Bias in size and age samples of *Plectropomus leopardus*, taken by line fishing among regions and management zones of the Great Barrier Reef

Thesis submitted by

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P.S. Never again!

Abstract

Successful management of any fishery requires accurate assessments of the status of stocks and their response to fishing. A major impediment, however, is the difficulty in collecting samples that are representative of the size and age characteristics of fish populations. Biased size/age data are likely to result in inaccurate stock assessments, which can lead to inappropriate management decisions. Hook and line gear is the main gear used in the Queensland reef line fishery on the Great Barrier Reef (GBR). The primary target species of this fishery is the common coral trout, *Plectropomus leopardus*. Hook and line gear is known to be size-selective, and so catches of *Plectropomus* spp. from the GBR line fishery are biased. To better quantify this bias, samples of *P. leopardus* collected by line fishing were compared with samples collected using a spear fishing method designed to minimise size selection, from 16 reefs across 7° of latitude on the GBR. Hook and line fishing caught very few (4%) fish below 310mm compared to spear fishing (38%). Similarly, line fishing caught very few 1 & 2 year old fish (3%) compared to spear fishing (35%). Estimates of the von Bertalanffy growth parameter K was significantly greater in the spear sample for 3 of 4 regions, while estimates of L_∞ were significantly greater in the line sample for all regions. Estimates of rates of total mortality were significantly greater in the line samples than the spear samples. The major differences in the size and age data, and in the estimates of population parameters derived from these data, were consistent in all regions and management zones. This consistency is important because it indicates that comparisons among regions and zones will be likely to be valid for either gear and not confounded by region or zone specific bias. This knowledge will greatly improve the interpretation of line caught samples of *P. leopardus*, anywhere on the GBR. Parameter estimates from both samples were used to calculate yield-per-recruit (YPR) to demonstrate possible implications of using biased estimates. YPR results indicated that line caught data over-estimated optimal levels of fishing effort that were as much as 3x greater than that estimated by the spear data. The line data was also shown to underestimate the YPR by up to 80%. The attention of fisheries researchers must therefore focus on how gear selectivity affects the samples collected from fish populations. By better understanding the selective nature of fishing gears the biases can then be accounted for in how we use such samples,

eg. population parameter estimation. The significant benefit would be derived from improved performance of fisheries models used for management. This study will help ensure that stock assessment models for the GBR line fishery are more reliable, enhancing the notion of sustainable fishing.

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Chapter 1. General Introduction

Successful management of any fishery requires biologists to be able to appropriately interpret the information stock assessments provide. Age and size distributions of fish populations are among the most important fisheries data required for stock assessment (Hilborn and Walters 1992). A major problem in stock assessments however, is the difficulty in collecting samples that satisfactorily represent age and size characteristics of populations (Schweigert and Sibert 1983; Miranda *et al* 1987; Hilborn and Walters 1992). Poor size/age data are likely to result in inaccurate stock assessments, which can lead to inappropriate management decisions. Ideally, samples should perfectly represent the populations from which they are drawn. However, all fishing gears used to sample fish populations are selective. That is, no fishing gear captures fish over the entire size/age range with equal probability, even if they have been adapted in some way for scientific surveys (Miranda *et al* 1987; Hovgard and Riget 1992; Pope *et al*, 1975). For this reason it is imperative that the selective characteristics of the fishing gears be understood before sample data are used in the estimation of population parameters for stock assessments (McCombie and Fry 1960; Garrod 1961; Hamley 1975; Ralston 1990; Hovgard and Riget 1992).

The most obvious selection characteristics of fishing gears relate to fish body size. For example, at its simplest the selectivity of hook and line gear is a function of mouth size and gape relative to hook size (Ralston, 1982; Cortez-Zaragoza *et al*,1989; Hilborn and Walters, 1992; Lokkeborg and Bjordal, 1992), while selectivity of gillnets is a function of the girth of a fish relative to mesh size (Hamley, 1975; Hilborn and Walters, 1992).

Another aspect of gear selectivity that is difficult to estimate is the vulnerability of the fish to capture by the gear, or catchability (Machiels *et al*, 1994). Catchability of an individual fish is a combination of its' availability and the probability of its' capture. Several factors determine catchability, such as non-random spatial distribution influenced by age- and/or size-specific behaviour (Miranda *et al*, 1987, Brock 1962; Morales-Nin and Ralston 1990;

Hilborn and Walters 1992; Davies 1995). Behaviour patterns such as larger individuals out-competing smaller individuals for baited hooks (eg. Bertrand, 1988; Lokkeborg and Bjordal 1992), and saturation of fish traps (Munro 1974; Whitelaw *et al* 1991) can affect vulnerability to capture. Fish movement also can influence catchability, particularly in the case of mobile fishing gears (eg. trawl nets) and the greater avoidance capabilities of larger individuals due to higher swimming speeds. Many of these factors influence the selectivity of fishing gears and consequently samples of fish rarely include all year-classes, or sizes within a year-class, in proportion to their true abundance in the population. Size selectivity of fishing gears can result in several biases. For example, where a species of fish does not exhibit a strong age-length relationship, using catch-at-age data that is biased due to size selection imposed by the fishing gear can yield inaccurate estimates of population parameters such as growth and mortality rates.

