and during surface longlining 1959 – 2003 (n = 10,309) in the southwest Pacific Ocean.
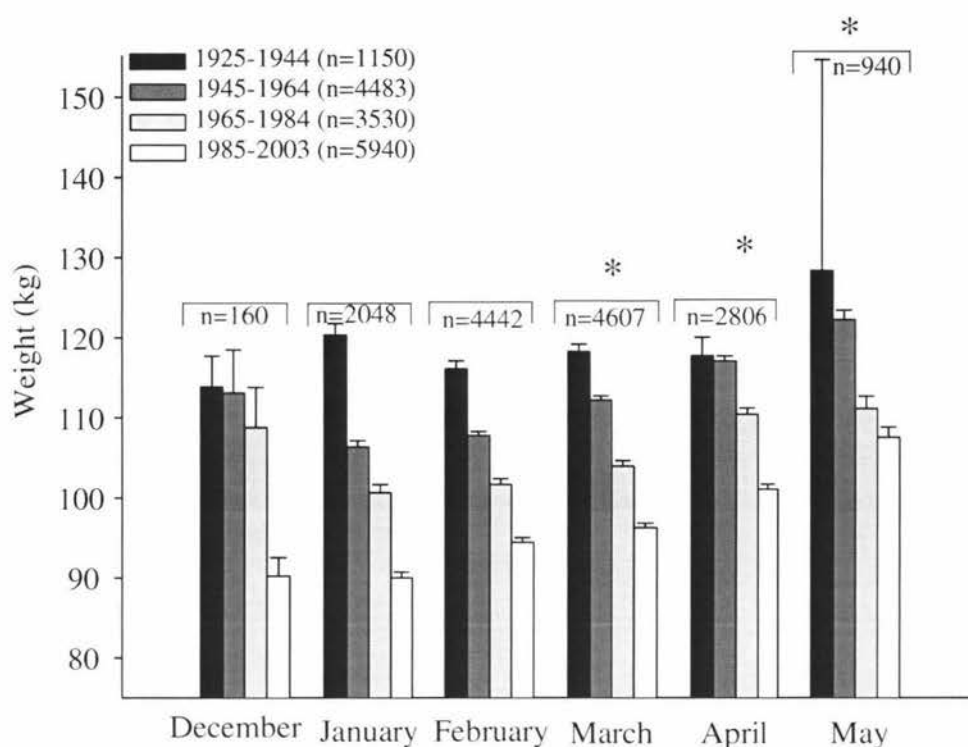
Figure 2.4 Mean monthly striped marlin weight (kg) for 20 year periods in the Bay of Islands Sword Fishing Club (BOISC) in New Zealand from 1925 – 2003 (n=15,114). Means ± S.E. and * indicates significant difference (P < 0.05) from pooled values in January.

Mean annual weight prior to the development of a commercial surface longline fishery in 1958 (114.2 ± 0.2 kg) in the southwest Pacific was significantly greater than after 1958 (100.8 ± 0.3 kg) (P = 0.011; Figure 2.3). The highest mean annual weight after the development of a surface longline fishery was 112.4 kg which occurred in 1978 but the highest mean before was 124.2 kg and occurred in 1925. From 1925 to 1944 the BOISC recorded approximately 6% (63/1150) of striped marlin which weighed less than 90 kg compared to 39% (2248/5951) from 1985 to 2003.

Average weight over 79 years and during most 20 year periods pooled by month increased from January (99.6 ± 0.5 kg) to May (114.6 ± 0.4 kg) (P = 0.013, Figure 2.4). Significant differences in pooled weight by month were also recorded by comparing January with March (P =0.044) and April (P = 0.025). Early records of

weight (1925-1964) show a trend for capture of large + 130 kg fish in December which is observed in the high mean weights during this time. Along with the increase in weight throughout the recreational fishing season (excluding December) there is a steady decline during all 20 year time periods from 1925 to 2003 observed within each month (Figure 2.4).

2.4.2 Length-Weight Relationship and Condition

Table 2.2 summarises lengths, weights and their relationships for striped marlin in New Zealand from samples of landed fish from 1985 to 1994 (n=684). Modal length of striped marlin was 2400 - 2499 mm LJFL and weight was 100-109 kg (Figure 2.5; 2.6). Approximately 99% of striped marlin landed in New Zealand's recreational fishery during this time were greater than 2000 mm LJFL and 50% were
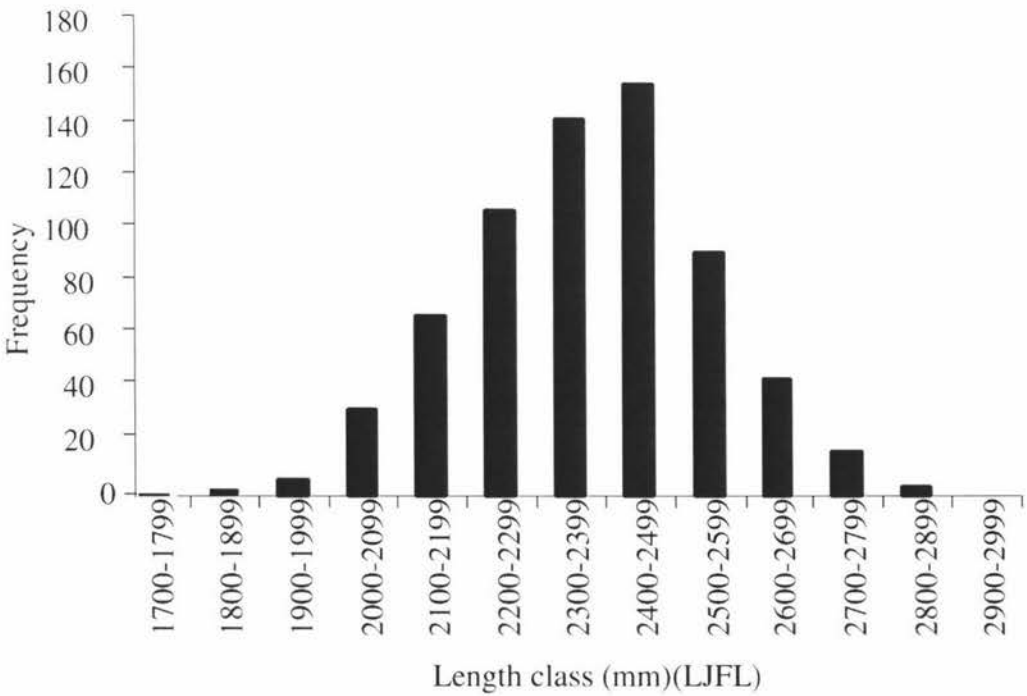
Figure 2.5 Lower Jaw-Fork Length mm (LJFL) frequency of striped marlin collected from 1985 to 1994 (n=684).

greater than 2380 mm LJFL. Average weight of females (106.2 ± 1.1 kg) was

significantly greater than males (90.2 ± 1.2 kg) (P < 0.001) but length was not

significantly different between sexes, months or years. Slightly fewer males (n = 295)

were captured compared to females (n = 395) which resulted in a 3:4 male to female

sex ratio.
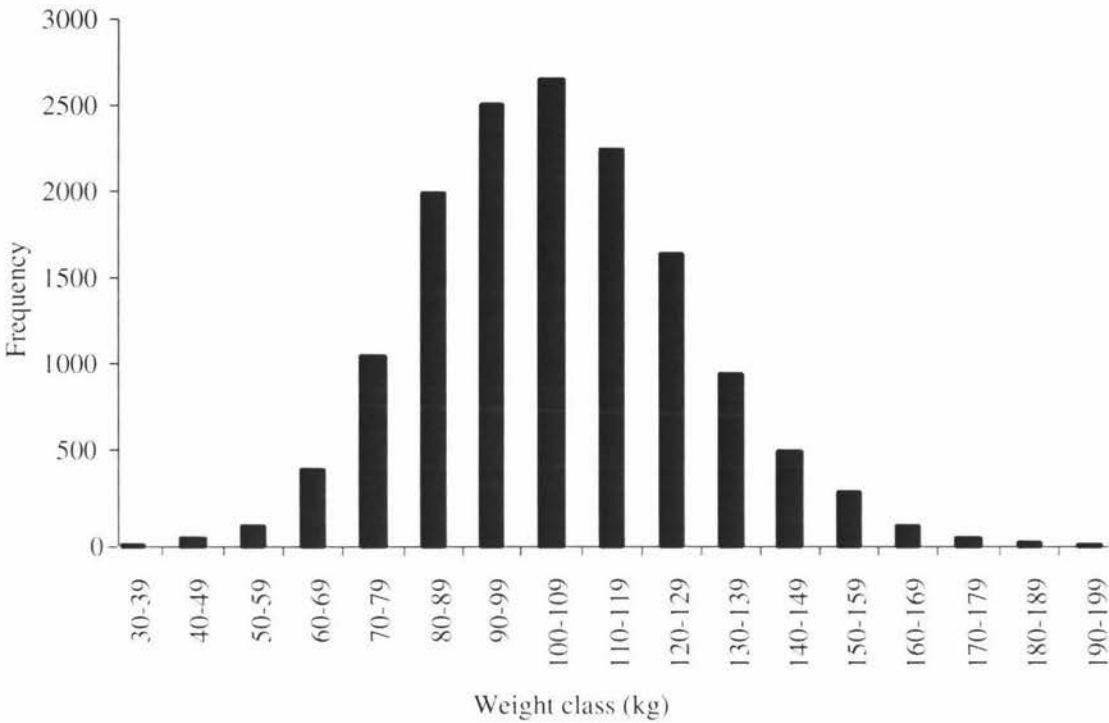
Figure 2.6 Weight (kg) frequency of striped marlin in the Bay of Islands Swordfish Club (BOISC) in New Zealand from 1925 to 2003 (n=15, 114).

There was no difference in L-W coefficients between sexes (P = 0.074), which

resulted in the single negative allometric L-W equation: W = 2E -08 LJFL^ 2.88

(Figure 2.7). However, there was a significant increase in L - W coefficients (P= 0.030) and relative weight (P < 0.001) from January to April (Figure 2.8). Significant

differences in relative weight were also observed comparing January with February (P =0.014) and March (P < 0.001).

Table 2.2 Total, sex, and biennial summaries of striped marlin body mean weight (kg), lower jaw-fork length (LJFL), length-weight relationship parameters and relative weight (Wr) from 1985 to 1994 in New Zealand. Means ± S.E.

		n	Body Weight (kg)	LJFL (mm)	Range LJFL (mm)	r^2	a	b	Relative Weight (Wr)
All		684	99.4 ± 0.9	2361 ± 10	1050 - 2830	0.78	2 E -08	2.88	101.9 ± 0.8
Sex									
	F	395	106.2 ± 1.1	2399 ± 11	1050 - 2830	0.74	2 E -08	2.89	104.9 ± 1.1
	M	289	90.2 ± 1.2	2305 ± 8	1760 - 2790	0.79	2 E -08	2.88	98.4 ± 1.3
Month									
	Jan.	61	96.9 ± 3.4	2382 ± 7	1760 - 2590	0.90	2 E -08	2.86	95.1 ± 1.2
	Feb.	205	100.1 ± 1.9	2383 ± 13	1050 - 2770	0.80	4 E -09	3.08	99.5 ± 0.9
	Mar.	220	101.8 ± 1.6	2371 ± 11	2170 - 2830	0.80	7 E -09	3.00	101.5 ± 0.8
	Apr.	87	108.3 ± 2.7	2385 ± 7	2050 - 2720	0.85	5 E -10	3.35	109.4 ± 3.4
Year									
	1985	64	102.5 ± 2.5	2415 ± 17	1050 - 2700	0.85	2 E -09	3.16	104.6 ± 4.7
	1987	137	99.9 ± 2.1	2398 ± 22	1220 - 2830	0.66	1 E -06	2.33	99.5 ± 1.9
	1989	177	89.1 ± 1.7	2312 ± 3	1760 - 2710	0.84	8 E -09	2.98	99.1 ± 1.1
	1991	80	103.5 ± 1.4	2394 ± 5	2110 - 2730	0.77	4 E -08	2.80	103.2 ± 0.8
	1993	226	107.4 ± 1.4	2462 ± 9	2030 - 2820	0.67	2 E -07	2.57	101.2 ± 1.1
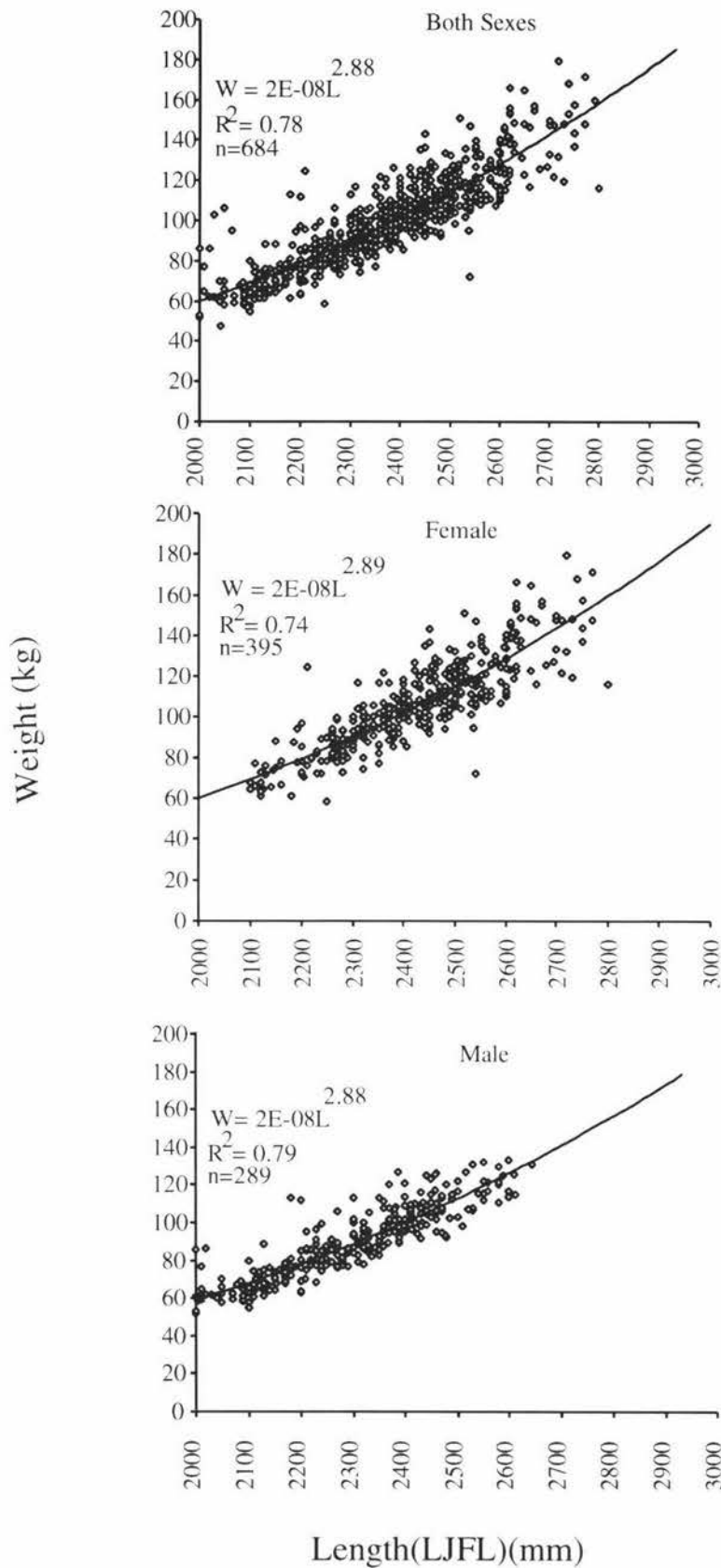
Figure 2.7 Lower Jaw-Fork Length mm (LJFL)-Weight relationship for female (n=395) and male (n=289) striped marlin in New Zealand (1985- 1994).
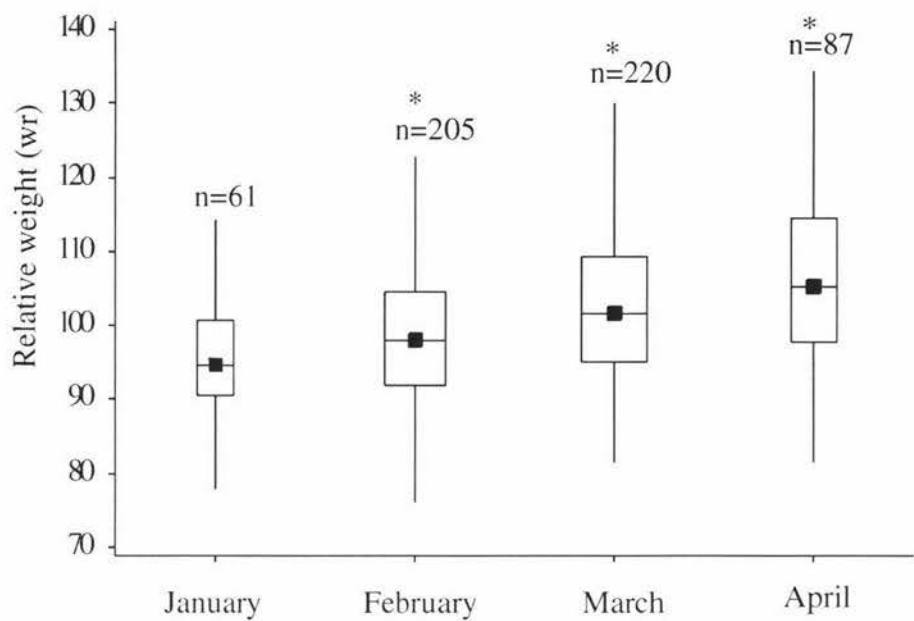
Figure 2.8 Relative weight (wr) for striped marlin (n=573). Median, interquartile and outlier range. * indicates significant difference (P < 0.05) from January.

2.4.3 Growth

Davie and Hall (1990) estimated 8 age classes from 173 dorsal spines and after excluding spines with vascular erosion of the core, 94 spines were used. A significant relationship (P = 0.010; r^2 = 0.83) was identified between LJFL and spine radius, which justified using dorsal spine age measurements to describe growth (Figure 2.9). Backcalculated LJFL at age data were applied to the von Bertalanffy growth model (r^2 = 0.96) and the following parameters were obtained: L∞=3010 mm, K=0.22 annual, and t_0= -0.04 (Table 2.3).

Table 2.3 von Bertalanffy growth estimates from New Zealand (Present study), Mexico (Melo-Barrera et al. 2003) and Hawaii (Skillman & Yong 1976) ± S.E.

Location	n	Sex	L ∞ LJFL (mm)	to (years)	k (annual)	Mode Age	Max Age
New Zealand	94	M-F	3010 ± 253	-0.04 ± 0.03	0.22 ± 0.12	7	8
Mexico	399	M-F	2210	-1.6	0.23	7	11
Hawaii	-	M	2774 - 3144	-0.521	.315- .417	-	12
Hawaii	-	F	2887 - 3262	0.136	.696- .709	-	11

Striped marlin in New Zealand from 1985 to 1994 grew an estimated 21% L∞

(616 mm) in the first year of life, 16% (472 mm) in the second year of life, and 5%,

(151 mm) by age eight (Figure 2.10). The modal age class from 1925 to 2003 in the

BOISC as predicted by the von Bertalanffy growth model was seven. The predicted

modal age from 1925 to 1944 was 8 years and was reduced to 6 during 1985 to 2003

(Table 2.1).
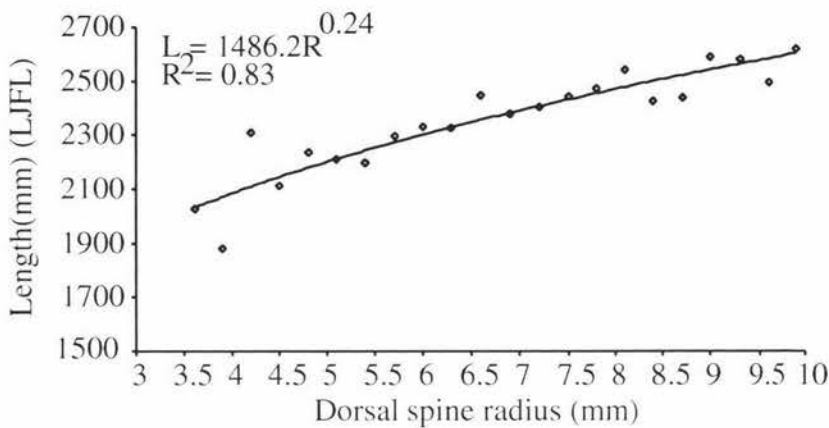
Figure 2.9 Dorsal spine radius (mm) and Lower Jaw-Fork Length (mm) relationship for (n=94) striped marlin in New Zealand.
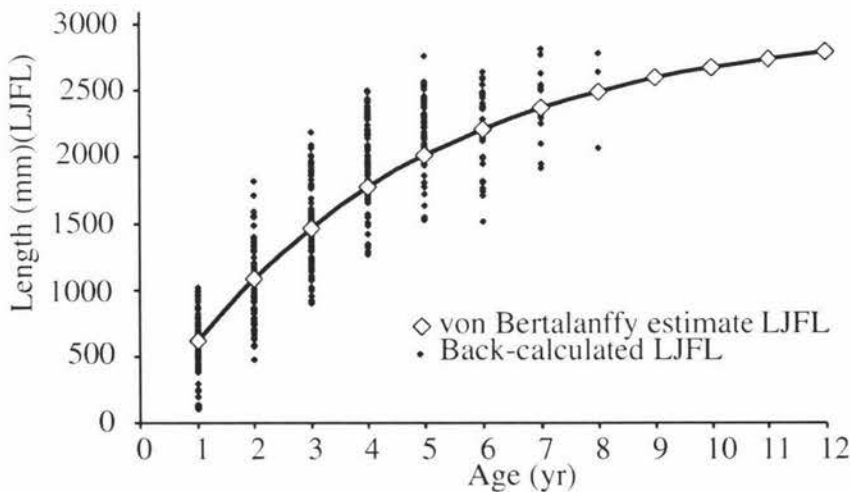
Figure 2.10 Lower Jaw-Fork Length mm (LJFL) at age (year) of striped marlin in New Zealand (n = 94) predicted by the von Bertalanffy growth model with back-calculated lengths.

2.5 DISCUSSION

The Pacific Ocean was a virgin striped marlin fishery in the 1920's and population characteristics during this period provide a standard by which billfish fisheries of today may be assessed (Figure 2.3). Average weight of striped marlin in New Zealand has declined during the past 79 years and there is a negative size shift in weight distribution (Table 2.1; Figure 2.2). A voluntary size minimum of 90 kg was set in 1988 for recreational fishing clubs in New Zealand and changes in the proportion of fish captured above and below this size limit is of particular interest. From 1925 to 1944 the probability of capturing a striped marlin < 90 kg was only 6% but from 1985 to 2003 the probability increased to 39% (Figure 2.2).