Many researchers have adopted the use of several different fishing gears to more effectively sample all size classes from a population. On the Great Barrier Reef (GBR) such studies have frequently used fence netting to supplement samples of scarids and acanthurids taken by spear fishing (Choat and Axe, 1996; Choat *et al*, 1996) or line and spear fishing in the case of Brown *et al* (1996) for collecting *Plectropomus leopardus*. Ferreira and Russ (1994) made use of all the above three methods to collect samples of *P. leopardus* from all size and age classes. This has enabled more realistic growth schedules to be constructed by including the smaller and younger fish for a given species. When using different fishing gears, estimates of mortality rates and mean size and age information are of limited use however, as each gear may have different biases and samples still might not be taken in proportion to their abundance in the natural population. Thus, it will be difficult to account for the range of biases when collecting the data from different gears.

The Great Barrier Reef Marine Park (GBRMP) in north-eastern Australia extends over an area of 14^{o} latitude and supports a coral reef system of considerable habitat heterogeneity. Considering the large variations in the biological and physical characteristics of habitats over large spatial scales (Williams, 1991), it is likely that species population structure and dynamics will also differ. Spatial variation in biological parameters within a species was recntly demonstrated by Grandecourt (1999) who found greater mean size and mean age for *Lethrinus nebulosus* populations from the Seychelles than those on the GBR. In one of the few studies over large spatial scales within the GBR, Williams (1997) found that mean age, rates of growth and mortality for *Lethrinus miniatus* differed significantly between different regions. Fishing can also alter the structure and dynamics of populations. Several studies have noted significant differences in the size structure of fish populations between fished areas and areas protected from fishing (eg. Beinssen, 1989; Ayling *et al*, 1991). Area-based management is used throughout the GBRMP. Two of the major zones used in the Park are 'General Use' zones (fishing allowed) and 'Marine National Park-B' zones (fishing prohibited). Although implemented as a conservation measure 'Marine National Park-B' zones effectively act as fisheries reserves as they exclude all forms of fishing.

The GBRMP supports a demersal commercial line fishery with an annual catch of 3,500 – 4,000 tonnes of finfish (Mapstone *et al* 1996a). A recreational fishing sector is estimated to take similar quantities (Blamey and Hundloe 1993). By far the dominant species taken by the commercial sector is coral trout, *Plectropomus* spp., constituting 35 – 45% by weight of the total catch (Mapstone *et al* 1996a). The most abundant of these species on the mid-shelf reefs of the GBR is the common coral trout, *P. leopardus* (Randall and Hoese, 1986) and research surveys by line fishing have found this species to comprise approximately 95% of the total number of Plectropomids taken (Davies and Mapstone, unpublished data).

A major project initiated by the Co-operative Research Centre (CRC) for the Sustainable Development of the GBR and being continued by the CRC for the Great Barrier Reef World Heritage Area is examining the Effects of Line Fishing (ELF) on the GBR (Mapstone *et al*, 1996b; Mapstone *et al*, 1998). An important part of this project is age determination of fish to provide age-based estimates of population parameters to be incorporated into population dynamics models. The sampling gear used for collection of samples is hook and line fishing gear akin to that used by the GBR commercial handline fishery. It is well known that such gears are size-selective (Ralston, 1982; Hilborn and Walters, 1992). Catches of *Plectropomus* spp. from the GBR line fishery contain very few fish below 300mm FL (Davies, 1996). It is to be expected then, that estimates of population parameters derived from such data will be biased. A better understanding of this bias is necessary to provide more accurate parameter estimates for the models being developed in the ELF Project and future management strategy evaluations or stock assessments for the GBR line fishery.

There are two ways one can attempt to overcome biased parameter estimation from using selective fishing gears. These are: i) Use a fishing gear that is not size selective to sample from fish populations representatively, or ii) gain an understanding of the selective nature of the fishing gear in question and account for this in the estimation of parameters. The first option is fairly difficult to achieve, if not impossible (Miranda *et al*, 1987; Hovgard and Riget, 1992). The second option is achieved by comparing variations of the same gear type, such as different mesh sizes (eg. Hamley, 1975; Ralston, 1990) or, by comparing different fishing gears (eg. Leclerc and Power, 1980). In this study multiple hook size comparisons could have been carried out. For example, the use of hook sizes ranging from 1/0 through to 12/0 hooks, fished at similar spatial and temporal scales. Several factors would have made the interpretation of such data difficult however. Larger fish out-competing smaller fish for baits could bias the catch (see Bertrand, 1988), and bait size may have to be altered to target different size classes (see Lokkeborg and Bjordal, 1992). Furthermore, a dietary shift with increasing size/age has been documented in *P. leopardus*, from predominately small invertebrates such as crustaceans to predominately fish, (St. John,). These factors are likely to bias sampling towards larger individuals.

Spear fishing is a fishing gear that can potentially be used to sample over the full size range of *P. leopardus* and provide samples of the population that are more representative than those from hook and line gear. In a study on the central GBR, Brown *et al* (1996) found that *P. leopardus* as young as 1-year-old were vulnerable to spear fishing, while line fishing seldomly caught fish below 3 years old. In speared samples from some reefs the 1-year-old fish dominated the catch, but it is not known whether this represented full recruitment to this fishing gear (Brown *et al*, 1996).