The expansion of surface longline fishing is perhaps a contributing factor to the decline in mean annual size but there may also be compounding variables such as broad scale changes in ocean temperature and current. As New Zealand is on the southern range of the distribution for striped marlin oceanographic changes my affect this fishery more than in tropical areas that have consistently high sea surface temperatures. Changes in recreational fishing areas and practices from drifting near reefs with baits in the early years versus trolling lures long distances more recently may also have an effect on the sizes of striped marlin over the 79 year time period.

One indication that factors aside from longlining have affected the average size of striped marlin in New Zealand is the period of low mean weights in the late 1940's and early 1950's before surface longliners moved into the southwest Pacific (Figure 2.3). While these years produce a downward trend in the mean weight regression between 1925 and 1958 it should be noted that for seven years in the 1950's mean weight per season was consistently greater than 115 kg which is similar to early seasons of the 20's and 30's. Since 1958 there has been a significant decline

in mean weight of striped marlin in the BOISC and distinct increase in the variability between seasons.

Despite these negative shifts in weight, the sizes of striped marlin from New Zealand are consistently larger than from most other fisheries. The average weight of striped marlin in New Zealand over the 79 year time period (104.9 kg) is much greater than longline and recreational weights from Hawaii (31.9 kg), Mexico (54.7 kg), Indian Ocean (65.0 kg) and U.S.A. (68 kg) (Squire 1983; van der Elst 1990; Dalzell & Boggs 2003; Ortega-Garcia et al. 2003, Figure 2.6). Lengths of striped marlin from New Zealand ranged from 1050-2830 mm (LJFL) and are among the widest range of sizes measured and not estimated (Skillman & Yong 1974; Miayabe & Bayliff 1984; Squire & Susuki 1990; Melo-Barrera et al. 2003, Table 2.2, Figure 2.5). Morrow (1952A) measured a range of 2019-2865 mm (LJFL) for striped marlin in New Zealand. Ponce Diaz et al. (1991) recorded a range of 1075-2255 mm (EFL, Eye-Fork Length) in Mexico and Melo-Barrera et al. (2003) recorded a range of 1600-2650 mm (LJFL) in this same recreational fishery.

The observation of negative allometric growth (b = 2.88) of striped marlin from New Zealand is not significantly different from reports in other regions of the Pacific Ocean and fall with in published ranges (Figure 2.7) (Ponce Diaz et al. 1991; Skillman & Yong, 1974; Melo-Barrera et al. 2003). However, Morrow (1952A) reported isometric body growth of striped marlin from New Zealand in a sample of 49 fish caught at the Bay of Islands. These differences in growth pattern may be the result of sampling error but are minimal even if they do exist. No difference was identified in the L - W relationship between sexes but female striped marlin were on average 9% longer and 16% heavier than males (Table 2.2; Figure 2.7). Skillman & Yong (1976) also found that females were generally longer than males that were

caught in Hawaii. The sexual dimorphism observed in striped marlin is not as distinct as that of blue or black marlin (*Makira nigricans, M. indica*) but may be a consideration in population assessments.

The large average size of striped marlin in New Zealand implies a high proportion of mature (reproductively active) fish. Nakamura (1985) cites size at first maturity of striped marlin in the central Pacific Ocean at approximately 1600 mm (EFL). Using these criteria, more than 98% (671/684) of striped marlin landed in New Zealand between 1985 and 1994 were mature compared to longline catches of 50% in the northwest Pacific, 65% northeast, and 75% in the west central Pacific Ocean (Squire & Suzuki 1990; Figure 2.6). Despite the high proportion of mature fish there is no evidence of reproduction around mainland New Zealand. However, the beginning (December) of the recreational fishing season in New Zealand coincides with the conclusion of known spawning activity in northern (warmer) waters in the Coral Sea near Australia (Ueyanagi & Wares 1975). This correlation along with southward shifts in longline catch rates show a migration of reproductively active striped marlin from northerly waters to New Zealand during the beginning of the austral summer (Squire & Suzuki 1990).

As striped marlin do not spawn near New Zealand, we propose that they migrate to New Zealand in the southern most part of their range to feed. Analysis of recreational catch rates in New Zealand has shown little correlation with environmental factors such as sea surface temperature or the southern Oscillation "El Nino" (Holdsworth et al. 2003). However, changes in condition (Wr) and (b) throughout the fishing season in New Zealand support the notion that striped marlin migrate to New Zealand to feed (Figure 2.8). Condition factors (Wr) significantly increased between January (95.1 ± 1.2) and April (109.4 ± 3.4) and are consistent

with b values in L - W relationships that describe an increase in the isometry coefficient from the beginning to the end of the recreational fishing season (Table 2.2; Figure 2.8). These data support the hypothesis that energetically depleted striped marlin migrate to New Zealand during the 4th quarter of the year to take advantage of abundant food resources and improve condition after spawning.

Large fish (+130 kg) are often captured early (December) and late in the season (May) with higher proportions of small fish landed during the warmers months of January through April. There is however, a general increase in size throughout the fishing season (Figure 2.4). Squire (1983) identified only a small seasonal increase ($\approx$ 4 kg) in size of striped marlin from recreational fishing clubs in southern California. The trend in capture of large fish in the beginning and end of the season in New Zealand may be the result of large striped marlin being more tolerant of cooler waters. Less tolerant smaller fish may migrate to New Zealand with warmer waters during January through April and depart before the waters cool later in the season. Large fish have greater thermal inertia which slows rates of cooling and facilitates body temperature regulation. The large body mass of adult striped marlin may confer advantages over smaller striped marlin which allows them to occupy regions of cooler water such as those surrounding New Zealand. Pillai & Ueyanagi (1978) attributed temporal changes in size structure of striped marlin in the Indian Ocean to reproductive cycles and Ponce-Diaz et al. (1991) found only small differences in size composition and condition of striped marlin throughout the year.

Several studies including the present have used the von Bertalanffy growth model to predict length at age of striped marlin and all have identified high rates of growth (Skillman & Yong 1976; Melo-Barrera et al. 2003, Table 2.3). Davie & Hall (1990) estimated between 2 and 8 age classes of striped marlin in New Zealand using

dorsal spine growth rings, which were used to model growth in the present study. As a result of the significant relationship (r^2=0.83) between LJFL and dorsal spine radius, the spines were used to model growth (Figure 2.9). It is however, important to note that aging methods for marlins including those used in the present study have not been validated. This continues to be a severe handicap and critical area of concern in managing these fisheries. According to the von Bertalanffy growth model, striped marlin in New Zealand reach up to 21% (616 mm) of asymptotic LJFL (3010 mm) in the first year of life (Figure 2.10).

Using the von Bertalanffy growth model to convert modal size classes to age reveals a drop from age 8 in the 1920's and 30's to age 6 in the period from 1985 to 2003 in the BOISC database. These growth estimates are based only from samples during 1985 to 1994 and do not represent actual growth of striped marlin prior to this time.

It may be expected that the large average size of striped marlin in New Zealand is the result of increased age or higher growth rates compared to other regions of the Pacific Ocean. However, the growth rate and modal age class of striped marlin in New Zealand are not greater than those estimated in Mexico and Hawaii (Table 2.3). This difference may be the result of extrapolations of the von Bertalanffy growth curve caused by the relative absence of small striped marlin in New Zealand's fishery. Only 4% (4/94) of striped marlin used in the present study were less than 1900 mm LJFL and estimates from the von Bertalanffy curve may have masked the rapid growth rates of juveniles. Skillman &Yong (1976) indicated that low estimates of growth for striped marlin in Hawaii were attributed to the absence of small fish during sampling. Future age and growth studies in the SW Pacific Ocean may benefit

with an increased sample size and increased proportion of small (< 1900 mm, LJFL) striped marlin.

2.6 MANAGEMENT IMPLICATIONS

The biological findings presented in this study may be used for estimating parameters in stock assessments and in comparing population characteristics of striped marlin from different regions of the Pacific and Indian Oceans. This paper outlines structural components (i.e. L-W relationship, age and growth, temporal size composition) of the striped marlin population that occurs near New Zealand, which are essential in developing models similar to those being used for stock assessments of other pelagic fishes (Labelle & Hampton 2003). Monthly increases in size composition of striped marlin have utility in a population model for estimating recruitment, movement, and recreational fishing selectivity-at-length. The decline in mean size over the past 79 years indicates a considerable change in spawning stock biomass and may have value in specifying a stock-recruitment function. The seasonal size changes observed in New Zealand's fishery may be used to better understand size-specific movements of striped marlin with relation to environmental variables such as sea surface temperature or Southern Oscillation Index.

The development of a stock assessment model for striped marlin is contingent upon the availability of several other important biological inputs not measured in this report. Differences in growth, L-W relationship, condition factors, and size structure of striped marlin between regions of the Pacific Ocean, alone do not imply stock separation. However, these data do provide quantitative results, which fishery managers may use to supplement molecular and catch data to determine stock boundaries and better describe population structure of striped marlin.

Chapter 3

Impacts of capture time, body mass and injury on conventional tag recoveries from striped marlin

3.1 ABSTRACT

Factors influencing tag recoveries from striped marlin in conventional tagging programmes were investigated by combining data gathered from cooperative billfish tagging programmes located in New Zealand, Australia and United States. Comments about capture time (n=10, 339), estimated weight (kg) (n=25,253) and presence of injury (n=502) were compared between recovered (n=183) and un-recovered (n=25,555) striped marlin. The distribution of capture times ($X^2 = 12.824$, df = 6, P = 0.045) and estimated weights ($X^2 = 30.933$, df = 5, P < 0.001) were significantly different between recovered and un-recovered fish. Small (< 30 kg) striped marlin which experienced capture times ranging from 20-29 min had the highest recovery percentage (1.31%). The proportion of tag recoveries was reduced in fish which experienced capture times exceeding 39 min and in fish weighing greater than 89 kg. Injury percentages were highest (7.35%) after long (60 + min) capture times of large (+120 kg) fish. Interestingly, short capture times (<10 min) of small (< 30 kg) fish also resulted in high rates of injury (5.30%). Results from this study show that small and large (14-140 kg) striped marlin which experience short or long (5-75 min) capture times can and do survive after recreational capture and tag and release. However, tag recovery rates and presumably post-release survivorship would improve if more striped marlin were tagged and released which weighed less than 89 kg and were captured in less than 39 min.

3.2 INTRODUCTION

Biology, physiology and behaviour of most fish can be carefully examined in a laboratory or field samples can be gathered with relative ease. In contrast to most fish however, marlin (Istiophoridae) can not easily be sampled or studied and quite often the only information available has come from recreational or commercial fishers. The difficulties associated with sampling and studying billfish are due to the obvious logistical issues of dealing with large animals that are relatively rare but distributed throughout the expanse of the world's tropical and temperate oceans (Prince & Brown 1991). Study of many pelagic shark and tuna species has benefited from their being held in captivity which has enhanced our knowledge of their growth, reproductive behaviours, and physiology (Holland 2003). Billfish however, have not been held in captivity due to their aggressive demeanor, large size and scarcity of suitable aquaria or shore pens. The difficulties associated with sampling and keeping live billfish in captivity have resulted in a small pool of biological information which fishery managers and biologists must gather to design fisheries management strategies.

Tag-and-recovery programmes have filled a particularly important niche for understanding and managing highly migratory species including billfishes. These tagging programmes are voluntary and are conducted by recreational or commercial fishers who tag, release and recover the fish (Ortiz et al. 2003). During 2003-2004, an estimated 65% of all recreationally captured striped marlin in New Zealand were tagged and released (Holdsworth & Saul 2004). These tagging programmes are economically feasible and as long as fish are recaptured they can provide information about individual growth, stock structure, and seasonal migrations. However, low recovery rates in billfish tagging programs have hindered progress in answering

fundamental biological questions necessary for sustainable fisheries management (Holland 2003).

While recovery rates for all billfish are low ($\approx$ 1% - 3%), recovery rates of striped marlin are among the lowest (0.38% - 1.35%) (Ortiz et al. 2003). At the present time the low recovery rates have primarily been attributed to tag shedding and non-reporting of recoveries by commercial fishers (Holland 2003). Another factor influencing recovery rates, particularly in New Zealand and Australia is the large size of the Pacific Ocean and geographical isolation from large scale fisheries which are important to recapturing highly migratory fishes (Ortiz et al. 2003). Under-reporting and tag shedding are large factors that undoubtedly influence tag recovery rates but the survival of tagged and released fish is essential to the success of any catch-and-release programme.

Developments in electronic tagging technology have started to answer questions about factors influencing the survival of captured and released billfish but these techniques are still in developmental stages and are cost prohibitive as each tag may cost upwards of $3000.00 USD (Holland et al. 1990; Pepperell & Davis 1999; Graves et al. 2002; Domeier et al. 2003). Electronic tagging of black marlin (*Makaira indica*) has shown that differences in post-release behaviour may be attributed to exhaustion resulting from extended capture times. Studies on blue marlin (*M. nigricans*) and striped marlin using electronic tags have estimated recreational mortality rates ranging from 11% to 26% (Graves et al. 2002; Domeier et al. 2003).

It has been shown in other marine catch-and-release fisheries that injury rate, time to capture and fish size can influence survival of released fish (Lukacovic & Uphoff 2002; Malchoff et al. 2002). Studies on billfish have found that circle hooks can reduce injury rates and that recreational capture can disturb acid-base balance

which may play a role delayed mortality (Wells & Davie 1986; Prince et al. 2002). Post-release alterations in physiology and survival of billfish may be related to injury, fish size and duration of capture but has not been verified or studied in depth. Bromhead et al. (2004) investigated striped marlin tag returns from Austraila and found that larger (>110 kg) fish were recaptured less frequently than smaller (40-70 kg) fish. However, this was only a preliminary investigation into the effects of striped marlin size on tag returns and was not explored further.

The decision to tag or not to tag a billfish is usually left up to the boat captain but at present time there exists little quantitative information on which to base an informed decision (*see* Prince et al 2002). This chapter presents information about the occurrence of injury and impacts of capture time, and fish size on tag recoveries and presumably post-release survival of recreationally captured striped marlin from three Pacific Ocean tagging programmes: 1) New Zealand Cooperative Billfish Tagging Programme (NZ); 2) New South Wales Fisheries Tagging Program, Australia (NSW) and; 3) National Marine Fisheries Service southwest, Fisheries Science Centre's Billfish Tagging Programme, United States (NMFS).

When billfish are tagged and released participants are encouraged to write comments about the condition of fish, time to capture, estimated weight and any other information about the fish or capture process at the time of release. These data in billfish tagging programmes have usually been lumped into a comments section and little studied but provide an opportunity to assess factors that influence the survival and subsequent recovery of striped marlin. The specific objectives of this study were to: 1) Determine if capture times and estimated weights (kg) on release influence tag recoveries of striped marlin; 2) Determine if the presence or absence of injury is related to capture time, weight or tag recovery (kg).

3.3 METHODS

3.3.1 Data acquisition and management

Information about capture time (min), weight (kg) and injury of striped marlin at release and recovery were gathered from the NZ, NSW, and NMFS tagging programmes. Each record was individually examined and duplicates or outstanding errors were discarded from analysis. The data were compiled into one database and comparisons were made between striped marlin tagged and recovered versus tagged but not recovered and overall recovery rates were calculated. Recovery percentages were calculated by dividing the total number of recoveries by the total number tagged. Quantitative information on survival was derived only from recaptures as the fate of un-recaptured striped marlin was not known.

3.3.2 Capture time analysis

Capture times (min) on first tag and release were pooled into 10 min categories for recovered and un-recovered striped marlin and proportions were compared between seven time categories. It was assumed that the error in recording capture times on release was ≤ 10 min. Capture times were also plotted against estimated weight (kg) on first release for both recovered and un-recovered striped marlin. Recovery rates were calculated by dividing the number of tag recoveries by the total number of fish tagged within each category of capture time. The NSW tagging programme did not record capture times and thus, was not used in this analysis.

3.3.3 Body mass analysis

Weight (kg) estimates on first tag and release were pooled into 30 kg categories for recovered and un-recovered striped marlin and proportions were compared between

six weight categories. It was assumed that the error in weight estimates on release was ≤ 30 kg. Body mass was also plotted against capture time on first release for both recovered and un-recovered striped marlin. Recovery rates were calculated by dividing the number of tag recoveries by the total number tagged in each weight category. Weights (lb) from the NMFS tagging programme were converted into kg.

In a review of release and recovery weights, Squire (1987) found that weight estimates of striped marlin were variable and unsuitable for growth studies. However, grouping estimates of weight into 30 kg categories should buffer much of the associated error of estimates and regardless the data precision necessary for the present analysis is not as high as is needed for growth studies.

3.3.4 Injury assessment

The presence of injury was recorded based on information provided in the comments section noted by the angler at the time of first tag and release. If fish were bleeding, severely fatigued, tagged improperly (i.e. eyes, gills), stomach everted or other significant compromise of condition was noted they were classified as injured. Injury percentages were calculated by dividing the number injured fish in capture time or weight (kg) category by the total number of fish tagged in capture time or weight (kg) category. Injury percentages are relative only to the dataset used in the present analysis and are not absolute measures of the occurrence of injury during recreational angling. The NMFS tagging programme began recording information about fish condition starting in 2001 and thus, only the years 2001-2004 were used in the present study. The NSW tagging programme recorded no comments about fish condition and was not used to calculate injury percentages.

3.3.5 Statistical analysis

Proportions of recovered versus not recovered striped marlin in 10 min capture time and 30 kg weight categories were compared using a Chi-squared test. A Chi-squared test was also used to determine if the proportion of injured striped marlin was equal between recovered and not recovered fish. Mean capture times and weights were compared between recovered and un-recovered fish using a one-tailed Mann-Whitney U test. All comparisons were based on a 0.05 level of significance.

3.4 RESULTS

3.4.1 Data distribution

Table 3.1 summarises release (n = 25,555) and recovery (n = 183) records gathered from the NZ, NSW, and NMFS tagging programmes. Complete records with capture time, estimated weight and fish condition were rare as there were fewer records of capture time compared to weight (Table 3.2; 3.3). Most records of capture time (n = 10,369/10,390) had estimated weights but few of the total estimated weights (n = 10,369/25,253) had associated capture times.

Recreational fishermen tagged 98.6% (12,022/12,201) and recovered 49.1% (28/57) of all striped marlin in the NZ tagging programme. As greater than 98% of all releases were conducted by recreational fishermen, recommendations do not necessarily pertain to commercially released striped marlin with the exception of weight on release.

The NMFS tagging programme provided valuable information on smaller sized (6-50 kg) striped marlin which generally required shorter capture times and had different rates of injury compared to larger fish tagged in the NZ and NSW programmes (Table 3.2; 3.3). The NZ tagging programme contributed to 93%

(468/502) of all injuries, 92% (9605/10,390) of capture times, and 43% (12,343/25,153) of all estimated weights (Table 3.2; 3.3). The NSW tagging programme contributed to 69% (111/162) of all recoveries with estimated weights.

Table 3.1 Dates and numbers of striped marlin tagged and recovered with recovery percentages from three Pacific Ocean tagging programmes.

Agency	Years Used	(n) Tagged	(n) Recovered	Percent Recovered
NZ	1976-2004	12,429	57	0.46
NSW	1974-2004	12,009	118	0.97
NMFS	2001-2004	1117	8	0.71
Cumulative	1974-2004	25,555	183	0.71

New Zealand Cooperative Billfish Tagging Programme (NZ); New South Wales Fisheries Tagging Program, Australia (NSW); National Marine Fisheries Service (NMFS) southwest, Fisheries Science Centre's Billfish Tagging Programme. (Only numbers used for present analysis are included and are not representative of entire datasets)

Table 3.2 Summary of striped marlin capture times and injuries on release in three Pacific Ocean tagging programmes. Mean ± SEM.

Agency	(n)	Mean Capture Time (min)	Range Capture Time (min)	(n) Injured
NZ	9605	36.2 ± 0.02	2 - 375	418
NSW	N/A	N/A	N/A	N/A
NMFS	785	17.1 ± 0.94	1 -173	34
Recovered	51	26.3 ± 2.09	5 - 75	1
Not Recovered	10,339	33.2 ± 0.03	1 - 375	451
Cumulative	10,390	33.2 ± 0.02	1 - 375	452

New Zealand Cooperative Billfish Tagging Programme (NZ); New South Wales Fisheries Tagging Program, Australia (NSW); National Marine Fisheries Service (NMFS) southwest, Fisheries Science Centre's Billfish Tagging Programme. (Only numbers used for present analysis are included and are not representative of entire datasets)

Table 3.3 Summary of striped marlin estimated weights (kg) and injuries on release in three Pacific Ocean tagging programmes. Mean ± SEM.

Agency	(n)	Mean Weight (kg)	Range Weight (kg)	(n) Injured
NZ	12,343	92.2 ± 0.61	20-200	468
NSW	11,739	77.1 ± 0.49	2-210	N/A
NMFS	1071	37.4 ± 0.96	6-114	34
Recovered	162	73.7 ± 1.73	14 -140	1
Not Recovered	24,091	85.1 ± 0.15	2 - 210	501
Cumulative	25,253	85.1 ± 0.14	2-210	502

New Zealand Cooperative Billfish Tagging Programme (NZ); New South Wales Fisheries Tagging Program, Australia (NSW); National Marine Fisheries Service (NMFS) southwest, Fisheries Science Centre's Billfish Tagging Programme. (Only numbers used for present analysis are included and are not representative of entire datasets)

3.4.2 Capture time

Capture times (n = 10,390) on first tag and release were recorded in the NZ and NMFS tagging programmes with a mean of 33.2 ± 0.02 min (Table 3.2). Capture time was highly variable but generally increased with weight (kg) in both recovered (r^2=0.09) and un-recovered (r^2=0.24) striped marlin (Figure 3.1; 3.2). The range of capture times for tag recoveries (5-75 min) was less than the range of capture times for fish that were not recovered (1-375 min). Recovered (26.3 ± 2.09 min) fish had on average 6.9 min shorter capture times compared to un-recovered (33.2 ± 0.03 min) striped marlin (P = 0.041). Mean capture time in the NZ tagging programme (36.2 ± 0.02 min) was significantly longer than mean capture time in the NMFS (17.1 ± 0.94 min) tagging programme (P < 0.001).

The distributions of capture time were significantly different between recovered and un-recovered striped marlin (X^2 = 12.824, df = 6, P = 0.045). A disproportionately high number (n = 35/51) of recoveries had capture times ranging from 20-39 min while a disproportionately low number (n = 6/51) of recoveries had capture times > 39 minutes (Figure 3.3). Overall, the recovery rates decreased with increasing capture time but the highest recovery rate (0.78%) occurred during 20-29 min and the lowest (0.17%) after 60 + min (Figure 3.4).
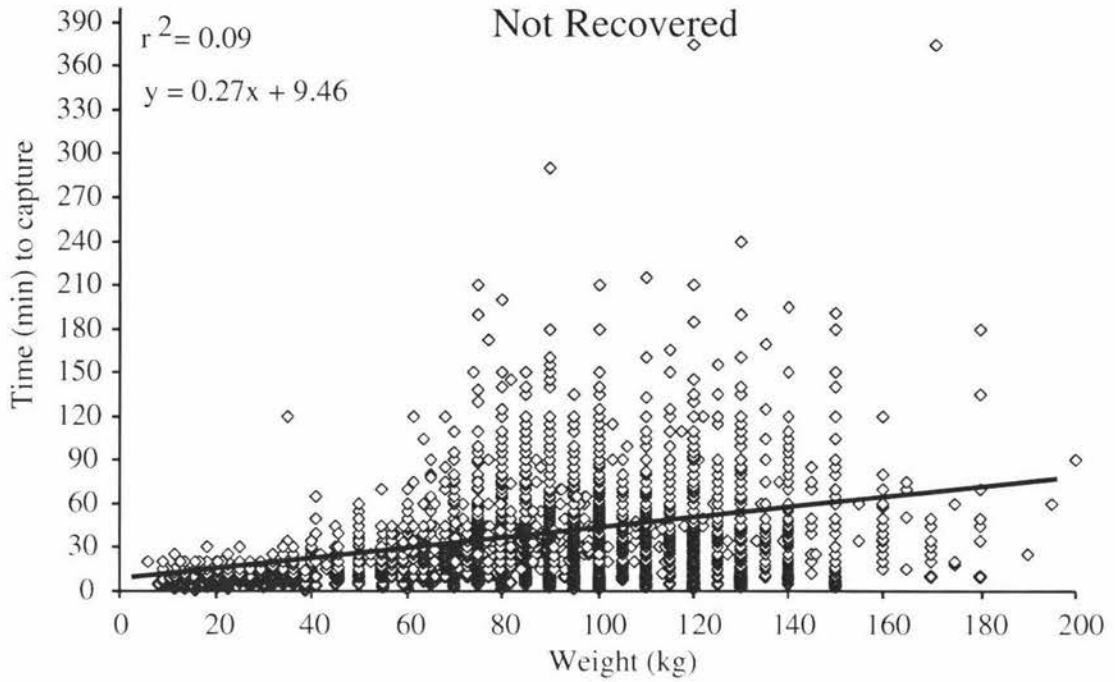
Figure 3.1 Capture time (min) versus estimated weight (kg) of un-recovered striped marlin in the NZ (n=9552) and NMFS (n=766) tagging programmes.
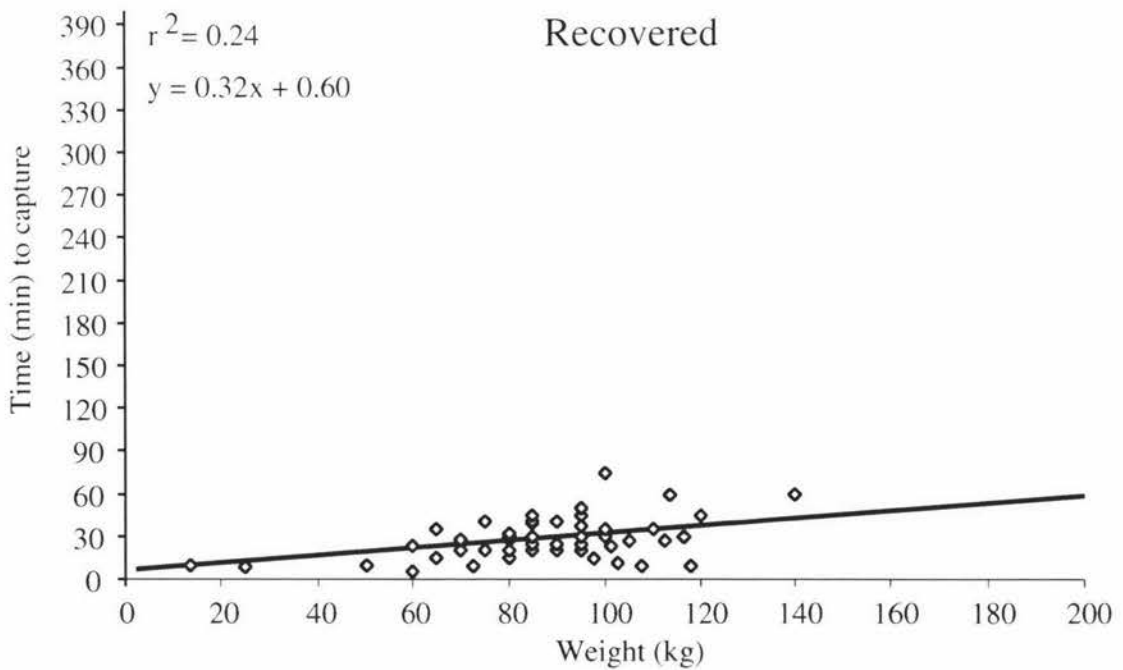
Figure 3.2 Capture time (min) versus estimated weight (kg) before first tag and release of recovered striped marlin in the NZ (n=48) and NMFS (n=3) tagging programmes.
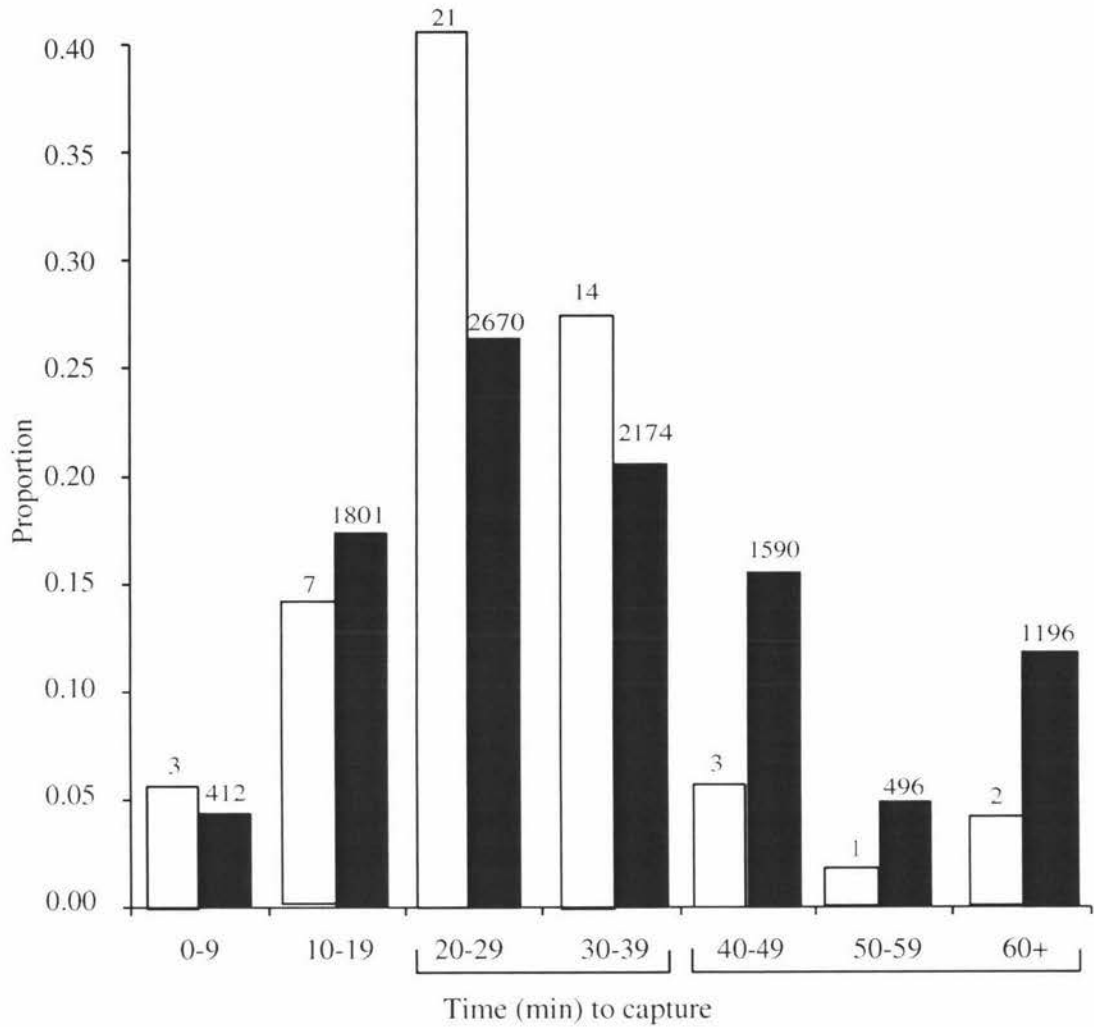
Figure 3.3 Proportion of striped marlin capture times before tag and release from the NZ, NMFS tagging programmes. □, Recovered (n=51); ■, Un-recovered (n=10,339). A disproportionately high number of recovered fish had capture times ranging from 20-39 minutes and a disproportionately low number of recovered fish had capture times > 39 minutes.
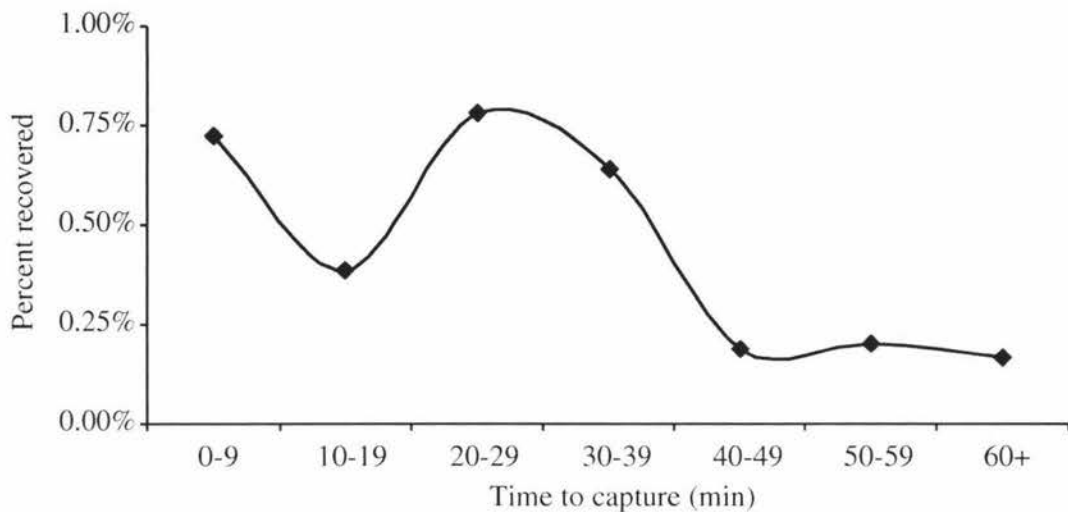
Figure 3.4 Percent of striped marlin◆ , Recovered (n=51/10390) and times to capture (min) before release in the NZ and NMFS tagging programmes.

3.4.3 Body mass

Weight (kg) estimates (n = 25,153) on first release were recorded in the NZ, NSW, and NMFS tagging programmes with a mean of 85.1 ± 0.14 kg (Table 3.3). From approximately 1-50 kg, capture times increased linearly but in fish weighing > 50 kg the time to capture became increasingly variable (r^2=0.09) (Figure 3.1. 3.2).The range of estimated weights for un-recovered (2-210 kg) striped marlin was larger the range for recoveries (14-140 kg). Recovered fish (73.7 ± 1.73 kg) were on average 11.3 kg lighter than un-recovered (85.1 ± 0.15 kg) striped marlin (P < 0.001). Mean estimated weight (kg) in the NZ tagging programme (92.2 ± 0.61 kg) was significantly greater than the NMFS (P < 0.001) and NSW (P = 0.010) tagging programmes (Table 3.3).

Weight distributions were significantly different between recovered and un-recovered striped marlin (X^2 = 30.933, df = 5, P < 0.001). A disproportionately high number (n = 129/162) of recoveries had estimated weights ≤ 89 kg while a disproportionately low number (n = 33/162) of recoveries had estimated weights (kg) > 89 kg (Figure 3.5). Overall the recovery rates decreased with increasing weight (kg) and the highest (1.31%) recovery rate was observed in the weight category 0-29 kg and the lowest (0.00%) in the 150 + kg weight category (Figure 3.6).
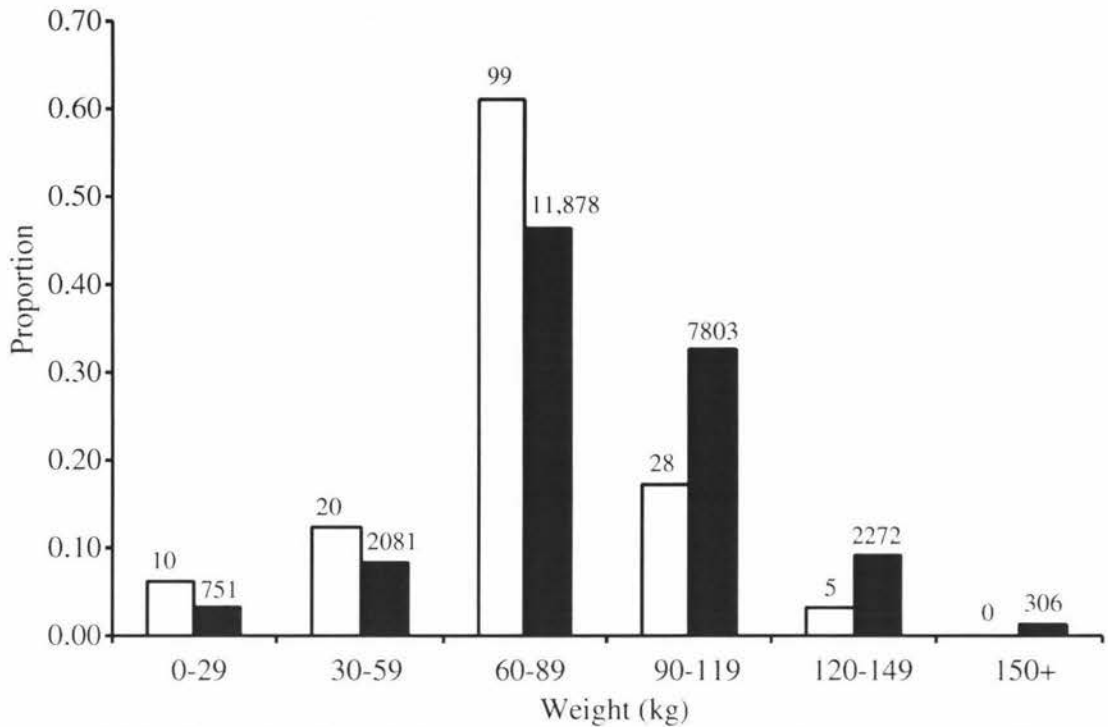
Figure 3.5 Estimated weight (kg) proportions of striped marlin tagged in the NZ, NSW, NMFS tagging programmes. □, Recovered (n=162); ■, Un-recovered (n=24,091).
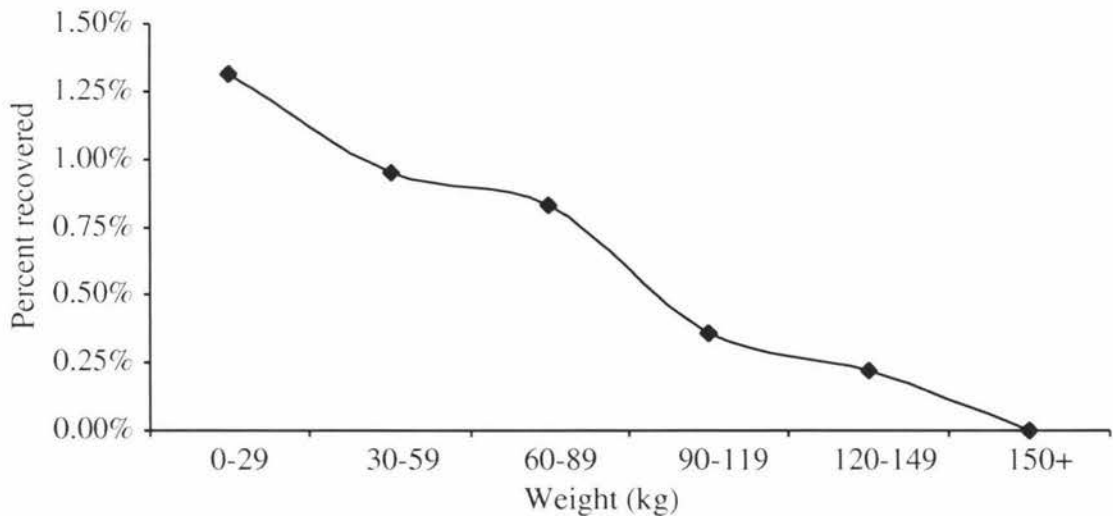
Figure 3.6 Percent of striped marlin ◆, Recovered (n=162/25,253) in weight (kg) class from the NZ, NSW and, NMFS tagging programmes.

3.4.4 Injury

Injuries (n = 502) were recorded from the NZ and NMFS tagging programmes and occurred across most of the range of weights (10-155 kg) and capture times (8-120 min). The injury rate was highest in short (0-19 min) and long (50 + min) capture

times with the lowest injury rate occurring at 20-29 min (2.34%; Figure 3.7). The rate

of injury was also highest in light (1-59 kg) and heavy (+ 90 kg) estimated weight

(kg) categories (Figure 3.8). The frequency of injury was not significantly different

between recovered (n = 1/51) and un-recovered (n = 501/13,363) striped marlin (X^2 =

0.432, df = 1, P = 0.510).
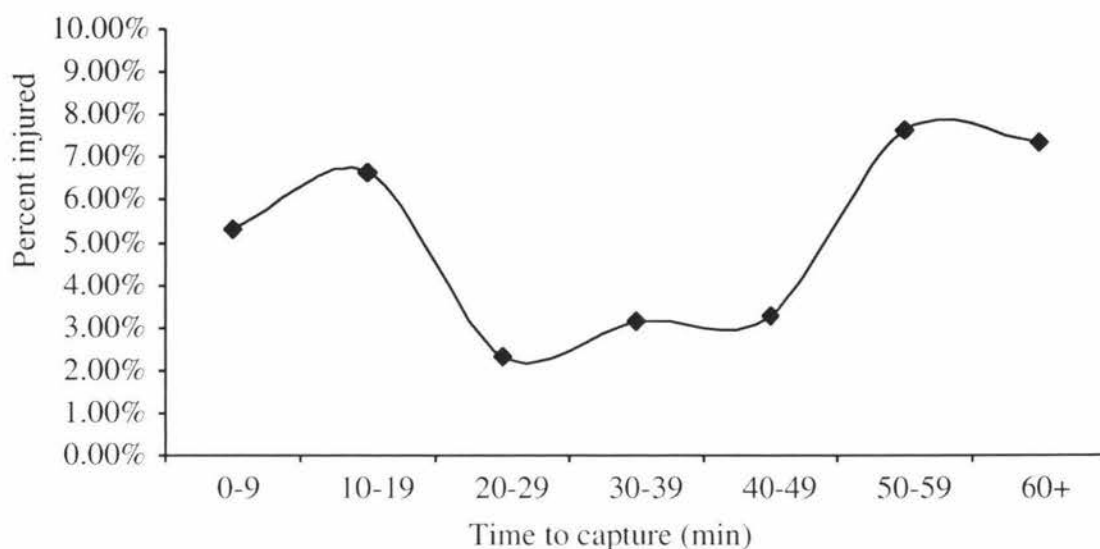
Figure 3.7 Percent of striped marlin ◆, Injured (n=452/10390) and times to capture (min) before release in the NZ and NMFS tagging programmes.
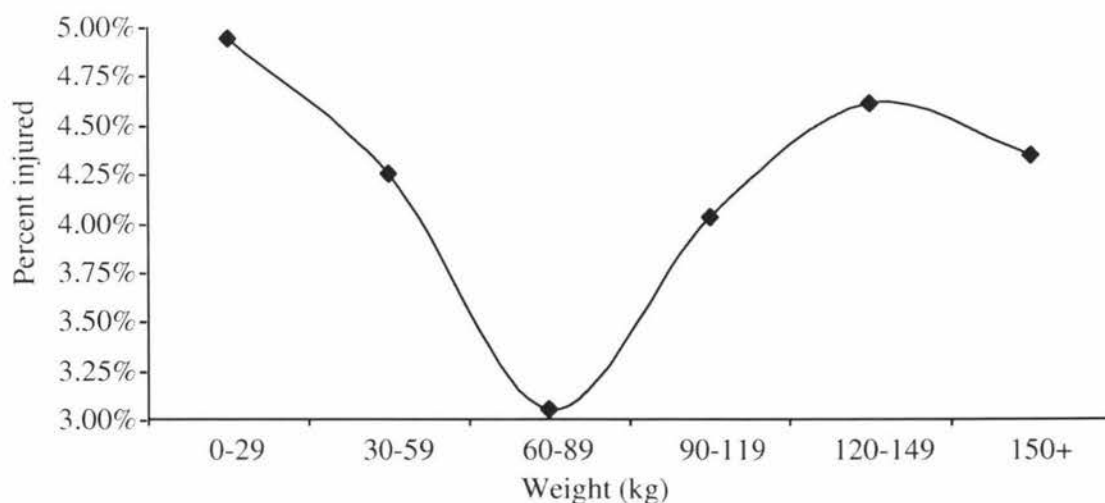
Figure 3.8 Percent of striped marlin ●, Injured (n=502/13,414) in weight (kg) classes estimated from the NZ and NMFS tagging programmes.

3.5 DISCUSSION

Tag recoveries of striped marlin occurred throughout a wide range of capture times (5-75 min), estimated weights (14-140 kg) and in the presence or absence of injury (Table 3.2; 3.3). These data suggest that striped marlin can survive a variety of circumstances on release and there is utility in tagging and releasing small or large striped marlin that have experienced long or short capture times. However, the probability of recapturing and presumably post-release survival of striped marlin is significantly influenced by both the duration of capture and body mass during tag and release (Figure 3.3; 3.5).

3.5.1 Capture time

Past research has identified that minimizing the duration of angling bouts can reduce academia in billfish but its direct relationship to the survival of marlin post-release has primarily been speculation (Skomal & Chase 2002). Rainbow trout exposed to only 6 min of exhaustive exercise have had morality rates of 40% but the relationship between capture time and billfish mortality is unclear (Wood et al. 1983). Based on the inverse relationship observed between recovery percentages and increasing time to capture, the present study supports the hypothesis that increasing capture time generally reduces tag recoveries and potentially post-release survival of striped marlin (Figure 3.4). However, the highest rate and number of tag recoveries occurred in the 20-29 min time category (Figure 3.3; 3.4). Tag recovery rates were expected to be higher in the 0-9 min and 10-19 min capture time categories but may have been influenced by the elevated rates of injury which occurred during these short capture events (Figure 3.7, *see* 3.5.3 Injury).

After a capture time of 39 min the proportion of recovered striped marlin rapidly decreases which suggests that this may be an important threshold for post-release survival (Figure 3.3). It does not however, appear that 39 min is the absolute duration of capture above which billfish die because their were tag recoveries from fish angled for up to 75 min. Electronic tags have also reported that black marlin have survived for 24 h subsequent to a 45 min angling bout and that striped marlin have survived after a 56 min capture period (Pepperell & Davis 1999; Domeier et al. 2003). Domeier et al (2003) found no significant differences between mean capture times of presumed dead (27.2 min) versus striped marlin which survived (23.5 min). However, tags on two fish with long capture times (126 and 150 min) did not report and fish may have died in this satellite tagging study (Domeier et al. 2003).   In contrast to Domeier et al. (2003), mean capture times in the present study were significantly (P=0.041) shorter in striped marlin recaptures (26.3 ± 2.09 min) than in those not recaptured (33.2 ± 0.03 min).