In this study I address the problem of bias in samples taken by hook and line gear from the GBR. To do this I compare the age- and size-structures obtained from line fishing surveys with those obtained by spear fishing surveys applied over the same spatial and temporal scales. An important assumption of spear fishing is that it is able to take samples that are representative of the population. In testing this assumption a pilot study developed a method that minimised size selectivity of spear fishing by enforcing a set of rules on fishers to randomise the selection of targets underwater (Welch, 1998). The common coral trout, *P. leopardus*, was the ideal specie for this study because of its' importance in the recreational and commercial line fisheries on the GBR. It is also an abundant species that exhibits behaviour allowing relative ease of capture by spearing.

Specifically my aims were, to:

1. Examine the effect of sampling gear on estimates of regional and zonal variation in both age and size structures of *P. leopardus*, and
2. Examine the effect of sampling gear on estimates of population parameters (growth and mortality) derived from samples obtained from line and spear fishing.
3. Examine and discuss the potential implications of 1. and 2. for future stock assessments.

Chapter 2. General Methods

ELF Project

Part of the ELF Project is a large-scale manipulative experiment on the GBR, Australia (see Mapstone *et al*, 1996b; Mapstone *et al*, 1998a). The study sites for the ELF experiment comprise 4 clusters of 6 reefs over 7° of latitude along the GBR (Figure 2.1). Within each cluster are two reefs that have always been 'open to fishing' (zoned 'General Use' (GU)) and 4 that have been 'closed to fishing' (zoned 'Marine National Park – B' (MNP-B)) for 10 – 12 years. Of these reefs, two of the 'MNP-B' reefs and the two 'GU' reefs were sampled by spear fishing. The clusters from north to south are hereafter reported as the Lizard Island, Townsville, Mackay and Storm Cay clusters respectively (Figure 2.1).

In 1995-96, baseline surveys of populations of coral reef fish were conducted on all reefs using underwater visual surveys and hook-and-line fishing gear. The ELF team, in association with contracted commercial line fishers, conducted sampling by line fishing of the Lizard Island, Townsville, Mackay and Storm Cay clusters in the months of October, November, December, 1995 and January 1996, respectively (Mapstone et al, 1998a; Davies et al, 1998). As this time period coincided with the spawning season in each region, sampling was conducted around the full moon to minimise potential bias in sampling due to fish aggregating for spawning over the peak spawning time around the new moon (Samoilys and Squire, 1994). Each reef was divided into six blocks, with three blocks on the leeward side and three blocks on the windward side of the reef. Each block was of approximately equal area of fishable habitat. Mapped block boundaries were located using Global Positioning Systems (GPS) or estimated distances and physical characteristics of individual reefs (eg. reef shape, location of bommies), with the aid of aerial photographs and/or maps. Effort was spread amongst blocks by enforcing minimum and maximum fishing times (hangs), a minimum number of hangs per block, and a minimum number of hangs for each of shallow (< 12m) and deep (>12m) depth strata. All hook and line gear was standardised across reefs. All fish were tagged, measured and weighed at sea and returned to the laboratory for removal of otoliths (and gonads).

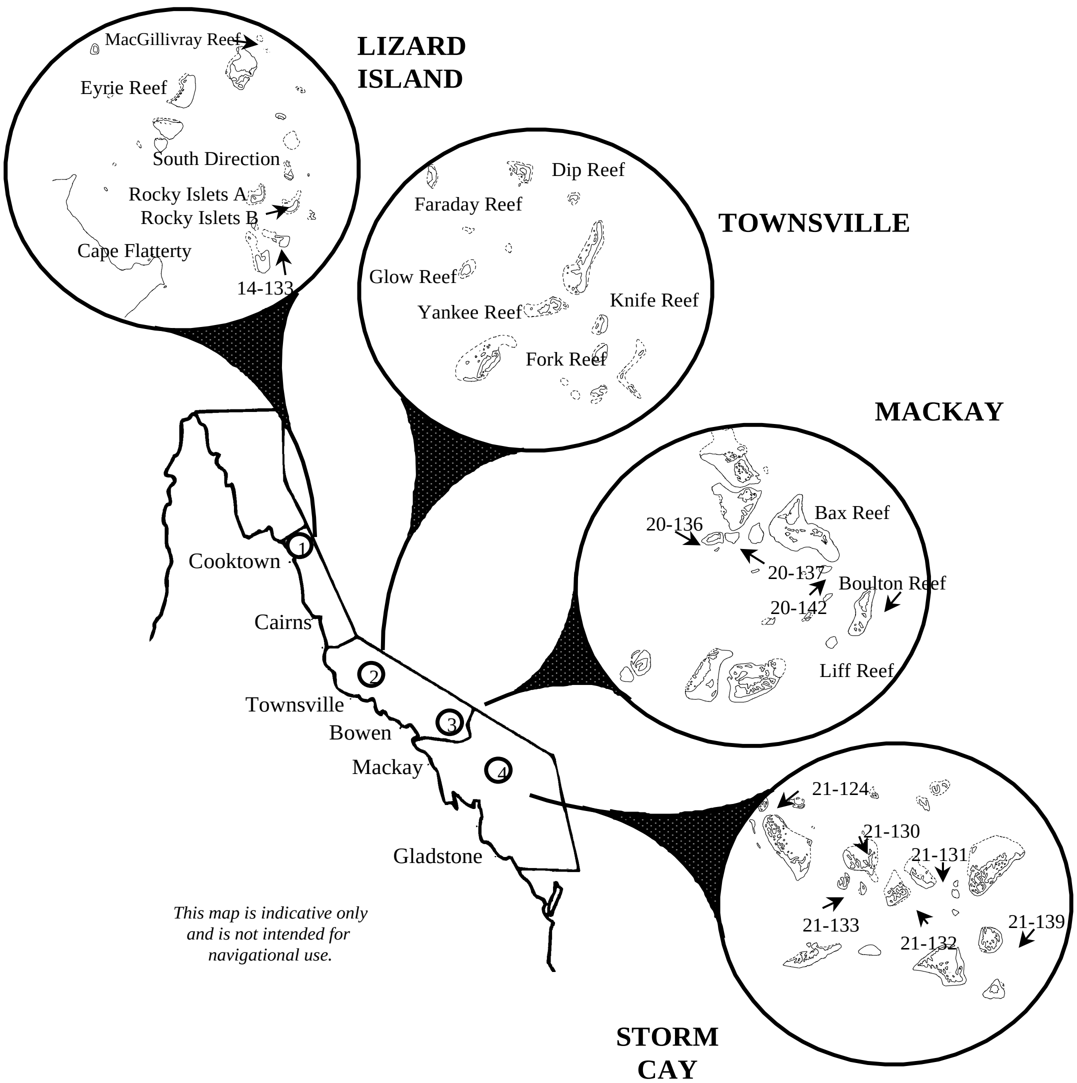


Figure 2.1: Map showing the ELF reef clusters.

The ELF experiment involves manipulations of fishing pressure on individual reefs in each cluster. Since the work reported here relates only to the pre-manipulation years, the manipulations will not be discussed further.[1] Baseline surveys were also conducted using spear fishing, targeting only the common coral trout, *P. leopardus*

Spear field methods

All spear fishing sampling was carried out during one field trip to each cluster within one week of the line fishing surveys. Sampling was structured similarly to the line fishing surveys, with the reefs divided into the same six blocks as discussed above.

Within block sampling was restricted to a depth of 10 metres due to safety requirements of repetitive diving. Spear sampling effort was spread evenly among blocks in two ways: i) using two depth strata: shallow (0-5 metres depth), and deep (5 -10 metres depth), and ii) different sampling teams diving different sites within each block. Two sampling teams were used, each comprising two spear fishers using SCUBA and a boat person. Each team did one dive per block and during each dive, one fisher sampled from the shallow stratum and the other from the deep stratum. This gave a total of 24 dives per reef, 4 per block, and 2 dives per depth stratum within each block. Due to logistic constraints, only one dive team was used at the Lizard Island cluster. While sampling this cluster the author dived all dives, while the other two team members alternated between being a fisher and a boat person. Start and end positions for each dive and diver were recorded using GPS. Also recorded was the duration of the dive.

The search time (bottom time) for each dive was initially set at 30 minutes. This had to be altered on several reefs, however, where high catch rates required a reduction in total effort. This was because the GBRMP Authority research permit enforced a strict limit on the number of fish that could be collected from each reef (150 *P. leopardus* only).

[1]All hook and line sampling was carried out as part of the ELF experiment. Data from these samples have been made available courtesy of the ELF Project, to enable comparisons with spear fishing samples for the purpose of this study, which also forms part of the ELF experiment.

Spearing procedure

A block was randomly selected and divers haphazardly selected a point of entry and swim direction in reef areas that allowed sampling to a depth of 10 metres. Divers used SCUBA to minimise the potential for bias toward large fish during searching as smaller fish are much harder to locate visually and are likely to be overlooked during free-diving spear fishing. To further minimise this potential bias, the horizontal search horizon was limited to an estimated six metres to be within the expected limits of underwater visibility and to allow for the fact that larger fish are obviously easier to sight over larger distances.

During each dive the fisher attempted to capture fish according to a strict target selection protocol, developed for this study in an earlier pilot study which aimed to minimise bias in the selection of targets when spear fishing (Welch, 1998). The protocol was as follows.

i) The fisher attempted to spear every lone fish seen, irrespective of size.

ii) When groups of fish were seen, one fish was selected as the target by following the rules:

   a) At the first encounter of more than one fish (= multiple encounter) the fisher targeted the first fish seen;

   b) At the second multiple encounter the second fish sighted in the group was targeted and so on up to a maximum of five fish per group;

   c) After going through the sequence of 1-5 the number of the fish to be speared started again at one (the first fish seen in a multiple encounter);

   d) If the fisher was due to spear the fourth fish sighted in a multiple encounter and there were only three fish then the third sighted would be speared (ie. the one closest to the fourth).

iii) The number of multiple encounters was recorded by the fisher at the conclusion of each dive to determine the frequency of, and therefore necessity for continued use of, the target selection rules outlined above.

iv) Each diver also recorded the number of fish sighted but not captured in 10cm size classes.

All fishers utilised the same equipment and method of capture. A stainless steel length of wire attached to a float at the surface was used to carry captured fish. The float was attached to a 14-metre length of rope, which in turn was attached to the butt of a rubber-powered spear gun. The float was painted fluorescent pink to be highly visible to the boat person, but of small enough size to be dragged to the bottom by the fisher to attach fish as required. This was important in preventing the fisher from ascending and descending (bounce diving) excessively during the course of a dive. Upon the capture of each fish the fisher killed it by spiking the spinal column just behind the head. After 'floating' the fish, the fisher re-loaded the spear gun and resumed searching.