Pepperell & Davis (1999) reported that black marlin exposed to long ($\approx$ 45 min) capture times often dove to greater depths than those exposed to shorter ($\approx$ 20 min) capture times and that fish exposed to shorter captures returned to "normal" swimming behaviour more quickly. Longer capture times apparently increase the length of time required for the fish to recover as well as influence post-release behaviour. This is a period of time when marlin may be more susceptible or attractive to sharks. Deaths of electronically tagged black marlin soon after release have been attributed to shark attacks and anecdotal evidence also exists for other pelagic game fishes (Jolly & Irby 1979; Block et al. 1998; Pepperell & Davis 1999).

Another negative consequence of extended capture times may involve the anglers and crew rather than the fish. After extended angling bouts fishermen and

crew may be less likely to handle, tag, and release the fish as effectively compared to after shorter bouts. In the present study injury rates were highest in long (60+ min) capture events (*see Injury 3.5.3*). Poor boat side handling and improper tag placement can contribute injuries leading to infection and death as well as tag shedding (Prince et al. 2002).

3.5.2 Body mass

With an average weight of 85.0 ± 0.14 kg, capturing striped marlin in less than 10 min was uncommon and not surprisingly many of the short capture times were associated with fish weighing less than 30 kg (Figure 3.1). Thus, it may be possible that post-release mortalities thought only to be related to extended capture times are also related to size specific survival or a combination of both. However, time to capture and estimated weight (kg) of striped marlin were highly variable (r^2=0.09) and are more likely related to methods of capture and skills of the angler and crew. Larger (+130 kg) striped marlin had the most variable capture times ranging from 10-300 min while smaller (< 50 kg) individuals had less variable capture times (Figure 3.1). These data indicate that smaller sized striped marlin are more manageable for the angler, crew and gear which in turn result in shorter capture times and increased tagging success.

In a previous investigation of striped marlin tag returns, Bromhead et al. (2004) identified a similar trend in decreasing recapture rate with increasing fish size. The potential for size specific survival is supported by studies on rainbow trout which demonstrate that after exhaustive exercise larger individuals experience a greater physiological disturbance than smaller individuals (Schmidt-Nielson 1984; Ferguson et al. 1993). Brill et al. (2002) used ultrasonic transmitters and found that juvenile

(74-106 cm fork length) northern bluefin tuna (*Thunnus thynnus*) were resilient to recreational capture and survived after release when hooking injury was minimal and handling time was reduced. Additionally, small (9.5-37 kg) striped marlin have been reported to survive 6-8h while attached to a longline but little data of this sort have been published for larger sized marlin (Boggs 1992).

The suggestion that small marlin have an increased rate of post-release survival compared to larger fish is further supported by the estimated weight (kg) distributions of recovered versus un-recovered striped marlin (Figure 3.5). Despite that approximately 44% (10,381/24,091) of all un-recovered striped marlin weighed more than 89 kg, only 20% (33/162) of all recovered striped marlin weighed greater than 89 kg. These data show that recovery rates of striped marlin would increase if all tagged and released fish had weighed less than 90 kg. Small (0-29 kg) striped marlin also exhibited the highest percentage of recapture while no striped marlin heavier than 150 kg has been recovered (Figure 3.6).

Another explanation for the elevated tag recovery rate in small striped marlin may simply be that larger fish die naturally before being recaptured. Smaller striped marlin are presumably younger and may have a greater chance of recapture than larger (older) fish simply due to the differences in life span. Striped marlin are estimated to have a life span ranging from 8-13 years but validated aging methods and long term recaptures are rare (Kopf et al. submitted). Ortiz et al. (2003) note that in all tagging programmes, striped marlin have particularly short times at large compared to other marlin as over 90% of recoveries occur within one year.

3.5.3 Injury

Results from the present study show that injury rates of striped marlin are highest during long (60+ min) and more interestingly, during short (0-9 min) capture times (Figure 3.7). The injuries occurring during long capture times may be due to severe fatigue or fish handling but the injuries reported during short (<10 min) capture times are most likely due to poor fish handling at the boat. Prince et al. (2002) notes that "playing a fish down" is a critical consideration before attempting to tag and release any gamefish. The general rule of thumb that the faster the fish is captured the more likely it is to survive may not be entirely true for gamefishes. For example, striped marlin that were captured in under 20 min frequently sustained injuries at the side of the boat and were frequently tagged around the gills and eyes (Figure 3.7). Poor tag placement can affect not only recapture rates because of physical damage but may also increase tag shedding which has proven to be a significant challenge in conventional tagging programmes. In contrast to short and long capture times, striped marlin captured within 20-29 min had a lowest rate of injury but also the highest recovery rate (Figure 3.3).

The trend of injury corresponding to estimated weight mirrors the "U' shaped injury rates observed with time to capture. Small (0-29 kg) and large (+ 120 kg) striped marlin had high injury rates while medium sized marlin had the lowest injury rates (Figure 3.8). Even though small striped marlin with short capture times were the most frequently injured there was no statistical effect on the rate of recapture (Figure 3.4; 3.6). This may also be related to the ability of small marlin to recovery from injury or the fact that larger marlin experience fewer but more severe and life threatening injuries.

3.6 CONCLUSION

Factors affecting tag recoveries from recreationally captured and released billfish appear to be dependent on a number of conditions, many of which are beyond the scope of this study. However, data from this study showed that striped marlin which weighed less than 90 kg and were captured within 20-29 min had the greatest potential for recapture and by inference had the greatest chance for post-release survival. Rates of injury were elevated during extremely short (0-9 min) and long (60+ min) capture times but did not affect tag recovery rates.

Anglers do not have a choice in the size of fish which is captured but they do have control over the gear used, size of fish being targeted and capture time. Size specific mortality of recreationally captured marlin has not been thoroughly examined but important questions may be answered by using satellite tags in conjunction with physiological measurements of acid-base status and utilization of metabolic fuels between different sizes of marlin after capture. Satellite tagging studies will continue to be useful for determining factors influencing post-release survival but these studies must be designed to address specific questions such as those regarding the impacts of different gears types, capture times, handling methods as well as temporal and environmental conditions (*see* Graves et al. 2002; Domeier et al. 2003).

For increased success in cooperative gamefish tagging programmes, anglers may inform their decision making by understanding how fish weight, time to capture and rate of injury affect tag recoveries. With the rising opposition to the capture of fish for recreation and increasing rate of pelagic fish depletion, the identification of capture methods which reduce welfare compromise and increase post-release survival is critical. For more information about the issues surrounding the welfare of recreationally captured fish see Appendix D.

Chapter 4

Diet and feeding ecology of striped marlin off the coast of

New Zealand

4.1 ABSTRACT

Striped marlin are oceanic predators which consume a variety of commercially and recreationally important prey items ranging from fish in the family Scombridae and Engraulidae to cephalopods and crustaceans. Understanding the trophic dynamics between predators, prey and their environment is necessary for the development of ecosystem based fishery management strategies which are being advocated for by fisheries managers. The present study investigated the stomach contents of recreationally captured striped marlin (n=20) from New Zealand during March of 2004. Eight fish taxa, one cephalopod and one crustacean species were collected. Fish accounted for 52.6% of the Index of Relative Importance (IRI) while cephalopods accounted for 46.6% and crustaceans < 1.0%. Squid (*Nototodarus spp.*) and jack mackerel (*Trachurus murphyi*) were the most important prey items accounting for 79.4% of the IRI. Thrirty-one percent (24/77) of prey items were in an advanced stage (bone material only) of digestions and 45.0% (9/20) of stomachs were classified as less than half full while 20.0% (4/20) were empty. The greatest number of prey in one stomach was 13 while the greatest number of species was 4 and 75.0% (15/20) of stomachs contained only two or three species. The average volume per prey specimen was 218 ± 192 mL and the estimated daily ration of food intake ranged from 0.962 to 1.28 kg/ for a 103.9 kg striped marlin.

4.2 INTRODUCTION

Striped marlin are apex predators of the pelagic ecosystem, thus gaining knowledge about their interactions with prey and other predators is essential for developing an ecosystem based management strategy. Traditional single species fisheries management is losing importance as there is growing interest in ecosystem based approaches which attempt to account for interactions between organisms ranging from plankton to large cetaceans (Godinot & Allain 2003; Latour et al. 2003). Understanding who eats what, how much and when is fundamental information required for most trophic models (Polovina 1984; Allain 2003). Predators such as marlin have major impacts on mortality and biomass changes in the species which they consume and thus are of considerable importance to the trophic ecology of the pelagic ecosystem. For example, swordfish (*Xiphias gladius*) off Georges Bank in the Northwest Atlantic are estimated to consume 6,000 to 11,000 tonnes of fish and squid during a 153 d residency (Stillwell & Kohler 1985).

Feeding habits and bioenergetics of striped marlin have been studied in the eastern Pacific but few studies have been conducted in the southwest Pacific Ocean (Abitia-Cardenas et al. 1997; Abitia-Cardenas et al. 1998; Moteki et al. 2001; Abitia-Cardenas et al. 2002). Saul (1983) conducted a review of striped marlin stomach contents in New Zealand but these data are largely unavailable to the international community as few manuscripts were printed. Baker (1966) and Morrow (1952) studied the diet of striped marlin in New Zealand but feeding habits may have changed during the last 40 to 50 years. It is likely that feeding habits of marlin shift as the organisms which they prey upon experience commercial exploitation and even more likely following overexploitation. Thus, the ability to compare the pre-

exploitation diet of striped marlin with their current diet is a unique opportunity that may provide insight about changes in food resource availability.

Stomach contents analysis have shown that striped marlin are indiscriminate predators which consume most every organism available to them. Their diet ranges from epipelagic fishes to demersal rays and even squid and prawns (Saul 1983; Abitia-Cardenas et al. 1997). This varied diet suits marlin well as the pelagic ecosystem they inhabit has particularly low productivity compared to coastal regions of the ocean. In an environment with a sporadic food supply, an indiscriminant diet is essential for sustaining such a large animal.

Squid are a consistent component of the diet of striped marlin throughout the Pacific Ocean and are identified in stomach contents analysis in Australia, Mexico, New Zealand, northern Chile, and Peru (Bromhead et al. 2004; Abitia-Cardenas et al. 1997 and 1998; Baker 1966; de Sylva 1962). Squid are likely to be consumed at night or evening when they rise to the surface rather than during the day when they are commonly found at depths exceeding 300 m (La Monte 1955). However, most prey items are epipelagic species which correlates with satellite tagging studies that show striped marlin spend nearly 66% of their time in the top 5 m of the water column (Sippel et al. unpublished). In the eastern Pacific Ocean, important prey items of striped marlin are saury (Scomberesocidae), anchovy (Engraulidae) and skipjack (Scombridae), (Evans & Wares 1972; Eldrige & Wares 1974).

The purpose of this study was to provide data on striped marlin diet and feeding ecology for future use in ecosystem trophic models in New Zealand. Daily ration, digestive states of prey, fullness coefficients and an Index of Relative Importance (IRI) were calculated from stomach contents of 20 striped marlin which were caught off the east coast of northland, New Zealand.

4.3 METHODS

Twenty striped marlin were collected in March of 2004 from the Whangaroa and Houhura weigh stations in east northland, New Zealand. Fish were captured by recreational fishers trolling lures and live baiting. Sex, weight (± 0.5 kg), Lower Jaw-Fork (LJFL, mm) and other morphometric measurements according to Rivas (1956) were collected at the weigh stations (Figure 1.1). Stomachs were removed and contents were fixed in 10% formalin within 24 h after capture. As tag-and-release of striped marlin is encouraged and commercial longlining for this species is prohibited in New Zealand, collecting scientific specimens has become more difficult and is reflected in the reduced sample size (n=20).

4.3.1 Prey Identification

Crustaceans and cephalopods were identified using Dell (1952); Clark (1986) and the Tree of Life web project (TOL 2004). Fishes were identified using Ayling & Cox (1982); Paul (2000); Paulin et al. (2001) and the Fish Base web page (Froese et al. 2004). Prey were identified to the lowest taxonomic level and were grouped by individual numbers (N), volume mL (V), occurrence (O), and by an Index of Relative Importance.

4.3.2 Index of Relative Importance, State of Digestion, and Fullness Coefficients

The Index of Relative Importance (IRI) is commonly used for fishes and provides an accurate representation of the significance of prey items within diets. The IRI helps remove bias caused by different rates of digestion between prey items by placing emphasis on occurrence but also accounts for total numbers and volume (Abitia-Cardenas et al. 1997):

$$IRI = (\%N + \%V)\, \%O$$

Number (**N**), volume mL (**V**), occurrence (**O**)

The state of digestion for each prey item was divided into four categories: 1) fresh; 2) whole, partially digested; 3) fragmented, advanced digestion; 4) hard part remains (Allain 2003). Each stomach was classified using five fullness coefficients: 0) empty; 1) less than half full; 2) half full; 3) more than half full; 4) full (Allain 2003). As the longitudinal folds in striped marlin stomachs can expand significantly to increase volume, fullness coefficients were probably not absolute representatives of the maximum stomach capacity, which is estimated to be 9.7 L in a 67.7 kg striped marlin (Scrimgeour 1984; Davie 1990).

4.3.3 Daily Ration

Daily ration (C) of food intake was calculated using mean weight of stomach contents (S =.837 kg) and previously published stomach evacuation rates (R= .0479 and .0639 kg/h) described by the equation (Stillwell & Kohler 1982, Stillwell & Kohler 1985):

$$C = 24\, SR$$

Daily ration (**C**), mean weight kg stomach contents (**S**), stomach evacuation rate (**R**)

Volume of prey was converted into weight using 1 mL =1 g. Previously published stomach evacuation rates for shortfin mako *(Isurus oxyrinchus)* were used and have also been used for estimating swordfish (*Xiphias gladius*) daily rations (Stillwell & Kohler 1985). Striped marlin and mako sharks were assumed to have similar evacuation rates because both are top predators in the pelagic ecosystem and have similar feeding preferences.

4.4 RESULTS

The average weight of striped marlin (n=20) was 103.9 ± 4.7 kg (± SEM) and LJFL

was 2342 ± 25 mm with a 7/12 female to male sex ratio (one not determined)

(Appendix C).

4.4.1 Numbers, Volume and Occurrence

Eight fish taxa, one cephalopod and one species of crustacean (amphipoda) were

collected (Table 4.1). Previously published information on occurrence of prey items

in striped marlin stomachs from New Zealand is compared to the present study and

consolidated in Table 4.2.

In the present study, arrow squid (*Notodarus spp.*) were most important based

on the IRI but jack mackerel (*Trachurus murphyi*) were the most abundant in number

(n=21) and also made up the greatest total volume (5390 mL). Arrow squid occurred

in most (60.0%) stomachs and was followed by occurrences of saury (*Scomberesox*

saurus) (35.0%) and jack mackerel (30.0%; Figure 4.1). Skipjack tuna (*Katsuwonus*

pelamis) made up a large proportion of the total volume as a result of one large (49

cm; 4010 mL) undigested specimen. The louvar (*Louvarus imperialis*) is an oceanic

species rarely found in New Zealand waters but a 310 g individual was identified in

stomach contents.

A total of 77 prey items were collected which was an average of

approximately four individuals per stomach at an average volume of 218 ± 192 mL

per prey specimen. The maximum number of prey items in one stomach was 13 while

the maximum number of species was four with most stomachs (15/20) containing two

or three species. Average volume of contents in stomachs was 837 ± 422 mL and the

greatest volume of prey contained in one stomach was 4121mL. The largest prey

items (mean= 604 ± 505 mL) were consumed by the smallest marlin and the number

of items per stomach generally increased with marlin size (Figure 4.2).

Table 4.1 Numbers, volumes, occurrences and Index of Relative Importance (IRI) of prey items in (n=20) striped marlin stomachs.

Prey	Num.	% Num.	Vol.	% Vol.	Occur.	% Occur.	IRI	% IRI
Arrow Squid *Nototodarus spp.*	18	23.4	3550	21.2	12	60.0	2674.5	47.6
Jack mackerel *Trachurus murphyi*	21	27.3	5390	32.2	6	30.0	1783.7	31.8
Saury *Scomberesox saurus*	10	13.0	281	1.7	7	35.0	513.3	9.1
Unidentified fish	9	11.7	420	2.5	4	20.0	283.9	5.1
Skipjack *Katsuwonus pelamis*	1	1.3	4010	23.9	1	5.0	126.2	2.2
Pilchard *Sardinops neopilchardus*	3	3.9	390	2.3	2	10.0	62.2	1.1
Koheru *Decapterus koheru*	2	2.6	1540	9.2	1	5.0	59.0	1.1
Crustacea Amphipoda	8	10.4	16	0.1	1	5.0	52.4	0.9
Blue mackerel *Scomber australicus*	3	3.9	707	4.2	1	5.0	44.6	0.8
Louvar *Louvarus imperialis*	1	1.3	310	1.9	1	5.0	15.7	0.3
Green puffer *Sphoeroides hamiltoni*	1	1.3	133	0.8	1	5.0	11.2	0.2
Total	77		16747		37		5626.7	
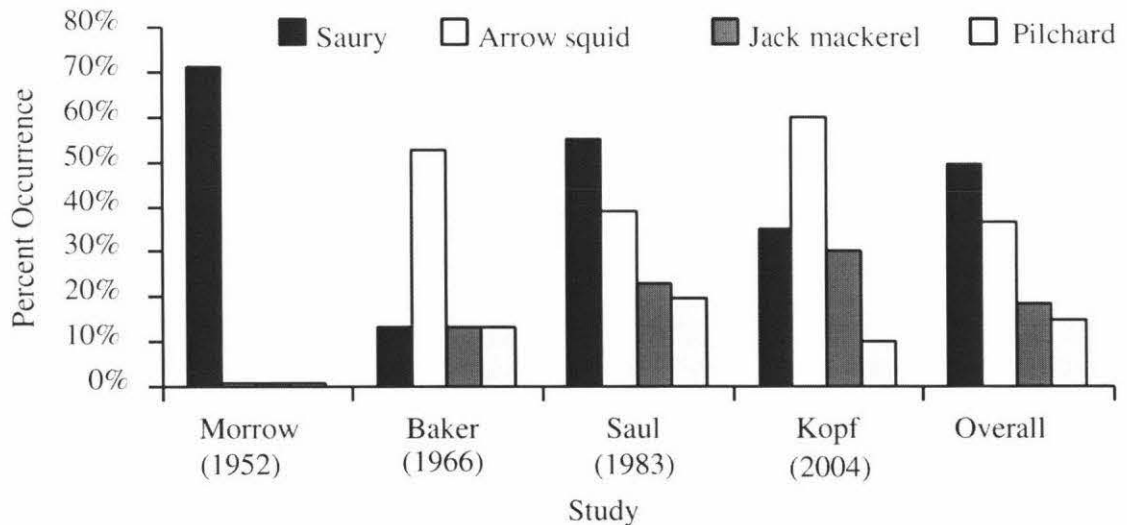
Figure 4.1 Percentage of stomachs containing the four most frequently encountered prey items in striped marlin collected from New Zealand.

Table 4.2 Occurrence and percent occurrence of prey items in striped marlin stomachs from four studies in New Zealand.

Common Name	Scientific Name	(n=38) Morrow (1952) Occur.	%Occur.	(n=38) Baker (1966) Occur.	% Occur.	(n=147) Saul (1983) Occur.	% Comp.	(n=20) Kopf (2004) Occur.	% Occur.	(n=243) Overall Occur.	% Occur.
Saury	*Scomberesox saurus*	27	71.1%	5	13.2%	81	55.1%	7	35.0%	120	49.4%
Arrow Squid	*Nototodarus spp.*	0	0.0%	20	52.6%	57	38.8%	12	60.0%	89	36.6%
Jack Mackerel	*Trachurus murphyi*	0	0.0%	5	13.2%	34	23.1%	6	30.0%	45	18.5%
Unidentifiable Squid	*n/a*	8	21.1%	0	0.0%	29	19.7%	0	0.0%	37	15.2%
Unidentifiable Fish	*n/a*	10	26.3%	7	18.4%	20	13.6%	4	20.0%	41	16.9%
Pilchard	*Sardinops neopilchardus*	0	0.0%	5	13.2%	29	19.7%	2	10.0%	36	14.8%
Kahawai	*Arripis trutta*	17	44.7%	1	2.6%	7	4.8%	0	0.0%	25	10.3%
Blue Mackerel	*Scomber australicus*	0	0.0%	8	21.1%	8	5.4%	1	5.0%	17	7.0%
Snapper	*Chrysophyrs auratus*	7	18.4%	6	15.8%	0	0.0%	0	0.0%	13	5.3%
Trevally	*Caranx georgianus*	0	0.0%	9	23.7%	2	1.4%	0	0.0%	11	4.5%
Skip Jack	*Katsuwonus pelamis*	0	0.0%	3	7.9%	8	5.4%	1	5.0%	12	4.9%
Yellowtail Kingfish	*Seriola lalandi*	0	0.0%	1	2.6%	8	5.4%	0	0.0%	9	3.7%
Butterfly Perch	*Caesioperca lepidoptera*	4	10.5%	3	7.9%	0	0.0%	0	0.0%	7	2.9%
Anchovy	*Engraulis australis*	0	0.0%	1	2.6%	6	4.1%	0	0.0%	7	2.9%
Koheru	*Decapterus koheru*	0	0.0%	3	7.9%	2	1.4%	1	5.0%	6	2.5%
Nautilus spp.	*Argonauta spp.*	1	2.6%	1	2.6%	2	1.4%	0	0.0%	4	1.6%
Jack Family	Carangidae	4	10.5%	0	0.0%	0	0.0%	0	0.0%	4	1.6%
Porcupine Fish	*Allomycterus jaculiferus*	1	2.6%	1	2.6%	1	0.7%	0	0.0%	3	1.2%
Blue Maomao	*Scorpis aequipinnis*	0	0.0%	3	7.9%	0	0.0%	0	0.0%	3	1.2%
Green Puffer	*Sphoeroides hamiltoni*	0	0.0%	0	0.0%	3	2.0%	1	5.0%	4	1.6%
Barracouta	*Thyrsites atun*	1	2.6%	1	2.6%	1	0.7%	0	0.0%	3	1.2%
Rays Bream	*Brama brama*	0	0.0%	0	0.0%	2	1.4%	0	0.0%	2	0.8%
Pink Maomao	*Caprodon longimanus*	1	2.6%	0	0.0%	1	0.7%	0	0.0%	2	0.8%
Dolphin Fish	*Coryphaena hippurus*	0	0.0%	0	0.0%	2	1.4%	0	0.0%	2	0.8%
Mako Shark	*Isurus oxyrhinchus*	0	0.0%	0	0.0%	2	1.4%	0	0.0%	2	0.8%
Frost Fish	*Lepidopus caudatus*	0	0.0%	0	0.0%	2	1.4%	0	0.0%	2	0.8%
Leather Jacket	*Parika scaber*	0	0.0%	1	2.6%	1	0.7%	0	0.0%	2	0.8%
Broad Squid	*Sepioteuthis bilineata*	0	0.0%	0	0.0%	2	1.4%	0	0.0%	2	0.8%
Crustacean	Crustacea (Amphipoda)	0	0.0%	0	0.0%	0	0.0%	1	5.0%	1	0.4%
Ray spp.	Batoidea	0	0.0%	1	2.6%	0	0.0%	0	0.0%	1	0.4%
Golden Snapper	*Centroberx affinis*	0	0.0%	0	0.0%	1	0.7%	0	0.0%	1	0.4%
Gar Fish	*Hyporamphus intermedius*	1	2.6%	0	0.0%	0	0.0%	0	0.0%	1	0.4%
Louvar	*Louvarus imperialis*	0	0.0%	0	0.0%	0	0.0%	1	5.0%	1	0.4%
Blue Shark	*Prionace glauca*	0	0.0%	0	0.0%	1	0.7%	0	0.0%	1	0.4%
Hammerhead Shark	*Sphyrna zygaena*	0	0.0%	0	0.0%	1	0.7%	0	0.0%	1	0.4%
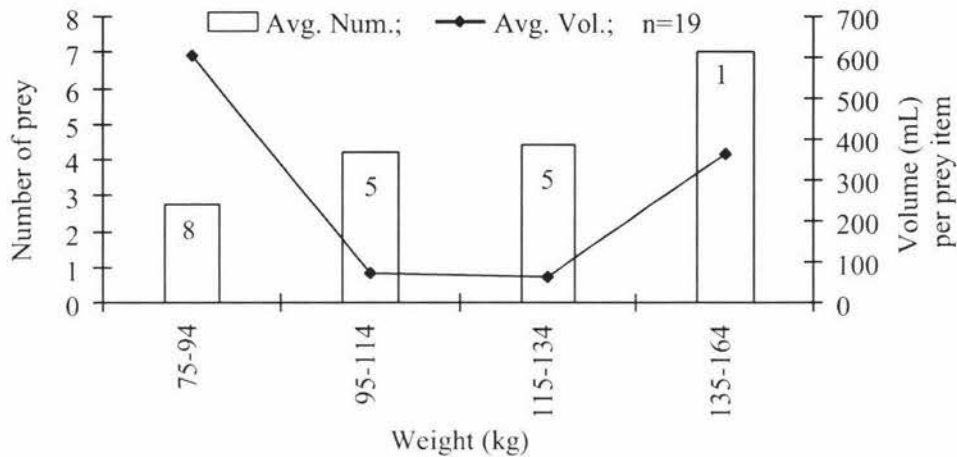
Figure 4.2 Weight classes kg of striped marlin versus average number and volume of individual prey items.