Fish captured from individual dives were tagged in the tender vessel immediately following the dive, and the fork length of each fish was measured to the nearest millimetre on the main vessel following completion of diving activities. Frames of all captured fish were frozen and returned to the laboratory. A sub-sample of smaller individuals was kept whole and returned for weighing. This was to complement weight measurements taken from line fishing surveys, which comprised only larger individuals.

Laboratory methods

All frames returned to the laboratory were measured (FL, mm) and gonads were removed and stored. Whole fish were weighed to the nearest gram using a Sartorius balance. Finally the sagittal otoliths were removed from each fish and stored for age determination (see Chapter 4).

Chapter 3. The effect of sampling gear on fish size structures across management zones and regions of the Great Barrier Reef

Introduction

Length data are commonly sampled from fisheries catches because they are simple to collect and are often the only form of data that can be collected. Length data are most useful when used in conjunction with age data to estimate growth. However, length-based methods in fisheries stock assessment can also be informative (Hilborn and Walters, 1992). For example, length modes taken from length frequency samples can be assumed to represent cohorts or strong recruitment pulses, and estimates of growth can be derived (eg Petersen method, 1892; Pauly, 1984). Several models exist that propose a relationship between mean length and mortality rate (eg. Beverton and Holt, 1957), so that the mortality rate can be estimated easily from a single length frequency sample if growth characteristics are known. Further, levels of recruitment or stock abundance can be estimated by a method of length-based cohort analysis (Jones, 1984 in Hilborn and Walters, 1992).

Estimates of population parameters from length frequency samples, however, are particularly sensitive to the violation of several key assumptions. One of these assumptions is that samples are representative of the population from which they are taken. It is doubtful that this assumption could ever be met, primarily due to the size selective nature of fish sampling gears (Pope *et al*, 1975; Miranda *et al* 1987; Hovgard and Riget 1992). For example, the size frequency of a sample taken by hook and line gear is strongly influenced by the size and gape of the mouth of a species relative to the hook size (Ralston, 1982; Cortez-Zaragoza *et al*,1989; Hilborn and Walters, 1992; Lokkeborg and Bjordal, 1992), and by the bait size (Johannessen, 1983, in Lokkeborg and Bjordal, 1992). Cortez-Zaragoza *et al* (1989) documented clear size selectivity for yellowfin tuna by trialing a wide range of hook sizes (240% difference in hook size). They found that the selection range increased asymptotically with hook size (in Lokkeborg and Bjordal, 1992). Koike *et al* (1968, in Lokkeborg and Bjordal, 1992) used a wide range of hook sizes also and found a shift in size composition of samples collected by each hook size. Using gillnets, the sample will depend on fish girth relative to the mesh size(s) used (Hamley, 1975; Hilborn and Walters, 1992), while trawl samples are influenced by the avoidance capabilities of individuals, typically meaning that larger fish are less likely to be retained by the gear due to their higher swimming speeds and, thus, capacity to avoid or escape from the gear.

There are other factors that influence the size structure of catches that are much more difficult to quantify. These factors include size-specific behaviours such as competition for baits (eg. Bertrand, 1988; Lokkeborg and Bjordal 1992), and non-random spatial distribution of fish (Brock 1962; Miranda *et al*, 1987, Morales-Nin and Ralston 1990; Hilborn and Walters 1992), or fishing effort (Hilborn and walters, 1992). For example, on the GBR, Davies (1996) found that location within a reef and the season of sampling influenced estimates of mean size and the size structure of the catch. Many of these factors influence the selectivity of fishing gears and emphasise the importance of careful attention to sampling methodology and design.

Despite the potential problems associated with using length data as a surrogate for age it may often be the only form of data that can be collected. By better understanding the selectivity of fishing gears, and the factors that influence it, more confidence could be placed in the use of length-based methods of fisheries stock assessment. In this chapter I compare the size structures of *P. leopardus* sampled by spear and line fishing gear to estimate the effect of sampling gear on size distributions, and to examine the consistency of such effects across different regions and different management zones of the GBR.

Methods

Data were collected as described in Chapter 2 (General Methods).

Data Analysis

Mean size

Mean size of fish captured was calculated for individual reefs from both the spear samples and the line samples. The mean size was compared between methods and among regions, zones and reefs by 4-way Analysis of Variance (ANOVA). Factors were the fixed effects of method (spear, line), region (Lizard Island - LI, Townsville - TVL, Mackay - MCK, Storm Cay - SC), and zone ('General Use' – B (GU-B), Marine National Park – B (MNP-B)), and the random factor reef, nested within region and zone. In keeping with the aims of this study, interest was focussed on the Method term and it's interaction with the Region and Zone terms. That is, how the effect of Method changed (or not) among different regions and management zones.

Population size structure

A 4-way frequency analysis was used to develop a log-linear model of size structure taken by spear and line in different regions and management zones. As log-linear models are highly sensitive to low expected cell values, to maximise the power of the test and minimise the probability of spurious significant effects, it is recommended that all expected frequencies are greater than zero, and no more than 20% of cells have expected frequencies less than five (SPSS Advanced Statistics 6.1; Tabachnick and Fidell, 1996). Size bins of 30mm were found to best achieve this while still retaining sufficient numbers of size bins to adequately describe the population. Nine size bins were used for each method, ranging from 310–340mm to 490–520mm with fish <310mm and >520mm pooled, over four regions and two management zones within each region. A total of 144 cells were used with all expected frequencies >1 and only nine <5.

Log-linear analyses of the FL data were carried out by initially fitting the fully saturated model to the data:

$$\ln(F_{ijkl}) = \mu + \lambda_i^M + \lambda_j^R + \lambda_k^Z + \lambda_l^S + \lambda_{ij}^{MR} + \lambda_{ik}^{MZ} + \lambda_{il}^{MS} + \lambda_{jk}^{RZ} + \lambda_{jl}^{RS} + \lambda_{kl}^{ZS} + \lambda_{ijk}^{MRZ} + \lambda_{ijl}^{MRS} + \lambda_{ikl}^{MZS} + \lambda_{jkl}^{RZS} + \lambda_{ijkl}^{MRZS}$$

Where:

μ = the average of the logs of the frequencies in all cells,

λ_i^M = the effect of the *i*th Method (spear, line),

λ_j^R = the effect of the *j*th Region (LI, TVL, MCK, SC),

λ_k^Z = the effect of the *k*th Zone (GU-B, MNP-B),

λ_l^S = the effect of the *l*th Size class (described above),

λ_{ij}^{MR}, λ_{ik}^{MZ}, λ_{il}^{MS}, λ_{jk}^{RZ}, λ_{jl}^{RS}, λ_{kl}^{ZS} = the effects of the 2nd-order interactions between factors,

λ_{ijk}^{MRZ}, λ_{ijl}^{MRS}, λ_{jkl}^{RZS}, λ_{ikl}^{MZS} = the effects of the 3rd-order interactions between factors, and

λ_{ijkl}^{MRZS} = the effect of the 4th-order interaction between factors.

Backward stepwise selection of effects for deletion using the HILOGLINEAR program in SPSS 8.0.0 was used with $\alpha = 0.05$ set as the criterion for eliminating terms from the model. Backward stepwise deletion of effects begins with the highest-order interaction terms and terms with a p > 0.05 (non-significant terms) are eliminated to achieve the most parsimonious model. By examining the relative contributions of individual terms to the model, sources of significant *k*th-order interaction effects were identified. To do this, a particular term was removed from the model and it's importance inferred from the resulting change in the Likelihood-ratio (L-R) chi-square value, χ^2, when the reduced model was fitted to the data.

The Method*Size term was not of interest in this study because a difference between methods was expected. To address the questions posed in this study the terms of interest were Method*Zone*Size, Method*Region*Size, and Method*Region*Zone*Size. I therefore focussed on the relative effects of these terms in the model. Post-hoc chi-square tests were carried out to determine causes of significant interaction effects. In all tests an $\alpha \leq 0.05$ was used as the criterion for statistical significance.

Results

Mean size

Analysis of mean size per reef indicated a significant Method*Region*Zone effect ($F_{0.05, 3, 8} = 4.07$; p = 0.021) (Table 3.1). Figure 3.1 shows that the significant difference in mean size between the sample taken by spear fishing and the sample taken by line fishing was evident in all management zones within regions. The significant interaction was due to a difference between methods in the relationships between zones and among regions. The most notable

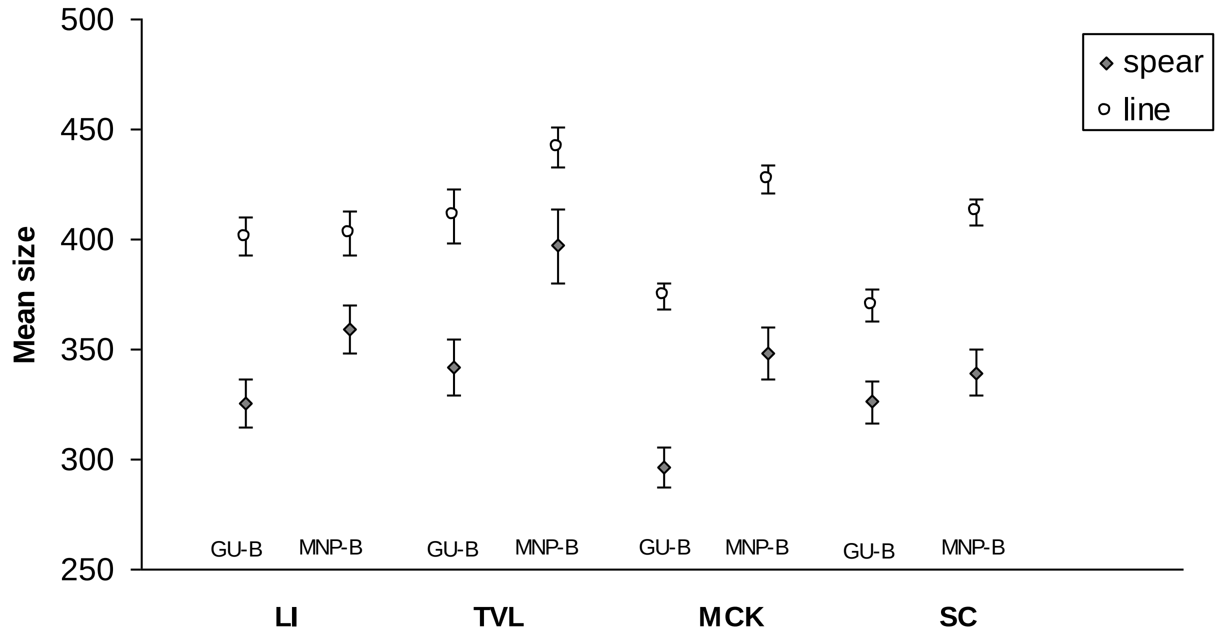


***Figure 3.1*:** Mean size of *P. leopardus* taken by spear fishing (dark symbol) and line fishing (light symbol) for each management zone from the Lizard Island (LI), Townsville (TVL), Mackay (MCK), and Storm Cay (SC) regions. Error bars represent 95% confidence limits.

result here was that the mean size of the catch taken by line fishing was consistently higher than that taken by spear fishing in all regions and management zones (Figure 3.1).