4.4.2 Index of Relative Importance

Many prey species were epipelagic fishes but mesopelagic arrow squid occurred in the highest proportion of stomachs (60.0%) and were the most important group based on IRI percentages (48.6%) (Figure 4.3). However, fish as a group accounted for 52.6% of the IRI while cephalopods accounted for 47.6 % and crustaceans < 1.0 %. Seven taxa exhibited IRI values greater than 1.0 % but only three taxa (arrow squid, jack mackerel and saury) accounted for 90.3% of the IRI.
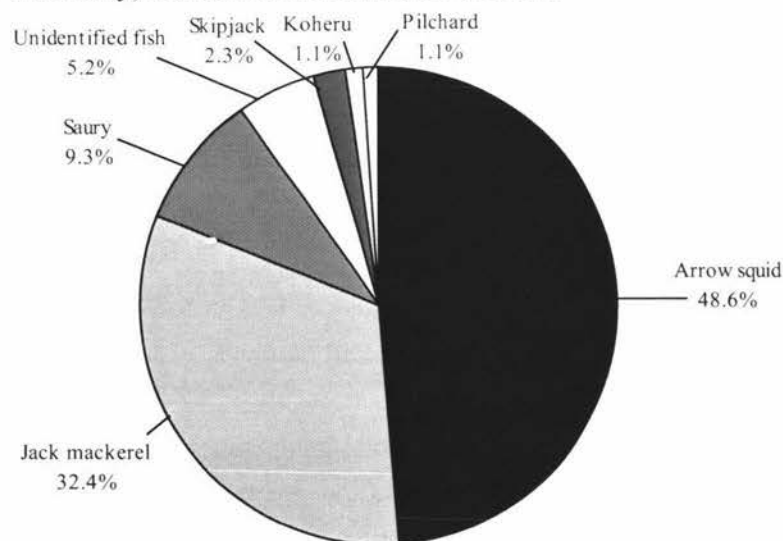
Figure 4.3 Percent contribution of prey items (>1.0%) to the Index of Relative Importance (IRI) from (n=20) striped marlin stomachs.

4.4.3 State of Digestion and Fullness Coefficients

The low volume per prey specimen was influenced by the fact that 31.2% (24/77) of prey items were at an advanced stage (4) of digestion in which only bone material was remaining (Figure 4.4). The next largest proportion of prey items (28.6%) were at the earliest stage of digestion (1) in which little or no tissue was digested. Prey in 70.0% (14/20) of stomachs were in the same state of digestion; 20.0% (4/20) stomachs exhibited two states of digestion and 10.0% (2/20) exhibited three states. Digestion appeared to be more rapid for cephalopods than fish because 66.7% (12/18) of cephalopods were at stage 4 of digestion compared to only 7.84% (4/51) of fish.

Total numbers, volume and occurrence of prey was affected by the fact that 20.0% (4/20) of the stomachs were empty in which three had been everted during capture. Forty-five percent (9/20) of stomachs were classified as less than half full while only 20% (4/20) were full (Figure 4.5).
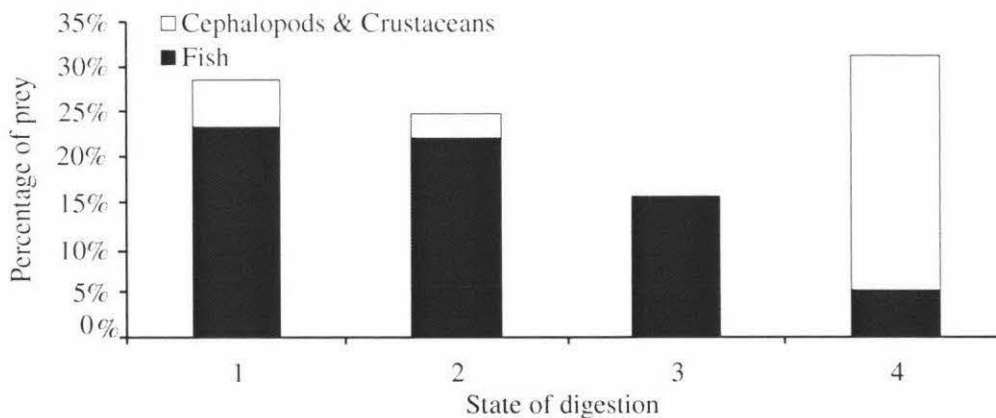
Figure 4.4 Percentage of prey at digestion state: 1) fresh; 2) whole, partially digested; 3) fragmented, advanced digestion; 4) hard part remains (Allain 2003).
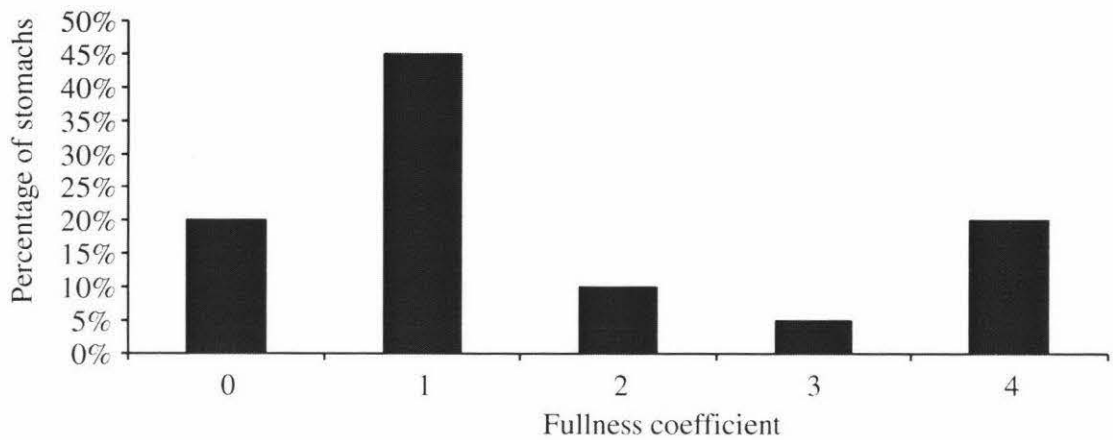
Figure 4.5 Percentage of stomachs at fullness coefficients: 0) empty; 1) less than half full; 2) half full; 3) more than half full; 4) full (Allain 2003).

4.4.4 Daily Ration

The minimum daily ration of food ranged from .962 to 1.28 kg/d (Table 4.3). In one year, a 103.9 kg striped marlin is expected to consume 3.2 to 4.5 times its body weight. As a stock assessment has not been conducted for striped marlin the total biomass of prey consumed in the New Zealand's Exclusive Economic Zone (EEZ) is unknown. Hypothetically, if 20,000 striped marlin migrate to New Zealand with an annual residency time of four months, the amount of biomass consumed may range from 2309 to 3072 metric tonnes.

Table 4.3 Summary of minimum daily, annual and body weight (BW) food rations for three pelagic fish species.

Study	Species	Average weight (kg)	kg/ day	kg/ yr	% BW day	x BW yr
Present study	Striped marlin *Tetrapturus audax*	103.9	.962-1.28	336.7-467.2	0.93-1.2	3.2-4.5
Stillwell & Kohler (1985)	Swordfish *Xiphias gladius*	58	.545-.926	199.0-338.0	0.94-1.6	3.4-5.8
Stillwell & Kohler (1982)	Shortfin mako *Isurus oxyrinchus*	63	2	730	3.2	11.6

4.5 DISCUSSION

Results from this study are in accordance with past reports of striped marlin diets which show a preference for epipelagic fishes and mesopelagic squid. Previous studies have also recorded demersal prey items such as searobins (*Prinotus spp.*) and mantis shrimp (*Squilla spp.*) but all species identified in the present study were inhabitants of the pelagic ecosystem (Abitia-Cardenas et al. 1997). A generalist feeding behaviour was observed by the identification of 10 different taxa within the 20 stomachs examined (Table 4.1). In consolidating previous research with the present study 28 fish, 4 cephalopod and 1 crustacean species have been identified in striped marlin stomachs from New Zealand (Morrow 1952; Baker 1966; Saul 1983; Table 4.2)

Feeding habit studies in Mexico have identified 17 species and 33 taxa (Abitia-Cardenas et al. 1997). The present study was the first to collect crustaceans (amphipoda) from striped marlin stomachs in New Zealand but unfortunately their digestive state did not permit identification to a lower taxonomic level. Additionally, the louvar which is a poorly understood and rarely collected mesopelagic fish species has not been identified in any previous striped marlin stomach contents analysis.

The IRI identified arrow squid, jack mackerel and saury as the primary prey in order of greatest contribution to the diet of striped marlin (Figure 4.3). Jack mackerel were the most important fish species in numbers and volume and ranked second in the IRI behind arrow squid (Table 4.1; Figure 4.3). Based on the same IRI equation, Abitia-Cardenas et al. (1997) identified chub mackerel (*Scomber japonicus*), California pilchard (*Sardinops caeruleus*) and the jumbo flying squid (*Dosidicus gigas*) as the three most important prey items in Mexico. Not surprisingly, the primary prey items identified off the coast of Mexico are nearly the geographic

species equivalent to the primary prey items identified in the stomachs of striped marlin from New Zealand. Similarly, Hubbs & Wisner (1953) report that saury (*Cololabis saira*) and anchovy (*Engraulis mordax*) were significant prey items off the coast of California.

Fish from the families Carangidae, Clupeidae and Engraulidae comprise the largest majority of fish prey consumed by striped marlin throughout the Pacific Ocean (Saul 1983; Abitia-Cardenas et al. 2002). These species are usually less than 30 cm in length and can be found in the inshore or offshore pelagic ecosystem usually in large schools occasionally containing millions of individuals. Feeding on schooling fish maximizes prey encounters while minimizing effort and energy expenditure (Abitia-Cardenas et al. 2002). Striped marlin are believed to utilize their agility by targeting small schooling species while their larger relative the blue marlin (*Makaira nigricans*) occupies a slightly different trophic niche by targeting and primarily consuming larger scombrids (Brock 1984).

With an average prey volume of 218 ± 192 mL the size of prey consumed in New Zealand is consistent with reports that striped marlin primarily target small schooling fishes and squid. The small size of skulls and other bones from thoroughly digested fish also suggests a preference for smaller sized fish (< 30 cm). However, if a large prey item presents itself as an easy target, striped marlin have the ability to capture and consume larger organisms as was seen by the identification of a 49 cm skipjack tuna. Moteki et al. (2001) identified scombrid fishes as the second most important (11.0% of the total number of fishes 347) family of fishes consumed by striped marlin off the coast of South America. Additionally, striped marlin were found to reduce trophic competition from other pelagic predators such as swordfish by targeting fast swimming scombrid fishes (Moteki et al. 2001). Compared to 6 other

pelagic predators Moteki et al. (2001) found that striped marlin feeding habits were most similar to yellowfin tuna (*Thunnus albacares*) who target both surface and midwater prey items.

Interestingly, the smallest weight class (75-94 kg) of striped marlin consumed the largest prey items but had the lowest number of prey items per stomach (Figure 4.2). This may have been influenced by the sample size but might also be related to size specific feeding strategies or rates of metabolism. Large striped marlin may out compete smaller marlin for energetically inexpensive schooling fish or smaller faster growing marlin may seek larger prey items such as skipjack tuna to sustain high rates of growth. Another explanation is that younger (smaller) striped marlin have not yet learned how to work bait schools.

Most (45.0%) stomachs were less than half full and 31.0% of prey were in the advanced stage four of digestion (Figure 4.4; 4.5). All prey within one stomach were usually in the same state of digestion (14/20 stomachs) and three states of digestion were observed in only two stomachs. These data indicate that digestion is rapid and that marlin consume large quantities during short feeding events rather than feeding continuously throughout the day. Additionally, most stomachs contained only two or three species which also supports the hypothesis that feeding occurs during short intense events. Saul (1983) reported similar findings of mostly two or three prey species per striped marlin stomach from New Zealand.

Compared to previous investigations of New Zealand striped marlin, the present study showed an increased preference for arrow squid which occurred in 60.0% of stomachs while saury (35.0%) and pilchard (*Sardinops neopilchardus*) (10.0%) occurred less frequently (Morrow 1952; Baker 1966; Saul 1983; Figure 4.1). The variability in saury and pilchard occurrence between studies suggests that these

prey items undergo seasonal changes in abundance or availability to striped marlin. As saury and pilchard shoal and spawn in inshore waters during the summer, marlin may prey upon them more frequently during years when warm blue water currents (where striped marlin are captured most frequently) converge closer to inshore waters.

Morrow (1952) identified a different composition of prey items compared to the three subsequent studies conducted in New Zealand by indentifying a higher percent occurrence of "other" species such as kahawai (*Arripis trutta*) and snapper *(Chrysophyrs auratus)* (Figure 4.1; Table 4.2). As kahawai and snapper are inshore species, it is possible that Morrow (1953) collected striped marlin from closer to shore as result of boat /engine limitations or methods of fishing during the 1950's.

Squid are consistent prey items of striped marlin throughout the Pacific Ocean and New Zealand is no exception with arrow squid accounting for 48.6% of the IRI (Figure 4.3). In Mexico, jumbo flying squid (*Dosidicus gigas*) are a common prey item throughout the year but are particularly important during the summer when they migrate to this region (Abitia-Cardenas et al. 1997). La Monte (1955) found only squid (unidentified spp.) in striped marlin stomachs captured off the coast of Peru and Chile.

In subtropical regions of cooler water such as New Zealand and Chile cephalopods seem to comprise a larger portion of the striped marlin diet compared to more tropical regions where epipelagic fish often dominate their diet (La Monte 1955; de Sylva 1962). The large composition of cephalopods in the diet of striped marlin from subtropical regions is likely due to higher squid concentrations rather than different geographic food preferences.

La Monte (1955) noted the abundance of squid on the surface at night and hypothesized that striped marlin were feeding at this time. To support this hypothesis,

La Monte (1955) collected undigested squid from marlin captured early in the morning and thoroughly digested squid from marlin captured later in the day. However, Bromhead et al. (2004) notes that longline catch rates of striped marlin are higher during the day than at night. In the present study, 66.7% of squid were classified at the advanced stage four of digestion which may indicate nighttime feeding of these prey items (Figure 4.4). There were however, several undigested squid collected from striped marlin captured during the afternoon hours. Satellite tagging studies in New Zealand show that striped marlin frequently make dives exceeding 100 m during the day (Sippel et al. unpublished). It is possible that striped marlin make diurnal dives to search for mesopelagic prey items such as tuna and squid. In contrast to squid however, only 7.8% of fish were at the advanced stage 4 of digestion which indicates day time feeding for these prey items. However, it must be considered that squid are likely to be digested more rapidly than fish because of their soft bodies and lack of scales.

The total number of striped marlin that enter the New Zealand EEZ is likely to be greater than 20,000 but most probably do not stay within the EEZ for the duration of four months. Satellite tagging studies have shown the striped marlin in New Zealand only spend about 8% of their time within range of the recreational fishing fleet (Sippel et al. unpublished).

Estimates of daily ration for striped marlin are proportionally less than estimates for swordfish and shortfin mako sharks (Stillwell & Kohler 1982; Stillwell & Kohler 1985; Table 4.2). Estimates for striped marlin may be underestimated because evacuation rates for mako sharks (used for striped marlin calculations) could be less than those in marlin. This is a reasonable assumption because marlin generally inhabit warmer waters than mako sharks and swordfish, which can

accelerate rates of metabolism and potentially evacuation rates. However, mako sharks are endothermic and rates of digestion may be accelerated as is true for bluefin tuna (*Thunnus thynnus*) which show an increase in stomach temperature of 10-15° C above ambient water temperature (Carey et al. 1984).

Consumption estimates indicate that during a 120 day residency in the New Zealand EEZ, a population of 20,000 striped marlin may consume between 2309 and 3072 metric tonnes of biomass (Table 4.3). The two primary prey items of striped marlin the jack mackerel and arrow squid both support large commercial fisheries in New Zealand which exceed 34,000 and 43,000 tonnes respectively (MAF 2004). Assuming an annual consumption rate of 3072 tonnes and calculated IRI percentages, striped marlin alone may consume the equivalent of ≈ 2.8 - 3.5% of New Zealand's current commercial catch of jack mackerel and arrow squid.

Chapter 5

General discussion and summary

The nature of billfish and their fisheries merits a need for worldwide cooperation from experts in fields ranging from fisheries, molecular science and physiology to international policy, economics and mathematics. There exists numerous challenges in studying and managing pelagic fishes but there is a dire need for fundamental biological information in order to ensure the sustainability of current fishing practices. Technologies in satellite tagging and molecular science will undoubtedly aid our understanding of these species and will hopefully address questions about stock structure, migration patterns and behaviour which have not been answered during the past century of research.

Information presented in this report may be used to help clarify uncertainties about striped marlin population size structure, growth, factors influencing conventional tag recoveries and the role of striped marlin in trophic dynamics of the pelagic ecosystem. Particular emphasis was placed on New Zealand's fishery but the highly migratory nature of this species undoubtedly has implications for other waters which striped marlin seasonally inhabit.

Ensuring the survival of striped marlin after release from recreational and commercial by-catch fisheries is essential if catch-and-release is to be a successful management strategy. Results from this study show that tag recovery rates and presumably post-release survivorship would improve if capture times in recreational fisheries were reduced to under 39 min and if an increased number of small (<90 kg) striped marlin were tagged and released. These data may be used to inform anglers about methods which maximise the potential for tag returns. Further research on post-

release survivorship of marlin is needed and may focus specifically on capture time, fish size, gear type, handling regimes as well as the effects of different environmental conditions.

As top predators, striped marlin play an important role in the trophic dynamics of the pelagic ecosystem of Pacific and Indian Oceans. Results from this study show that show that striped marlin are a generalist predator which prey on numerous organisms ranging from fish to crustaceans and cephalopods. Squid (*Nototodarus spp.*) are an important component of the diet of striped marlin in New Zealand but fishes such as jack mackerel (*Trachurus murphyi*) and saury (*Scomberesox saurus*) are also common.

Striped marlin are fished commercially but are more well known by recreational fishers who target them because their large size and athletic abilities. The size of striped marlin in New Zealand's recreational fishery has significantly declined over the past 79 years. The decline in average size may be attributed to commercial longlining but a size decline occurs in most fish populations which experience exploitation. The reduced size of striped marlin in New Zealand may indicate a decline in Pacific Ocean spawning stock biomass, especially because 98% of striped marlin captured in New Zealand are mature.

Despite high rates of growth, caution must be taken in that in that some biological features of this species such as large size at maturity and susceptibility to longline gear imply a certain degree of vulnerability to overexploitation. However, the status of striped marlin stocks will continue to be a mystery until improvements are made in commercial and scientific data collection. These uncertainties about management, basic biology and population dynamics of striped marlin require immediate attention and international collaboration.

REFERENCES

Abitia-Cardenas, L. A.; Galvan-Magna, F.; Muhlia-Melo, A. 1998: Trophic spectrum of striped marlin *Tetrapturus audax* (Philippi, 1887) off the coast of Cape San Lucas, Baja California Sur, Mexico. SO - Revista de Biologia Marina y Oceanografia 33(2): 277-290.

Abitia-Cardenas, L. A.; Galvan-Magana, F.; Rodriguez, M.F. 1997: Food habits and energy values of prey of striped marlin, *Tetrapturus audax*, off the coast of Mexico. SO - Fishery Bulletin 95(2): 360-368.

Abitia-Cardenas, L. A.; Muhlia-Melo, A.; Cruz-Escalona, V.C.; Galvan-Magna, F. 2002: Trophic dynamics and seasonal energetics of striped marlin *Tetrapturus audax* in the southern Gulf of California, Mexico. Fisheries Research (Amsterdam) 57: 287-295.

Allain, V. 2003: Diet of mahi-mahi, wahoo and lancetfish in the western and central Pacific. Oceanic Fisheries Programme, Secretariat of the Pacific Community, Noumea, New Caledonia. SCTB16 Working paper. BBRG-6.

Armas, R.G.; Sosa-Nishizaki, O.; Rodriguez, R.F.; Perez, V.A.L. 1999: Confirmation of the spawning area of the striped marlin, *Tetrapturus audax*, in the so-called core area of the eastern tropical Pacific off Mexico. Fisheries Oceanography 8: 238-242.

Ayers, D.; Francis, M.P.; Griggs, L.H.; Baird, S.J. 2004: Fish bycatch in New Zealand tuna longline fisheries, 2000–01 and 2001–02. New Zealand Fisheries Assessment Report 2004/46.

Ayling, T.; Cox, G.J. 1984: Collins guide to the sea fishes of New Zealand. William Collins Publishers Ltd., Auckland, New Zealand.