Source	**SS**	**df**	**MS**	**F-ratio**	**p**
A (Method)	31604.174	1	31604.174	448.120	**<< 0.001**
B (Region)	9134.754	3	3044.918	5.552	**0.023**
C (Zone)	12162.365	1	12162.365	22.175	**0.002**
A*B	882.814	3	294.271	4.173	**0.047**
A*C	130.778	1	130.778	1.854	0.210
B*C	1856.417	3	618.806	1.128	0.394
A*B*C	1216.841	3	405.614	5.751	**0.021**
A*D(B*C)	564.209	8	70.526		
D (Reef) (B*C)	4387.691	8	548.461		

Table 3.1: ANOVA table for the analysis of mean size of *P. leopardus* taken by spear fishing and line fishing surveys from reefs across different regions and management zones on the GBR. Significant p values are in bold.

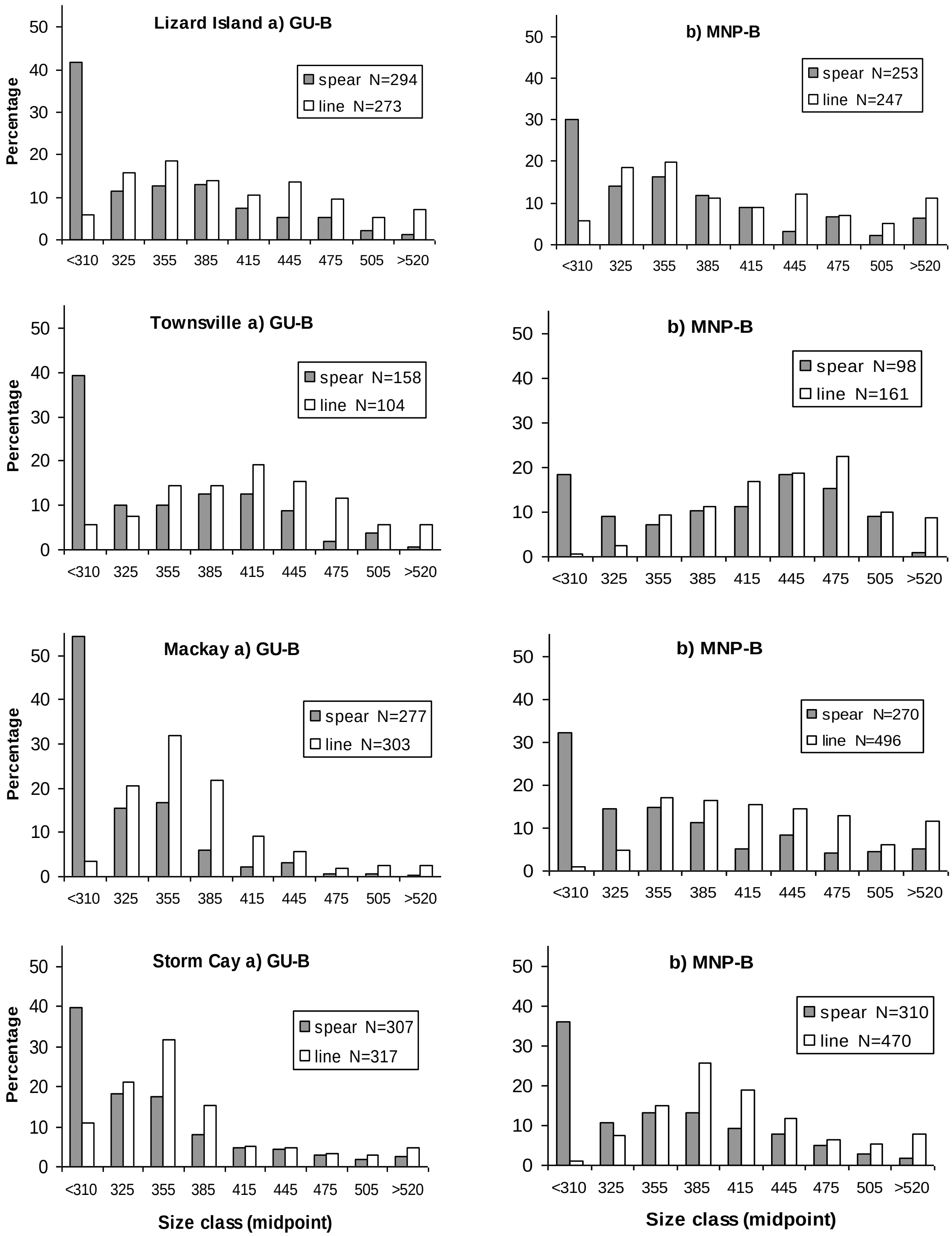
Population size structure

The best-fit log-linear model to describe the data contained all main effects and all interaction effects (L-R $\chi^2_{,0}$ = 0.000, p = 1.000). The effect of the 4th-order interaction was significant (L-R $\chi^2_{,24}$ = 39.072, p = 0.027). To resolve the 4th-order interaction further I fitted 3-way models (Method*Zone*Size) for each region and 3-way models (Method*Region*Size) for each zone.