Block, B.A. 1986: Structure of the brain and eye heater tissue in marlins, sailfish, and spearfishes. Journal of Morphology 190: 169-189.

Block, B. A.; Booth, D.T.; Carey, F. G. 1998: Depth and temperature of the blue marlin, *Makaira nigricans*, observed by acoustic telemetry. Marine Biology 114: 175–183.

Boggs, C. H. 1990: Vital rate statistics for billfish stock assessment. *In* Stroud, Richard H.(editor), Planning the Future of Billfishes: Research and Management in the 90s and Beyond.Proceedings of the Second International Billfish Symposium, Kailua-Kona, Hawaii, August 1-5,1988, Part 1: 225-233.

Boggs, C. H. 1992: Depth, capture time and hooked longevity of longline caught pelagic fish: timing bites of fish with chips. Fishery Bulletin 90: 642-658.

Brill, R. W.; Holts, D. B.; Chang, R. K. C.; Sullivan, D.; Dewar, H.; Carey, F. G. 1993: Vertical and horizontal movements of striped marlin (*Tetrapturus audax*) near the Hawaiian Islands, determined by ultrasonic telemetry, with simultaneous measurement of ocean currents. Marine Biology 117: 567–574.

Brill, R.W. 1996: Selective advantages conferred by the high performance physiology of tunas, billfishes and dolphin fish. Comparative Biochemistry and Physiology 113A(1): 3-15.

Brill, R.W.; Lutcavage, M.; Metzger, G.; Bushnell, P.; Arendt, M.; Lucy, J. 2002: Survival of juvenile northern bluefin tuna following catch and release, using ultrasonic telemetry. Trans. Amer. Fish Soc. 30: 180-183.

Brock R.E. 1984: A contribution to the trophic biology of the blue marlin (*Makaira nigricans*) in Hawaii. Pacific Science 38: 141-149.

Bromhead, D.; Pepperell, J.; Wise, B.; Findlay, J. 2004: Striped marlin: biology and fisheries. Final Report to the Australian Fisheries Management Authority Research Fund and the Fisheries Resources Research Fund. Bureau of Rural Sciences. Canberra, Australia.

Carey, F.G.; Kanwisher, J.W.; Stevens, D. 1984: Bluefin tuna warm their viscera during digestion. Journal of Experimental Biology 109: 1-20.

Clark, M.R. 1986: A handbook for the identification of cephalopod beaks. Oxford Clarendon press.

Clothier, C. R. 1950: A key to some southern California fishes based on vertebral characters. Calif. Dep. Fish Game Fish Bull. 79: 1-83.

Dalzell, P.; Boggs, C.H. 2003: Pelagic fisheries catching blue and striped marlin in the US Western Pacific Islands. Journal of Marine and Freshwater Research 54: 419-424.

Davie, P.S.; Hall, I. 1990: Potential of dorsal and anal spines and otoliths for assessing age structure of the recreational catch of striped marlin. Proceedings of the Second International Billfish Symposium, Kailua-Kona, Hawaii,Part 2: 287-294.

Davie, P. S.1990: Pacific Marlins: Anatomy and Physiology. Palmerston North, New Zealand, Massey University Printery and Simon Print.

Davie, P. S.; Sparksman, R. I. 1986: Burnt tuna: An ultrastructural study of postmortem changes in muscle of yellowfin tuna *Thunnus albacares* caught on rod and reel and southern bluefin tuna *Thunnus maccoyii* caught on handline or longline. Journal of Food Science 51: 1122 -1128 & 1168.

Dell, R.K. 1952: The recent cephalopoda of New Zealand. Wellington, New Zealand. Dominion Museum bulletin no. 16.

de Sylva, D.P. 1962: Red water blooms off northern Chile, April-May 1956, with reference to the ecology of the swordfish and striped marlin. Pacific Science 16(3): 271-279.

Domeier, M. L.; Dewar, H.; Nasby-Lucas, N. 2003: Post-release mortality rate of striped marlin caught with recreational tackle. Marine and Freshwater Research 54: 435-445.

Ehrhardt, N.M.1992: Age and growth of swordfish (*Xiphias gladius*) in the Northwestern Atlantic. Bulletin of Marine Science 50(2): 299-301.

Eldridge, M. B.; Wares, P.G. 1974: Some biological observations of billfishes taken in the Eastern Pacific Ocean, 1967-1970. In: Shomura, R.S. and Williams, F., (Eds.) Proceedings of the International Billfish Symposium, Kailua-Kona, Hawaii, 9-12 August 1972. Part 2. Review and Contributed Papers: 89-101.

Evans, D.H.; Wares, P.G. 1972: Food habits of the striped marlin and sailfish off Mexico and southern California.Fish Wildl. Serv. Res. Rep. 76: 1-10.

FAO, Fisheries 2004: Databases and statistics. World Wide Web: http://www.fao.org/fi/statist/statist.asp. Accessed 2004.

Farman, R.S.1990: The adequacy of current billfish fishery statistics for stock assessment and management purposes. Proceedings of the Second International Billfish Symposium, Kailua-Kona, Hawaii, Part 1:215-223.

Ferguson, R.A.; Kieffer, J.D.; Tufts, B.L. 1993: The effects of body size on the acid-base and metabolite status in the white muscle of rainbow trout before and after exhaustive exercise. Journal of Experimental Biology 180: 195-207.

Finnerty, J.R.; Block, B.A. 1995: Evolution of cytochrome b in the Scombroidei (Teleostei): molecular insights into billfish (Istiophoridae and Xiphiidae) relationships. Fishery Bulletin 93: 78-96.

Fritsches, K.; Warrant, E. 2004-In Press: Do tuna and billfish see colours? Pelagic Fisheries Research Program, University of Hawaii 9(1): 1-3.

Froese, R.; Pauly, D. Editors. 2004: Fish Base. World Wide Web: www.fishbase.org. Accessed 2004.

Galvan-Magana, F. 2001: Trophic overlap between three billfish species from Cabo San Lucas, Mexico. Abstract: Third International Billfish Symposium.

Godinot, O.; Allain, V. 2003: A preliminary ECOPATH model for the warm pool pelagic ecosystem. Fisheries Programme, Secretariat of the Pacific Community, Noumea, New Caledonia. SCTB16 Working paper. BBRG-5.

Gonzalez-Armas, R.; Sosa-Nishizaki, O.; Funes-Rodriguez R.; Levy-Perez, A. 1999: Confirmation of the spawning area of the striped marlin, *Tetrapturus audax* in the so-called core area of the eastern tropical Pacific off Mexico. Fisheries Oceanography 8(3): 238-242.

Graves, J.E.; McDowell, J.R.1994: Genetic analysis of striped marlin population structure in the Pacific Ocean. Canadian Journal of Aquatic Science 51:1762-1768.

Graves, J.E.; McDowell, J.R. 1995: Inter-Ocean genetic divergence of istiophorid billfishes. Marine Biology 122: 193-203.

Graves, J.E. 1998: Molecular insights into the population structures of cosmopolitan marine fishes. The Journal of Heredity 89: 427-437.

Graves, J.E.; Lockhurst, B.E.; Prince, E.D. 2002: An evaluation for pop-up satellite tags for estimating post-release survival of blue marlin (*Makaira nigricans*) from a recreational fishery. Fishery Bulletin 100: 134-142.

Graves, J.E.; McDowell, J.R. 2003: Stock structure of the world's istiophorid billfishes: a genetic perspective. Marine and Freshwater Research 54: 287-298.

Gregory, K.; Conrad, G.M.1939: Body forms of the black marlin (*Makaira nigricans marlina*) and striped marlin (*Makaira mitsukurii*) of New Zealand and Australia. Amereican Museum of Natural History, Bulletin 76 (8): 443-456.

Hanamoto, E. 1977: Fishery Oceanography of Striped Marlin Part 2 Spawning Activity of the Fish in the Southern Coral Sea. SO - Nippon Suisan Gakkaishi-Bulletin of the Japanese Society of Scientific Fisheries. 43(11). 1977 (RECD 1978): 1279-1286.

Hinton, M.; Bayliff, W. 2002: Status of striped marlin in the Eastern Tropical Pacific Ocean in 2001 outlook for 2002. BBG-1: Working paper for the 15th Meeting of the Standing Committee on Tuna and Billfish, Honolulu, Hawaii.

Hinton, M.; Maunder, M. 2003: Status of striped marlin in the Eastern Pacific Ocean in 2001 and outlook for 2003/2004. Draft: For the 4th meeting of the IATTC scientific working group.

Holdsworth, J.; Saul, P.; Browne, G. 2003: Factors effecting striped marlin catch rates in the New Zealand Recreational Fishery. Journal of Marine and Freshwater Research 54: 473-481.

Holdsworth, J.; Saul, P. 2003: New Zealand billfish and gamefish tagging, 2001-02. Fisheries assessment report: Blue Water Marine Research Ltd, Whangarei.

Holdsworth, J.; Saul, P.2004: New Zealand billfish and gamefish tagging 2003-2004. Fisheries assessment report: Blue Water Marine Research Ltd, Whangarei.

Holland, K.; Brill, R.; Chang, R. K. C.1990: Horizontal and vertical movements of Pacific blue marlin captured and released using sportfishing gear. Fishery Bulletin 88: 397-402.

Holland, K. 2003: A perspective on billfish biological research and prospects for the future. Journal of Marine and Freshwater Research 54: 343-7.

Holts, D.; Bedford, D. 1990: Activity patterns of striped marlin in the Southern California Bight. In: Stroud, R.H., (Ed.) Planning the future of billfishes. Research and management in the 90's and beyond. Part 1: 81-93.

Hubbs, C.L.; Wisner, L. 1953: Food of marlin in 1951 off San Diego California. Calif. Fish Game 39 (1): 127-131.

International Game Fish Association. 2004: World records. web site: http://www.igfa.org/records.asp. Accessed: October 19, 2004.

Jolley, J.W.; Irby, E.W. 1979: Survival of tagged and released Atlantic sailfish (*Istiophorus platypterus*: Istiophoridae) determined by acoustical telemetry. Bulletin of Marine Science 29: 155-169.

Journal of Marine and Freshwater Research (JMFR) 2003: Billfish special issue. Proceedings of the 3rd International Billfish Symposium in Cairns, Queensland Australia, 19-23 August 2001. Marine and Freshwater Research 54(4).

Kerstetter, D. W.; Luckhurst, B.E.; Prince, E.D.; Graves, J.E. 2003: Use of pop-up satellite archival tags to demonstrate survival of blue marlin (*Makaira nigricans*) released from pelagic longline gear. Fishery Bulletin 101: 939-94.

Kingett-Mitchell, L. 2002: The economic contribution of the New Zealand Recreational Billfish Fishery in 2000-2001., New Zealand Marine Research Foundation.

Kopf, R.K.; Davie, P.S., Holdsworth, J. Unpublished: Size trends and growth of striped marlin, *Tetrapturus audax* in the New Zealand recreational fishery. Submitted 2004: to the New Zealand Journal of Marine and Freshwater Research.

Koto, T. 1963: Some considerations on the growth of marlins, using size frequencies in commercial catches. III. Attempts to estimate the growth of striped marlin, *Tetrapturus audax* (Philippi) in the western North Pacific Ocean. Report of Nankai Regional Fisheries Research Laboratory 17: 63-85.

Kume, S; Joseph, J.1969: Size composition and sexual maturity of billfish caught by the Japanese longline fishery in the Pacific Ocean east of 130W. Bulletin of the Far Seas Fisheries Research Laboratory 2: 115-162.

Labelle, M.; Hampton, J. 2003: Stock assessment of albacore tuna in the South Pacific Ocean. Secretariat of the Pacific Community Noumea, New Caldonia. SCTB16 Working Paper ALB-1.

La Monte, F.R. 1955: A review and revision of the genus Makaira. Bull. Am. Mus. Nat. Hist. 107 (3): 323-358.

Latour, R.J.; Brush, M.J.; Bonzek, C.F. 2003: Toward ecosystem-based fisheries management: strategies for multispecies modeling and associated data requirements. Fisheries Management 28 (9): 10-22.

Leis, J. M.; Goldman, B.; Ueyanagi, S. 1987: Distribution and Abundance of Billfish Larvae Pisces Istiophoridae in the Great Barrier Reef Lagoon and Coral Sea near Lizard Island Australia. SO - Fishery Bulletin 85(4): 757-766.

Lukacovic, R.; Uphoff, J.H. 2002: Hook location, fish size, and season as factors influencing catch-and-release mortality of striped bass caught with bait in the Chesapeake Bay. Trans. Amer. Fish Soc. 30: 97-100.

Ministry of Agriculture and Fisheries (MAF) 2004: Summary of the assessments of the sustainability of current TACCs and recent catch levels and status of the stocks for the 2004-05 fishing year. Reports on Jack Mackerel and Squid. Accessed World Wide Web:
http://www.fish.govt.nz/sustainability/research/stock/status.htm

Malchoff, M.H.; Gearhart, J; Lucy, J.; Sullivan, P.J. 2002: The influence of hook type, wound location and other variables associated with post catch-and-release mortality in the U.S. summer flounder recreational fishery. Trans. Amer. Fish Soc. 30: 101-105.

Melo-Barrera, F.N.; Uraga-Felix, R.; Velazquez-Quinonez, C. 2003: Growth and length-weight relationship of the striped marlin in Cabo San Lucas, Baja California Sur, Mexico. Ciencias Marinas 29(3): 305-313.

Melo-Barrera, F.N.; Felix-Uraga, R. 2002: Estructura de tallas y edad del marlin rayado, en Cabo San Lucas, BCS, Mexico in Melo-Barrera et al. (2003) Growth and length-weight relationship of the striped marlin in Cabo San Lucas, BCS, Mexico. Ciencias Marinas 29(3): 305-313.

Merrett, N.R. 1970: Gonad development in billfish (Istiophoridae) from the Indian Ocean. Journal of Zoology, London 160: 355 -370.

Merrett, N.R. 1971: Aspects of the biology of billfish (Istiophoridae) from the equatorial western Indian Ocean. Journal of Zoology, London 163: 351-395.

Miller, D. L.; Jorgenson, S. C. 1973: Meristic characters of some marine fishes of the western Atlantic Ocean. U.S. Fish Wildlf. Serv. Fish. Bull. 71(1): 301–312.

Miyabe, N.; Bayliff, W.H. 1987: A review of the Japanese longline fishery for tunas and billfishes in the eastern Pacific Ocean, 1971-1980. Inter-Amer. Trop. Tuna Comm., Bull. 19(1): 164.

Morrow, J. 1951: A striped marlin without a spear. Copeia 4: 303-304.

Morrow, J.E. 1952 (A): Allometric growth of striped marlin from New Zealand. Pacific Science VI: 53-58.

Morrow, J.E. 1952: Food of striped marlin *Makaira mitsukurii* from New Zealand. Copeia 3: 143-145.

Morrow, J.E. 1957: Races of the striped marlin (*Makaira mitsukurii*) in the Pacific. Bulletin of the Bingham Oceanogra.phic Collection XVI (2): 72-86.

Moteki, M.; Arai, M.; Tsuchiya, K.; Okamoto, H. 2001: Composition of piscine prey in the diet of large pelagic fish in the eastern tropical Pacific Ocean. Fisheries Science 67: 1063-1074.

Nakamura, I. 1985: FAO species catalogue, Vol. 5. Billfishes of the world. An annotated and illustrated catalogue of marlins, sailfishes, spearfishes and swordfishes known to date. Fisheries Synopsis. No. 125. (FAO: Rome).

Nishikawa, Y.; Honma, M.; Ueyanagi, S.; Kikawa, S. 1985: Average distribution of larvae of oceanic species of scombrid fishes, 1956-1981. Bull. Far Seas Res. Lab. S. Series 12: 99.

Ortega-Garcia, S.; Klett-Traulsen, A.; Ponce-Diaz, G. 2003: Analysis of sportfishing catch rates of striped marlin (Tetrapturus audax) at Cabo San Lucas, Baja California Sur, Mexico, and their relation to sea surface temperature. Marine and Freshwater Research 54: 483-488.

Ortiz, M., Prince, E.D.; Serafy, J.E.; Holts, D.B.; Davy, K.B.; Pepperell, J.G.; Lowry, M.B.; Holdsworth, J.C. 2003: A global overview of the major constituent-based billfish tagging programs and their results since 1954. Marine and Freshwater Research 54: 489-507.

Parker, A.R. 2001: Marlin colors - the perfect disguise. In: Miller, M.L., Daxboeck, C., Dahl, C., Kelly, K. and Dalzell, P., (Eds.) Facing the challenge of resource conservation, sustainable development, and the sportfishing ethic. Proceedings of the 1998 Pacific Island Gamefish Tournament Symposium: 29 July - 1 August, 1998, Kailua Kona, Hawaii: 165-169.

Paul, L. 2000: New Zealand Fishes: Identification, natural history and fisheries. Reed Books, New Zealand.132-133.

Paulin, C.; Stewart, A.; Roberts, C.; McMillan, P. 2001: New Zealand FISH a complete guide. Te Papa Press, Wellington, New Zealand.

Pepperell, J.G.; Davis, T.L.O. 1999: Post-release behaviour of black marlin (Makaira indica) caught and released by sportfishing gear off the coast of the Great Barrier Reef (Australia). Marine Biology 135: 369-380.

Pillai, P. P.; Ueyanagi, S. 1978: Distribution and biology of the striped marlin Tetrapturus audax (Philippi) taken by the longline fishery in the Indian Ocean. Bulletin of the National Research Institute of Far Seas Fisheries 16: 9-32.

Polovina, J.J. 1984: Model of a coral reef ecosystem: the ECOPATH model and its application to French Frigate Shoals. Coral Reefs 3: 1-11.

Ponce-Diaz, G.; Ortega-Garcia, S.; Ramirez-Gonzalez, P.G. 1991: Analysis of sizes and weight-length relation of the striped marlin, *Tetrapterus audax* (Philippi, 1887) in Baja California Sur, Mexico. Ciencias Marinas 17(4): 69-82.

Prince, E.D.; Brown, B. 1991: Cooardination of the ICCAT enhanced research program for billfish. In Guthrie, D.; Hoening, J.M; Holliday, M.; Jones, C.M.; Mills, M.J.; Moberly, S.A.; Pollock, K.H.; Talhelm, D.R., editors. Creel and angler surveys in fisheries management. Amer. Fish Soc. Symp. 12: 13-18.

Prince, E.D.; Ortiz, M.; Venizelos, A. 2002: A comparison of circle hook and "J" hook performance in recreational catch-and-release fisheries for billfish. Am. Fish. Soc. Symp. 30: 66-79.

Prince, E.D.; Ortiz, M.; Venizelos, A.; Rosenthal, D. 2002: In-water conventional tagging techniques developed by the cooperative tagging center for large, highly migratory species. Am. Fish. Soc. Symp. 30: 155-171.

Radtke, R.L. 1983: Istiophorid otoliths: extraction, morphology, and possible use as ageing structures. Proceedings of the International Workshop on Age Determination of Oceanic Pelagic Fishes: Tunas, Billfishes, and Sharks. US Dep. Commerce. NOAA Technical Report NMFS. 8: 123-129.

Ricker, W.E. 1975: Computation and interpretation on biological statistics of fish population. Bulletin of Fisheries Research Board Canada 191:1-392.

Rivas, L.R. 1956: Definitions and methods of measuring and counting in the billfishes. Bulletin of Marine Science, Gulf and Caribbean 6(1): 18-27.

Saul, P.J. 1983: Review of the catch of big gamefish from the Bay of Islands, New Zealand, 1925-1983. Palmerston North, N.Z. Massey University Press.

Saul, P.; Holdsworth, J. 1992: Cooperative gamefish tagging in New Zealand waters, 1975–90. New Zealand Fisheries Technical Report No. 33.

Schmidt-Nielsen, K. 1984: Scaling: Why is animal size so important? Cambridge, New York: Cambridge University Press pp. 241.

Scrimgeour, A.S. 1984: Aspects of the anatomy of the striped marlin (*Tetrapturus audax*) and the black marlin (*Makaira indica*). Bachelor of Philosophy Thesis, Massey University, Palmerston North, New Zealand.

Shomura, R.S.;Williams, F. 1974: Proceedings of the International Billfish Symposium Kailua-Kona, Hawaii, 9-12 August 1972. Part 1, Report and Symposium, Part 2. Reviews and Contributed Papers.

Sippel, T.J.; Davie, P.S.; Holdsworth, J.C.; Block, B.A. Unpublished: Migrations and environmental preferences of striped marlin (*Tetrapturus audax*) tagged in New Zealand with satellite transmitting archival tags.

Skillman, R. A.; Yong, M. Y. Y. 1976: von Bertalanffy Growth Curves for Striped Marlin *Tetrapturus a udax* and Blue Marlin *Makaira nigricans* in the Central North Pacific Ocean. SO - Fishery Bulletin 74(3): 553-566.

Skillman, R. A.; Yong, M. Y. Y. 1974: Length-weight relationships for six species of billfishes in the central Pacific Ocean. NOAA. Tech. Rep. NMFS, SSRF, 675 (2): 126-137.

Skillman, R.A. 1990: Status of Pacific billfish stocks. Proceedings of the Second International Billfish Symposium, Kailua-Kona, Hawaii. Part 1, Pp. 179-206.

Skomal, G. B.; Chase, B. C. 2002: The physiological effects of angling on post-release survivorship in tunas, sharks, and marlin. Am. Fish. Soc. Symp. 30: 135-138.

Squire, J.L. 1974: Migration patterns of Istiophoridae in the Pacific Ocean as determined by cooperative tagging programs. In: Shomura, R.S. and Williams, F. Proceedings of the International Billfish Symposium Kailua-Kona, Hawaii, 9-12 August 1972. Part 2 Review and Contributed Papers: 226-235.

Squire, J.L. 1983: Weight frequencies of striped marlin, *Tetrapturus audax*, caught off Southern California. Marine Fisheries Review 45: 7-9.

Squire, J.L. 1987: Striped marlin migration patterns and rates in the Northeast Pacfic Ocean as determined by a cooperative tagging program: its relation to resource managment. Marine Fisheries Review 49: 26-43.

Squire, J.L.; Susuki, Z. 1990: Migration trends of striped marlin in the Pacific Ocean. Proceedings of the Second International Billfish Symposium, Kailua-Kona, Hawaii, Part 2: 67-80.

Stillwell, C.E.; 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 Science 39: 407-414.

Stillwell, C.E.; Kohler, N.E. 1985: Food and feeding ecology of the swordfish *Xiphias gladius* in the western North Atlantic Ocean with estimates of daily ration. Marine Ecology 22: 239-247.

Stroud, R.H. 1989: Planning the future of billfishes : research and management in the 90s and beyond. Proceedings of the Second International Billfish Symposium. Savannah, Ga.: National Coalition for Marine Conservation.

Torres, F.J.; Pauly, D. 1991: Tabular data on marine fishes from southern Africa. Part 2: Growth Parameters. FishByte 9(2): 37-38.

Tree of Life (TOL) web project 2004: World Wide Web electronic publication. http://tolweb.org. Accessed 2004.

Ueyanagi, S. 1974: On an additional diagnostic character for the identification of billfish larvae with some notes on the variations in pigmentation. In: Shomura, R.S. and Williams, F., (Eds.) Proceedings of the International Billfish Symposium Kailua-Kona, Hawaii, 9-12 August 1972. Part 2. Review and Contributed Papers: 73-78.

Ueyanagi, S.; Wares, P.G. 1975: Synopsis of biological data on striped marlin, *Tetrapturus audax* (Philippi, 1887). In: Shomura, R.S. and Williams, F., (Eds.) Proceedings of the international billfish symposium, Kailua-Kona, Hawaii, 9-12 August 1972, Part 3. Species synopses: 132-159.

van der Elst, R.P. 1990: Aspects of the biology and sport fishery for billfishes in the s.w. Indian Ocean. Proceedings of the Second International Billfish Symposium, Kailua-Kona, Hawaii, Part 1: 147-158.

Walters, V. 1962: Body form and swimming performance in scombrid fishes. American Zoologist 2: 143-149.

Wares, P. G.; Sakagawa, G.T. 1974: Some morphometrics of billfishes from the Eastern Pacific Ocean. In: Shomura, R.S. and Williams, F., (Eds.) Proceedings of the International Billfish Symposium Kailua-Kona, Hawaii, Part 2: 107-121.

Wege, G.J.; Anderson, R.O. 1978: Relative weight (Wr): a new index of condition for largemouth bass. Pages 79-91 in G.D. Novinger and J.G. Dillard, editors. New approaches to the management of small impoundments. American Fisheries Society, North Central Division, Special Pub. 5, Bethesda, Maryland.

Wells, R.M.G.; Davie, P.S. 1986: Oxygen binding by the blood and hematological effects of capture stress in two big game-fish: mako shark and striped marlin. Comparative Biochemistry and Physiology 81A: 643-646.

Wells, R.M.G.; McIntryre, R.H.; Morgan, A.K.; Davie, P.S. 1986: Physiological stress responses in big game fish after capture: observations on plasma chemistry and blood factors. Comparative Biochemistry and Physiology 84A (3): 565-571.

Wood, C. M.; Turner, J. D.; Graham, M. S. 1983: Why do fish die after severe exercise? Journal of Fish Biology 22: 189-201.

Whitelaw, W. 2003: Recreational billfish catches and gamefishing facilities of Pacific Island nations in the Western and Central Pacific Ocean. Journal of Marine and Freshwater Research 54: 463-471.

Appendices

Appendix A. Ten year weight (kg) frequency distribution for striped marlin (n=15, 114) in the Bay of Islands Swordfish Club (1925-2003). Weights include estimates for tag-and-release starting in 1976. Modal weight (kg) class shaded.

Weight (kg)	1925-1934	1935-1944	1945-1954	1955-1964	1965-1974	1975-1984	1985-1994	1995-2003	SUM
0-9	0	0	0	0	0	0	0	0	0
10-19	0	0	0	0	0	0	0	0	0
20-29	0	0	0	0	0	0	0	0	0
30-39	0	0	0	0	1	6	3	3	13
40-49	0	0	3	7	1	14	9	15	49
50-59	0	1	5	9	9	18	28	44	114
60-69	3	2	11	26	25	71	120	194	452
70-79	6	5	62	70	61	153	337	417	1111
80-89	21	25	198	154	109	364	527	651	2049
90-99	71	52	415	265	142	478	475	662	2560
100-109	81	165	584	396	136	563	360	421	2706
110-119	94	157	507	335	108	431	272	401	2305
120-129	77	103	371	273	78	298	196	299	1695
130-139	56	80	214	191	47	164	103	136	991
140-149	33	46	108	110	31	105	47	74	554
150-159	23	19	46	57	20	51	49	46	311
160-169	6	9	15	30	10	22	13	13	118
170-179	7	3	8	8	0	4	15	7	52
180-189	1	3	1	4	1	6	2	3	21
190-199	0	1	2	0	0	1	0	4	8
200-209	0	0	0	0	1	0	0	2	3
210-219	0	0	0	0	0	0	0	0	0
220-229	0	0	0	0	0	0	0	1	1
230-239	0	0	0	0	0	0	0	0	0
240-249	0	0	0	0	0	0	0	1	1
Sum	479	671	2550	1935	780	2749	2556	3394	15114

Appendix B. Monthly weight (kg) frequency distribution for striped marlin (n=15,142) in the Bay of Islands Swordfish Club. Weights include estimates for tag-and-release but no marlin were recorded from August through November. Modal weight (kg) class shaded.

Weight (kg)	December	January	February	March	April	May	June	July	Sum
0-9	0	0	0	0	0	0	0	0	**0**
10-19	0	0	0	0	0	0	0	0	**0**
20-29	0	0	0	0	0	0	0	0	**0**
30-39	0	5	5	3	0	0	0	0	**13**
40-49	2	6	18	19	4	0	0	0	**49**
50-59	3	24	41	38	6	1	1	0	**114**
60-69	13	110	174	106	39	10	0	0	**452**
70-79	17	208	365	339	153	28	1	0	**1111**
80-89	24	341	674	642	295	69	4	0	**2049**
90-99	28	360	815	787	435	129	6	0	**2560**
100-109	24	342	802	820	541	161	10	0	**2706**
110-119	21	294	638	692	476	168	19	0	**2305**
120-129	14	180	439	515	366	165	17	1	**1695**
130-139	5	93	239	314	229	87	16	1	**991**
140-149	3	50	124	160	154	52	11	0	**554**
150-159	3	25	65	99	73	37	9	0	**311**
160-169	1	4	23	39	26	20	5	0	**118**
170-179	1	3	11	23	7	6	1	0	**52**
180-189	1	3	4	8	2	3	0	0	**21**
190-199	0	0	3	0	1	4	0	0	**8**
200-209	0	0	0	3	0	0	0	0	**3**
210-219	0	0	0	0	0	0	0	0	**0**
220-229	0	0	1	0	0	0	0	0	**1**
230-239	0	0	0	0	0	0	0	0	**0**
240-249	0	0	1	0	0	0	0	0	**1**
Sum	**160**	**2048**	**4442**	**4607**	**2806**	**940**	**99**	**2**	**15114**

Appendix C. Morphometric measurements taken from striped marlin (n=20) used in diet analysis from New Zealand.

ID	Date	Port	Sex	Weight (kg)	LJFL Staight (mm)	LJFL Curve (mm)	EFL Curve (mm)	Body Depth Straight (mm)	Body Depth Curve (mm)	Height First Dorsal (mm)	Pectoral Length (mm)
1U	24-Mar-04	WHANGAROA	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
17	20-Mar-04	HOUHURA	M	88.8	2325	2381	2004	488	402	476	507
18	20-Mar-04	HOUHURA	M	90.4	2370	2394	2010	510	385	405	411
19	20-Mar-04	HOUHURA	M	82.6	2182	2220	1871	499	406	410	452
22	21-Mar-04	HOUHURA	M	76.6	2289	2357	1973	n/a	n/a	n/a	n/a
23	21-Mar-04	HOUHURA	F	88	2141	2185	1842	n/a	n/a	n/a	n/a
25	21-Mar-04	HOUHURA	F	125.2	2432	2491	2106	n/a	n/a	n/a	n/a
26	21-Mar-04	HOUHURA	M	131.6	2390	2379	2001	572	n/a	459	n/a
28	22-Mar-04	HOUHURA	M	107.6	2419	2442	2064	536	445	486	553
30	22-Mar-04	HOUHURA	M	100.4	2375	2413	2025	546	465	405	467
32	22-Mar-04	HOUHURA	M	84.4	2281	2319	1966	485	412	449	517
33	23-Mar-04	HOUHURA	F	76.8	2157	2191	1831	492	386	409	484
36	24-Mar-04	HOUHURA	M	111.4	2323	2385	2020	544	461	493	556
37	24-Mar-04	HOUHURA	F	89.2	2289	2339	1971	504	426	457	474
38	24-Mar-04	HOUHURA	M	116.4	2388	2356	2015	575	475	479	490
39	24-Mar-04	HOUHURA	F	132.4	2450	2503	2165	n/a	463	451	499
41	27-Mar-04	WHANGAROA	F	146.6	2582	2656	2190	635	518	513	556
42	27-Mar-04	WHANGAROA	M	110.2	2336	2439	2024	558	471	457	555
43	28-Mar-04	WHANGAROA	M	95.4	2275	2296	1937	509	429	446	n/a
45	29-Mar-04	WHANGAROA	F	121	2488	2546	2163	537	453	500	551

Appendix D. Swimming behaviour of rainbow trout during simulated capture by hook-and-line

ABSTRACT

To determine the effects of hook impalement, rainbow trout *Oncorhynchus mykiss* (Walbaum) were exposed to simulated capture attached by an elastic line fixed to a force transducer. Tension exerted (swimming behaviour) was compared between three conditions where trout were attached to the elastic line by: (1) a hook through the upper jaw (Hook), (2) a surgically implanted mouth anchor (Non-hook) and (3) a surgically implanted mouth anchor but also impaled with a hook unattached to any line (Impale). Mean tensions (n = 54, P = 0·210) and physiological parameters (muscle lactates, plasma lactates, K^+, Na^+, cortisol, and haematocrits) measured were not significantly different between conditions. However, tensions exerted during the final 10 min of the Hook condition were significantly less than tensions exerted during the final 10 min of Non-Hook (n = 36, P < 0·001) and Impale (n = 36, P = 0·030) conditions. Regardless of being hooked, swimming activity was highest during min 0 – 5 and lesser tension was exerted during min 6- 20. In all trials the highest mean tensions were observed during min 1 but these were not significantly different between conditions (n = 54, P = 0·368). Results from this study show that in rainbow trout: (1) hook impalement plays a minor role in behavioural and physiological responses during capture by hook-and-line (2) the escape response elicited during capture is related more to restricting free movement than to hooking in the mouth.

INTRODUCTION

Fishery managers are primarily interested in how angling affects population, community and ecosystem dynamics but the impacts of capture by hook-and-line on individual fish are critical components in fisheries policy and also have implications for animal welfare (Cooke et al. 2002). Interest in the welfare of fish is rising and in particular there is intense debate about how fish are affected by angling (Balon 2000; LeChat 1996). Quantifiable and objective measures of the effects of catch-and-release on the welfare of fish will be necessary for policy governing this sport (Cooke et al. 2002). Capture of fish can cause tissue damage (Davie & Sparksman 1986), changes in haemtatology and blood borne hormones (Wells et al. 1986; Wells 1987) and a variety of post-release impacts such as suppressed reproductive function and death (Wood et al. 1983; Melotti et al. 1992).

Arguments concerning the welfare of angled fish naturally drift toward whether or not fish can experience pain, suffering, or fear (Gregory 1999; Rose 2002). Fish do not possess the same neurological structures that mammals possess which allow consciousness and suffering, however but as demonstrated from behavioural, physiological and anatomical research it appears that they may experience some of the adverse effects of pain that mammals experience (FSBI 2002; Rose 2002). Regardless of whether or not fish experience pain as humans do, the recreational fishing community will soon be held liable for the welfare of fish which are affected by angling. Despite this controversy, there exists little empirical evidence on which make recommendations about how to improve the welfare of angled fish.

Anatomical studies have revealed that rainbow trout *(Oncorhynchus mykiss)* (Walbaum) possess nociceptors (A delta and C fibres) which are used for pain perception in other vertebrate groups (Sneddon 2002). Although rainbow trout have

nociceptors and may feel pain, three species of elasmobranches probably do not have the neural system even for simple nociception (Snow et al. 1993). Other research has demonstrated that teleosts are capable of learning to avoid noxious stimuli such as electrical shocking and that analgesics can reduce physiological and behavioural disturbances caused by events perceived as painful by people (Davis & Klinger 1994; Sneddon 2003). These approaches have been critised because they may not distinguish nociceptive responses from pain or separate Pavlovian conditioning from true learning or do not accurately interpret the neurobiology of fish (Rose 2002; LeChat 1996). For example, the application of morphine may reduce physiological and behavioural responses regardless of whether or not the animal can experience pain and "simple" invertebrates have been conditioned to avoid noxious stimuli without conscious learning (Braithwaite & Huntingford 2004; Rose 2002).

Rose (2002) proposes that fish are unable to experience pain because they lack complex cerebral hemispheres that allow a consciousness and emotional response, which are necessary for humans to experience pain. This view relies heavily on the concept that psychological and neurological functions associated with pain are entirely dependent on specific neurological structures, which fish do not possess and that fish do not experience using other parts of the nervous system. However, it has been demonstrated that birds and mammals perceive and process the same visual information via different neurological structures (see Braithwaite & Huntingford 2004). Differences in animal brain structure and processing duties of parts of the brain may allow fish to experience pain using different parts of the brain compared with the neurological structures that humans require to experience pain (Braithwaite & Huntingford 2004).

Regardless of the controversy surrounding recreational fishing and its relationship with animal welfare, no research has attempted to quantify behaviour of fish during capture. The capture of a fish by hook-and-line can broadly be described as a chronological sequence of activities: (1) fish attraction to the lure, (2) hooking, (3) behavioural restriction, (4) retrieval, (5) landing, (6) dispatch/release. The time from hooking to landing is a primary period in which stress responses are evoked and is potentially a time of welfare comprise. The purpose of this study is to determine the relative importance of hook impalement versus behavioural restriction in generating escape response swimming during recreational capture.

This study used a force transducer to quantify the behavioural response of rainbow trout impaled with a hook during simulated capture using a fixed but elastic line. Swimming behaviour away from the fixed point as described by tension and was compared between three conditions where trout were attached to a force transducer by: (1) a hook through the upper jaw (Hook), (2) a surgically implanted mouth anchor (Non-hook) and (3) a surgically implanted mouth anchor but also impaled with a hook unattached to any line (Impale).

MATERIALS AND METHODS

Study Animals and Surgical Procedures

Rainbow trout (n = 18) mean body mass 0·28 kg ± 0·02 (all means ± S.E.) were obtained from the New Zealand National Trout Centre in Turangi. Prior to experimentation fish were acclimated to approximately 15 ° C water temperature for a minimum of one week in a 3600 L cylindrical holding tank. Fish were fed to satiation twice daily using proprietary pellets.
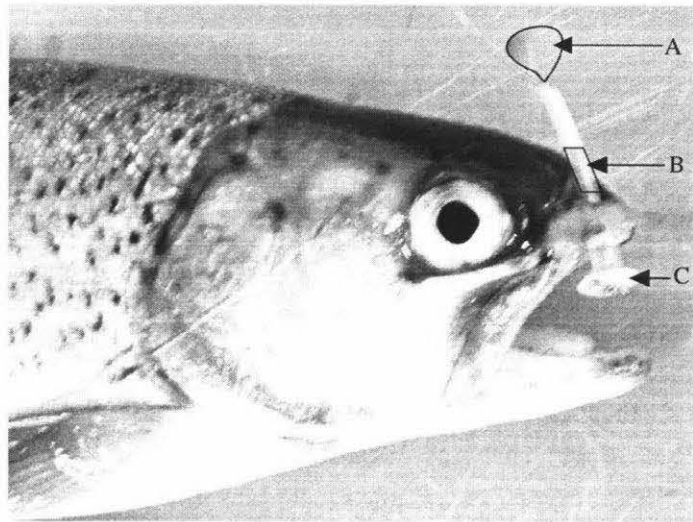
Figure 1. Rainbow trout implanted with plastic mouth anchor inserted between the ethmoid and premaxilla bones. A, suture wire loop; B, anchor coupling; C, anchor base. Anchor base placed flush against palate during experiments and leader attached to suture wire (A) melted into anchor (* see Figure 2).

In preparation for surgery fish were dip netted from the holding tank and anaesthetized in 20 L of 0·04% Benzocaine. Once anaesthetised, fish were weighed ± 0·01 kg. During surgery fish were implanted with a mouth anchor inserted through the palate between the ethmoid and maxillary bones (Figure 1). The mouth anchor was 30 mm in length and made of 1 mm diameter polyethylene tubing melted at the base to form a flange 3 mm in diameter. A coupling made of polyethylene tubing was placed dorsally around the mouth anchor, which secured the base of the mouth anchor flush

against the palate of the fish's mouth. Orthopedic suture wire was threaded through the polyethylene tubing and fastened to a floating fly line leader (Figure 2).

The floating fly line leader was 1150 mm in length with a loop tied 300 mm above attachment to the fish. A 10 mm diameter styrofoam float was glued to the free end of leader to provide additional buoyancy. After surgery fish were resuscitated and isolated in one of four identical 1035 L cylindrical experimental tanks and time back to feeding was recorded (Figure 2). Mean surgery time was 9 min 22 s and mean time back to feeding was 48 h which was the length of time between experiments.
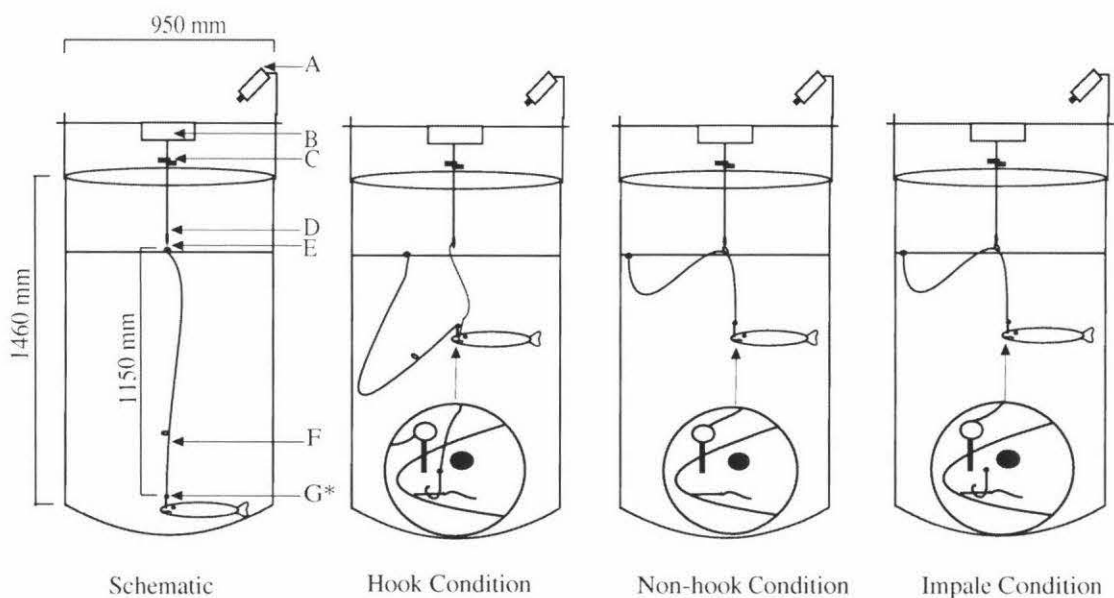
Figure 2. Schematic drawing, Hook, Non-hook, and Impale conditions conducted in 1035 L plastic experimental tanks filled with 787 L water. A, Video camera; B, Mount for force transducer; C, Force transducer; D, Bungee with swivel attached at water level; E, Styrofoam float attached to leader; F, Braided core floating fly line leader with loop; G, Polyethylene mouth anchor (* see Figure 1).

Blood and Muscle Samples

After the final trial each fish was euthased by a sharp blow to the head and blood and muscle tissue were collected. Approximately 1500 μL blood was collected from the caudal vein using 21 or 22 guage needles. Blood was placed into capillary tubes for

haematocrit measurements and 1.5 mL eppendorf tubes for centrifugation and subsequent plasma ion, lactate and cortisol analysis. Both tubes were centrifuged for 6 min at 10,000 rpm and haematocrits were read immediately while blood plasma (supernatant) was stored for three months at -70° C. Plasma cortisols were measured and validated using an ImmuChem™ Coated Tube Cortisol 125 Radio Immuno Assay (RIA) Kit from M.P. Biomedicals formerly I.C.N. Biomedicals Inc. (Appendix E)

Plasma lactate was determined using a Sigma Lactate, nicotinamide adenine dinucleotide (NAD) reduction kit. Plasma (50 μL) was deproteinated in 150 μL of 6% perchloric acid and refrigerated for 1 h. Deproteinated plasma was centrifuged for 20 min at 10,000 rpm and 12.5 μL of supernatant was added to the Sigma reagents. To determine lactate concentrations, deproteinated and centrifuged plasma was read on a spectrophotometer at 340nm. Sodium and potassium concentrations (50 μL plasma diluted in 4.95 mL distilled water) were measured using a flame photometer.

Approximately 1000 mg of white muscle from below the dorsal fin was collected for lactate analysis. Muscle tissues were stored at -70° C for three months prior to analysis. Muscle lactates were determined using a Sigma Lactate, nicotinamide adenine dinucleotide (NAD) reduction kit. In preparation for analysis, 100 mg of muscle was placed in liquid nitrogen and ground into fine residue using a mortar and pestle. Muscle residue (100 mg) was deproteinated in 150 μL of 6% perchloric acid and refrigerated for 1 h. Samples were centrifuged for 20 min at 10,000 rpm and 12.5 μL of the supernatant was added to the Sigma reagents. To determine muscle lactate concentrations, deproteinated and centrifuged samples were read on a spectrophotometer at 340 nm.

Force Transducer

A MasTec Ltd. force transducer (model LCL-020, Full Bridge Thin Beam Load Cell) with a 90 Newton (N) capacity was used to measure tension. Voltage output was calibrated in (N) and the signal digitised and recorded on MacLab 8S, using Chart ver. 3.5 (AD Instruments). Eight tension measurements were recorded each sec in order to ensure sensitivity to single fast tail beats.

Experimental Procedures

Using the procedures outlined in the Hook condition, a pilot study was conducted to determine if trout fitted with surgically implanted mouth anchors responded the same as trout not fitted with surgically implanted mouth anchors. After the pilot study, all fish were surgically implanted with a mouth anchor to which was tied a floating fly-line leader. Fish were recovered for 48 h in individual tanks before experimentation. During experiments, the floating fly-line leader was used to attach fish to the force transducer. Fish were acclimated for a minimum of 48 h between experiments.

To separate the behavioural effects of being hooked; tethered but not hooked; and hooked but not tethered to the hook, three experimental conditions (Hook, Non-hook, Impale) were devised and are described below and in Figure 2. The three experimental conditions were replicated on 18 rainbow trout and tension was measured for 20 min. To avoid disturbing fish during trials, they were observed on a monitor using a video camera mounted above the tanks. If the fish detached during a trial or were not attached to the force transducer within 45 s of netting the trial was discontinued. The order of the conditions was randomized and after all three conditions were completed trout were euthanased by a sharp blow to the head.

Hook Condition

During the Hook condition a hook impaled through the upper jaw of the trout (n=18) attached the fish to the force transducer. Trout were quickly restrained underwater in a nylon net by pulling the floating fly-line leader. A size 10 long shank fishing hook was manually impaled through the upper jaw of the fish. The hook, attached to a 300 mm length monofilament (5·00 kg test line), was then connected to the swivel on an elastic line below the force transducer (Figure 2). Trout were released within 45 s of netting.

Non-hook Condition

During the Non-Hook condition trout (n=18) were attached to the force transducer by the previously implanted mouth anchor. Trout were quickly restrained using the same technique described in the Hook condition but fish were not impaled with a hook. Trout were restrained in the net for approximately 30 s to simulate time and handling which occurred for hook impalement during the Hook and Impale conditions. After 30 s, the loop in the fly line leader was connected to the swivel on an elastic line below the force transducer (Figure 2). Trout were released within 45 s of netting.

Impale Condition

During the Impale condition trout (n=18) were attached to the force transducer by the previously implanted mouth anchor but additionally a hook was impaled through the upper jaw which was unattached to any line. Trout were quickly restrained and impaled with a hook using the same technique as described in the Hook condition but were fixed to the force transducer by the mouth anchor (Figure 2). Trout were released within 45 s of netting.

Data and Statistics

Tension (N) measurements were normalized for body mass (kg) and average tension every 0·50 s was used in analysis. Tension, blood and muscle measurements were compared between conditions using a one-way ANOVA. Differences in mean tension were distinguished using Tukey test. All tests were evaluated on 0·05 level of significance.

RESULTS

The pilot study showed that mouth anchors did not influence swimming behaviour as tensions were similar between hooked trout fitted with mouth anchors (0·13 ± 0·08 N / kg body mass) and those without mouth anchors (0·16 ± 0·03 N /kg body mass) (n = 21, P = 0·67). After the pilot study, 18 rainbow trout were exposed to three, 20 min capture trials over a seven day period and no mortality was observed. There were no differences the mean tension exerted during 20 min capture periods between the three conditions (n = 54, P = 0·210, Table I). The largest difference in tension occurred between the Hook (0·16 ± 0·03 N/ body mass kg) and Non-hook (0·26 ± 0·04) conditions but these were not statically different (n = 36, P = 0·069, Table I).

Table I. Summary of mean body mass (kg) and tensions (Newtons / body mass kg) exerted during 20 min experimental conditions with rainbow trout. Mean tensions were highest in all conditions during min 1. All means ± S.E. * No significant difference between conditions (P < .05)

Condition	n	Body mass (kg)	Mean Tension min 1-20 (N / body mass kg)	Mean Tension min 1 (N / body mass kg)
Hook	18	0·28 ± 0·02	0·16 ± 0·03	0·70 ± 0·16
Non-hook	18	0·28 ± 0·02	0·26 ± 0·04	1·03 ± 0·17
Impale	18	0·28 ± 0·02	0·21 ± 0·04	0·92 ± 0·18

Table II. Summary of plasma and muscle physiology with P values from ANOVA's comparing three experimental conditions using rainbow trout. All means ± S.E. * No significant differences between conditions (P < .05).

Physiological Parameter	P values	Hook (n=6)	Non-Hook (n=6)	Impale (n=6)
Plasma Cortisol (ng/mL)	0·738	159·4 ± 19·0	186·4 ± 32·9	162·1 ± 26·3
Plasma Lactate (mmol/L)	0·966	7·33 ± 0·12	6·64 ± 0·29	6·84 ± 0·15
Muscle Lactate (μmol/g)	0·887	24·30 ± 1·56	24·27 ± 1·61	25·39 ± 2·45
Plasma Na^+ (mmol/L)	0·891	146·50 ± 5·89	145·50 ± 3·32	151·20 ± 7·84
Plasma K^+ (mmol/L)	0·911	5·50 ± 0·59	5·92 ± 0·38	5·64 ± 1·14
Haematocrit	0·945	31·03 ± 0·21	28·14 ± 0·23	30·22 ± 0·53

There were also no differences in cortisols, plasma lactates, muscle lactates, sodiums, potassiums, or haematocrits between any of the experimental conditions (Table II). Non-hook trout exhibited the lowest levels of all physiological parameters measured except for plasma cortisol and potasium concentrations. Conversely, Impale and Hook condition trout accounted for the highest levels of muscle and plasma lactates as well as plasma sodium concentrations.

In all trials the greatest mean tension was exerted during min 1 (0·70-1·03 N / kg body mass) but these were not significantly different between the conditions (n = 54, P = 0·368, Table I). Regardless of being hooked, the general pattern of behaviour was an initial period of rigorous swimming activity lasting from 1 to 5 min and subsequently fish either swam continuously in circles or positioned themselves stationary in the center of the tank (Figure 3). After vigorous swimming activity subsided occasional bursts of activity occurred and were most frequent during the final 10 min of Non-hook and Impale conditions (Figure 3). Conversely, trout exposed to the Hook condition exhibited fewer bursts of activity, which is apparent in reduced mean tensions exerted during the final 10 min of the capture periods. During

min 11-15 and 16-20, Hook condition trout exerted on average 0·10 N /kg body mass

less than Non-hook and Impale trout (Figure 3).
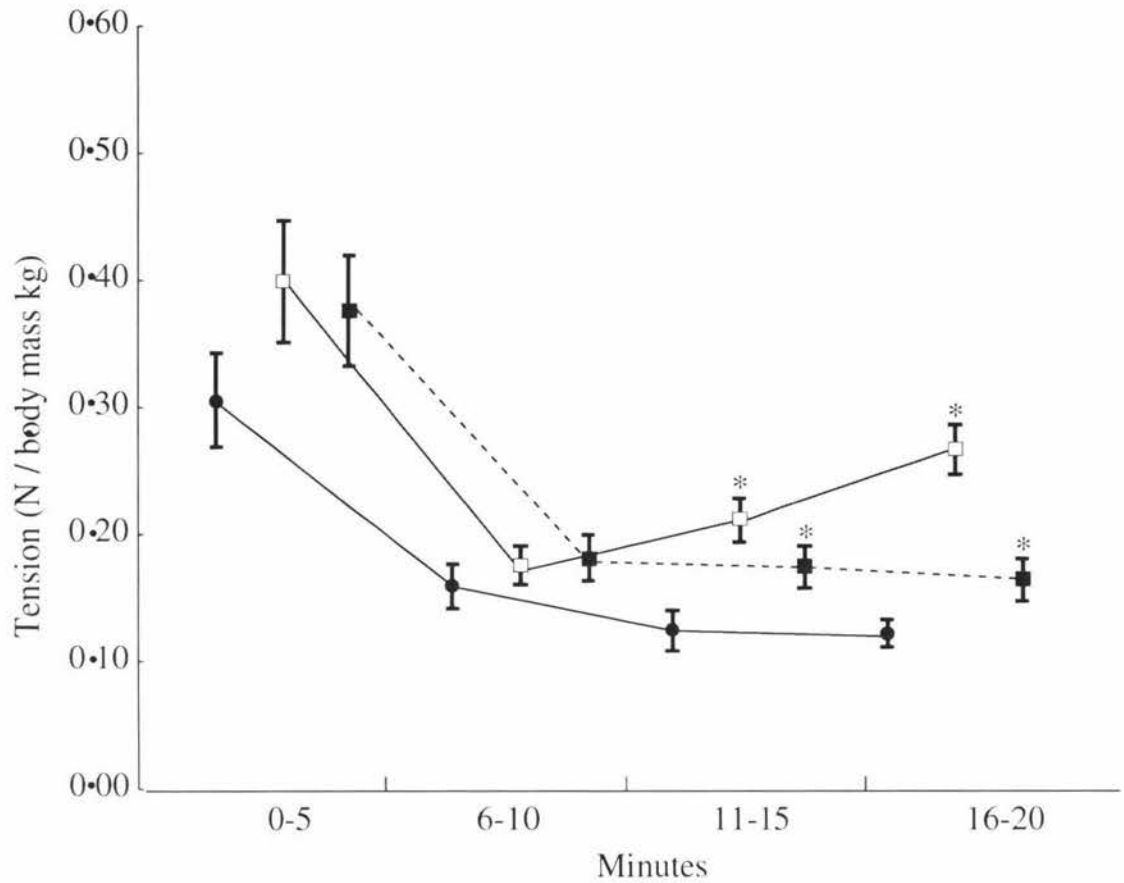

Figure 3. Mean tensions (Newtons / body mass kg) exerted by rainbow trout during 5 min categories between •, Hook (n=18); □, Non-hook (n=18) and; ■, Impale (n=18) conditions. Means ± S.E. * indicates Hook is significantly different from Non-hook and Impale conditions respectively during min 11-15 (n = 36, P < 0·001; n =36, P =0·04) and 16-20 (n = 36, P < 0·001, n = 36, P < 0·03).

DISCUSSION

In this simulated capture rainbow trout impaled by and tethered to a hook, on average exerted less, but not statistically different amounts of tension compared to trout which were not hooked, or not tethered to a hook (Table I). These findings support non-experimental observations collected by Gregory (1999) who noted that the process of capturing "playing" carp (*Cyprinus caprio* L.) appears to be more aversive than hooking in the mouth. These behavioural observations are supported by similar levels of physiological disturbance measured between the Hook, Non-hook, and Impale condition trout (Table II). There were no significant differences in any of the physiological parameters measured and most were within range of previously cited levels of exercised trout.

Plasma cortisol levels were high but within range of previous reports (100-200 ng/mL) for rainbow trout following exhaustive exercise (Milligan 1996). Conversely, levels of plasma and muscle lactate recorded in this study were relatively low compared to rainbow trout exercised to exhaustion but were substantially higher than previously measured baseline levels (Wood et al. 1983; Milligan & Wood 1986; Milligan & Girard 1993). The 20 min duration of capture may account for the reduced muscle lactate levels in the present study because these lactates have been shown to peak approximately 2 h after exhaustive exercise (Wood et al. 1983). However, muscle lactates begin to rise immediately upon exercise and thus, the 20 min capture period was sufficient time to allow the development of a lactate response in muscle and likely in the blood (Milligan & Girard 1993).

Plasma sodium concentrations were near previously reported baseline levels (145-147 mmol/L) but potassium concentrations were 1-2 mmol/L greater than previous reports (Hille 1982; Eddy 1985). Extracellular ion concentrations generally

increase 1- 4 h after exercise but this is followed by a net loss in the system. Potassium however, has been shown to increase immediately (< 30min) in the muscle after exercise (Wood et al. 1983). The rapid response time of potassium compared sodium may account for the elevated levels of potassium measured in this study.

Results from this study demonstrate that the escape behaviour and physiological disturbances displayed by rainbow trout during angling appear to be related more to behavioural restriction than to impalement by a hook. The limited effect of hooking on escape behaviour is supported by the fact that when captured by hook-and-line certain elasmobranches, which do not have the capacity for nociception exhibit a similar flight response compared to fish which possess nociceptors (Rose 2002). Rose (2002) describes the adaptive advantages of having reduced nociceptive reactivity, especially in the oral cavity of predatory fish, which may consume prey that have spines or bony exoskeletons. However, anglers observe that rainbow trout have a particular oral sensitivity that has also been demonstrated in behavioural, anatomical and hook avoidance research using various teleosts (Beukeman 1970; Sneddon 2002; Sneddon 2003).

It may be expected that hooked fish would exert less tension in an attempt to avoid discomfort from pulling on the wound caused by impalement if *per se* the hooking experience is painful. Conversely, it is possible that hooked fish would exhibit more erratic swimming behaviour in response to the discomfort caused by hook impalement. Increased activity associated with painful situations in fish is supported by Sneddon (2003) who found that rainbow trout injected with acetic acid in the mouth rubbed their lips against gravel and had increased opercular beat rate compared to control groups. In contrast to Sneddon (2003), erratic swimming behaviour in the present study was reduced during the perceived painful condition of

impalement and tethering to a hook (Figure 3). Behavioural responses to pain may vary according to a variety of different influences such as the type of trauma experienced and species affected (Kavaliers 1988). Perhaps hooking rainbow trout in this study was painful but behavioural restriction was viewed as a greater threat or compromise of welfare which culminated in the escape response.

Molony et al. (2002) noted that behaviours associated with pain in lambs are most frequently displayed soon after the perceived painful event. If this observation is applicable to rainbow trout this indicates that the tension measured during the first min of the capture process may be most indicative pain related behaviour. In this study tension exerted was highest during the first min of the capture process regardless of whether or not the fish was hooked (Figure 3). These data indicate that if the high tension exerted during min 1 is a pain related response (or if it is not pain related), the act of behavioural restriction is more aversive than hook impalement.

Despite the similarity in tensions exerted between conditions during the first half of capture periods, trout in the Hook condition exerted a reduced mean tension during the final 10 min compared to Non-hook and Impale conditions (Figure 3). This shows that while hook impalement had little effect on the swimming behaviour of the trout during the preliminary stages of the capture process, behaviour is different once the trout has ceased high intensity swimming. High intensity swimming usually subsided between 3 to 5 min but did not appear to be related to exhaustion. When viewed on the monitor the reduction in swimming appeared to be related to associative learning that the fish could position themselves where no tension was being pulled. This associative learning was not carried over between trials as this same behaviour occurred whether it was the first or final trial.

After high intensity swimming ceased (3-5 min) the three conditions were identical for several minutes but after approximately 10 min, Hook condition trout exerted significantly less tension for the remaining capture period (Figure 3). These data suggest that once the trout had determined that being tethered was no longer a threat, the effect of being tethered by a hook significantly changed behaviour. Additionally, once the fish had settled ($\approx$ 10 min), swimming behaviour was different when trout were tethered to a hook compared to only being impaled but not tethered to a hook (Figure 3).

Wood et al. (1983) noted that rainbow trout subjected to only 6 min of exhaustive exercise resulted in 40% mortality over a 12 h period. Conversely, no mortality was observed during 20 min experimental conditions in the present study. This suggest that a short (6 min) but intense capture process may be more stressful compared to a long (20 min) less intense capture. The general rule of thumb used by anglers that the faster the fish is captured-and-released the more likely the fish is to survive needs to be explicitly addressed. Further research on this topic may compare survival and stress in short but intense angling bouts with long less intense angling bouts.

Conclusions

Quantitative and empirical information regarding the welfare of recreationally captured fish are becoming more important and are critical for making impartial judgments about the treatment of fish in this sport. The process of fish capture by hook-and-line roughly includes the steps of attraction to the lure, impalement on a hook, restriction of its behaviour, handling, and either dispatch or release. Regardless of whether or not fish feel pain, each of these steps in the process needs careful

examination in a variety of situations in order to determine strategies that improve survival and welfare of angled fish.

Results from this study have shown that behavioral restriction is a critical factor influencing the escape response during angling and that hook impalement has little effect on the swimming behaviour or physiological response of rainbow trout during simulated capture by hook-and-line. This suggests that developing methods of angling which reduce the aversive impacts during behavioural restriction (i.e. capture time, capture stress) is more critical than preventing fish from being impaled on a hook. Results from this study are not measures of the ability or inablity of rainbow trout to experience pain but they are indicators of the relative insignificance of hook impalement versus behavioural restriction during capture by hook-and-line.

REFERENCES

Anand, K. J. S.; Craig, K. D. 1996: New perspectives on the definition of pain. Pain 67(1): 3-6.

Balon, E. K. 2000: Defending fishes against recreational fishing: an old problem to be solved in the new millennium. Environmental Biology of Fishes 57: 1-8.

Beukema, J.J. 1970: Acquired hook avoidance in pike Esox lucius L. fished with artificial and natural baits. Journal of Fish Biology 2: 155-160.

Braithwaite, V. A.; Huntingford, F. A. 2004: Fish and welfare: do fish have the capacity for pain perception and suffering? Animal Welfare 13: S87-92.

Broglia, C.; Rodriquez, F.; Salas, C. 2003: Spatial cognition and its neural basis in teleost fishes. Fish and Fisheries 4: 247-255.

Cooke, S. J.; Schreer, J. F.; Dunmall, K. M.; Phillip, D. P. 2002: Strategies for quantifying sublethal effects of marine catch-and-release angling: insights from novel freshwater applications. Am. Fish. Soc. Symp. 30: 121-134.

Cooke, S. J.; Bunt, C. M.; Ostrand, K. G.; Philipp, D. P.; Wahl, D. H. 2003: Angling-induced cardiac disturbance of free-swimming largemouth bass (Micropterus salmoides) monitored with heart rate telemetry. Journal of Applied Icthyology 20: 28-36.

Davie, P. S.; Sparksman, R. I. 1986: Burnt tuna: An ultrastructural study of postmortemchanges in muscle of yellowfin tuna Thunnus albacares caught on rod and reel and southern bluefin tuna *Thunnus maccoyii* caught on handline or longline. Journal of Food Science 51: 1122 -1128 & 1168.

Davis, R. E.; Klinger, G.F. 1994: NMDA receptor antagonist MK-801 blocks learning of conditioned stimulus-unconditioned stimulus contiguity but not fear of conditioned stimulus in goldfish *Carassius auratus* L. Behavioural Neuroscience 108: 935-940.

Domeier, M.; Dewar, H.; Nasby-Lucas, N. 2004: Mortality rate of striped marlin (*Tetrapturus audax*) caught with recreational tackle. Marine and Freshwater Research 54: 435-45.

Eddy, E.B. 1985: Uptake and loss of potassium by rainbow trout in fresh water and dilute sea water. Journal of Experimental Biology 118: 277-286.

Ferguson, R. A.; Kieffer, J. D.; Tufts, B. L. 1993: The effects of body size on the acid-base and metabolite in the white muscle of rainbow trout before and after exhaustive exercise. Journal of Experimental Biology 180: 195-207.

Fisheries Society of the British Isles (FSBI) 2002: Fish Welfare. Granta Information Systems. 29.10.2002.

Goodyear, C. P. 2002: Negative implications of large minimum size regulations on future mean size at age: an evaluation using simulated striped bass data. Am. Fish. Soc. Symp. 30: 217-229.

Gregory, N. 1999: Do fish feel pain? ANZCCART News, 12: 1-3.

Hille, S. 1982: A literature review of the blood chemistry of rainbow trout. Journal of Fish Biology 20: 535-569.

Kavaliers, M. 1988: Evolutionary and comparative aspects of nociception. Brain Res. Bull. 21: 923-931.

Laland, K.N.; Brown, C.; Krause, J. 2003: Learning in fishes: from three-second memory to culture. Fish and Fisheries 4: 199-202.

LeChat, M. R. 1996: An argument in defense of fishing. Fisheries 21 (7): 20-21.

Melotti, P.; Roncarati, A.; Garella, E.; Carnevali, O.; Mosconi, G.; Polozonetti-Magni, A. 1992: Effects of handling and capture stress on plasma glucose, cortisol, and androgen levels in brown trout. Journal of Applied Ichthyology 8: 234-239.

Milligan, C.L.; Girard, S.S. 1993: Lactate metabolism in rainbow trout. Journal of Experimental Biology 180: 175-193.

Milligan, C.L.; Wood, C.M. 1986: Tissue intracellular acid-base status and H+ exchange with the environment after exhaustive exercise in rainbow trout. Journal of Experimental Biology 123: 93-121.

Molony, V.; Kent, J. E.; McKendrick, I. J. 2002: Validation of a method for assessment of acute pain in lambs. Applied Animal Behavioural Science 76: 215-238.

Pankhurst, N. W.; Dedual, M. 1993: Effects of capture and recovery on plasma levels of cortisol, lactate and gonadal steroids in a natural population of rainbow trout. Journal of Fish Biology 45: 1013-1025.

Rose, J. D. 2002: The neurobehavioral nature of fishes and the question of awareness and pain. Reviews in Fisheries Science 10(1): 1-38.

Sneddon, L. U. 2003: The evidence of pain in fish: the use of morphine as an analgesic. Applied Animal Behaviour Science 83(2): 153-162.

Sneddon, L. U. 2002: Anatomical and electrophysiological analysis of the trigeminal nerve in a teleost fish. Neuroscience Letters 319: 167-171.

Snow, P. J.; Plenderleith, M. B.; Wright, L. L. 1993: Quantitative study of primary sensory neurone populations of three species of elasmobranch fish. Journal of Comparative Neurology 334: 97-103.

Skomal, G. B.; Chase, B. C. 2002: The physiological effects of angling on post-release survivorship in tunas, sharks, and marlin. Am. Fish. Soc. Symp. 30: 135-138.

Thompson, J. A.; Hughes, S. G.; May, E. B.; Harrell, R. M. 2002: Effects of catch and release on physiological responses and acute mortality of striped bass. Am. Fish. Soc. Symp. 30: 139-143.

Wells, R. M. G. 1987: Stress responses imposed by fish capture and handling: a physiological perspective. Food Technology in Australia 39(10): 479-481.

Wells, R. M. G.; McIntyre, R. H.; Morgan, A. K.; Davie, P.S. 1986: Physiological stress responses in big gamefish after capture: Observations on plasma chemistry and blood factors. Journal of Comparative Biochemistry and Physiology 84A: 565- 571.

Wood, C. M.; Turner, J. D.; Graham, M. S. 1983: Why do fish die after severe exercise? Journal of Fish Biology 22: 189-201.

Appendix E. Cortisol assay method and validation from Appendix D

Written and performed by: Dr. John Cockrem and Jane Candy
Massey University
Institute of Veterinary Animal and Biomedical Sciences (IVABS)
Palmerston North, New Zealand

Plasma sample preparation

Each plasma sample was thawed and used neat for the assay of cortisol.

Radioimmunoassay of cortisol

Cortisol levels in plasma were measured by radioimmunoassay. Samples were assayed in duplicate. 25 mL of plasma was incubated with 1000 mL of iodinated cortisol in anti-cortisol coated tubes (^{125}I-cortisol and tubes ImmuChem^{TM} Coated Tube cortisol ^{125} I RIA kit for in vitro diagnostic use, MP Biomedicals, USA; 20 000 cpm) for 45 minutes at 37°C, then the supernatant was aspirated off. The pellets were counted on a LKB Wallac 1261 Multigamma gamma counter for 2 minutes each.

The cross-reactivity of the cortisol antibody with other steroids was tested by MP Biomedicals. Cross-reactions are as follows: prednisolone (45.6%), 11-desoxycortisol (12.3%), corticosterone (5.5%), prednisone (2.7%), cortisone (2.1%), 17-hydroxyprogesterone (1.0%), progesterone (0.25%) and dexamethasone, dihydrotestosterone and testosterone (<0.10%).

Parallelism and hormone additions

A serial dilution of plasma in steroid diluent (MP Biomedicals, USA) was parallel to the cortisol standard curve. The quantitative recovery of cortisol in was measured by adding different amounts of standard cortisol to one plasma sample. The recovery of added cortisol was $104.2 \pm 5.5\%$.

Assay sensitivity

The sensitivity of the cortisol assay was the minimum hormone level that could be consistently distinguished from zero. It was determined as the hormone concentration at the mean - 2 standard deviations from the zero hormone point on the standard curves. The assay sensitivity, expressed as ng steroid/dl plasma, was 1.4 ng/ml.

Intra- and inter-assay variation

A plasma sample that gave approximately 70% binding on the standard curve was used as a low quality control. Solutions of cortisol in PBSG at concentrations that gave approximately 50 and 20% binding on the standard curve were used as medium and high quality controls. The mean concentrations of cortisol in these solutions were 19.3 ± 1.3, 32.2 ± 1.2 and 199.4 ± 8.6 ng/mL respectively. The intra-assay coefficient of variation for each solution was determined by conducting an assay in which each solution was assayed multiple times. The intra-assay coefficients of variation for cortisol were 7.0% (n = 14), 3.9% (n = 9) and 4.3% (n = 11) for low, medium and high solutions respectively. Inter-assay coefficients of variation were not determined as all samples were assayed in a single assay.