By fitting the Method*Zone*Size models to each region it was found that zone did not significantly affect the size structures taken by each method in the Townsville, Lizard Island or Mackay regions (M*Z*S: [LI: L-R $\chi^2_{,8}$ = 5.932, p = 0.655; TVL: L-R $\chi^2_{,8}$ = 5.706, p = 0.680; MCK: L-R $\chi^2_{,8}$ = 8.498, p = 0.386]). In the Storm Cay region the Method*Zone*Size effect was significant (M*Z*S: L-R $\chi^2_{,8}$ = 35.096, p < 0.001). To resolve this further a chi-square test of Method*Size was carried out for each of the GU-B and MNP-B zones in the Storm Cay region. In each zone there was a significant effect of method on size class frequencies (M*S: [GU-B: $\chi^2_{,8}$ = 74.147, p < 0.001; MNP-B: $\chi^2_{,8}$ = 199.794, p < 0.001]). In the GU-B zone, the significant effect of method was removed by omitting the <310mm size class ($\chi^2_{,7}$ = 6.198, p = 0.517). This varied in the MNP-B zone in that the effect of method was removed after removal of the <310mm and the 310-340mm size classes ($\chi^2_{,6}$ = 10.315, p = 0.112). Spear fishing caught more fish <310mm than line fishing in the Storm Cay GU-B and MNP-B zones. In the Storm Cay MNP-B zone spear fishing also caught more fish in the 310-340mm size class than line fishing (Figure 3.5b).

By fitting the Method*Region*Size models to data from each zone it was found that region significantly affected the size structures taken by each method in both the GU-B and MNP-B zones (M*R*S: [L-R $\chi^2_{,24}$ = 53.026, p = 0.001 and L-R $\chi^2_{,24}$ = 66.654, p < 0.001, respectively]). This was examined further using chi-square tests of Method*Size for each region in both the GU-B and MNP-B zones. For the GU-B zone, removal of the <310mm size class achieved similar frequency distributions between methods in the Lizard Island, Townsville and Storm Cay regions (M*S: [LI: $\chi^2_{,7}$ = 12.714, p = 0.079; TVL: $\chi^2_{,7}$ = 12.499, p = 0.085; SC: $\chi^2_{,7}$ = 6.198, p = 0.517]) (Figures 3.2a, 3.3a and 3.5a respectively). In the Mackay GU-B zone, removal of both the <310mm and 310-340mm size classes was required to remove the effect of method on frequency distributions (M*S: $\chi^2_{,7}$ = 7.466, p = 0.280) (Figure 3.4a). For the MNP-B zone, not significantly different size frequencies between methods was achieved by removing the <310mm size class in both the Lizard Island and Townsville regions (LI: $\chi^2_{,7}$ = 13.208, p = 0.067; TVL: $\chi^2_{,7}$ = 13.570, p = 0.059) (Figures 3.2b and 3.3b). Agreement between observed and expected frequencies between methods was greatly improved in the Storm Cay region by removing the <310mm and 310-340mm size classes ($\chi^2_{,6}$ = 10.315, p = 0.112) (Figure 3.5b), and in Mackay by removing the <310mm, 310-340 and 340-370mm size classes ($\chi^2_{,5}$ = 7.816, p = 0.167) (Figure 3.4b).

To summarize, the obvious major effect of method present in all regions and zones was that spear fishing caught more fish than line fishing in the <310mm size class. Also, in all regions more fish <310mm were captured by both methods in the GU-B zone relative to the MNP-B zone, and this was more notable in the spear samples. Further, relatively more fish >400mm were captured in the MNP-B zones by both spear and line fishing.



Figures 3.2 – 3.5: Relative frequency (%) of *P. leopardus* for each of the size classes <310mm, >520mm, and 30mm size classes in between, from the spear (dark bars) and line (light bars) samples for each of the GU-B (a) and MNP-B (b) zones. Figures 3.2-3.5 represent the LI, TVL, MCK and SC regions respectively. N = sample size.

Discussion

Sampling gear selectivity

The overwhelming difference in the samples taken by spear fishing and line fishing occurred in the smaller size classes. Fish less than 310mm in particular comprised a much larger proportion of the speared sample and were all but absent from the line samples on most reefs. This was clearly indicated in the analysis of the size frequencies, and was further reflected by the significantly lower mean size in the speared sample. To a lesser extent the higher mean size of fish taken by line fishing was further accentuated by this gear taking more fish in the larger size classes (>370mm) relative to spear fishing.

These results were a very clear demonstration of gear-specific size selectivity. The selectivity curve developed by Strachan-Fulton (1996) for the hook and line gear from which these data came showed an increase in selectivity (probability of capture) with size, to full recruitment to the gear at a size of approximately 390mm. Constant selectivity was inferred above this size. Very few fish were captured below approximately 290mm (selectivity ≈ 0.20) (Strachan-Fulton, 1996). No such curve has been developed for spear fishing. In this study fish less than 310mm comprised 3.92% of the line caught sample, but 38.18% of the spear caught sample. Examination of the range of sizes taken by spear and line fishing also demonstrated the selective nature of each gear. The mean size range for line fishing was 272.8 – 604.9mm while for spear fishing it was 147.6 – 592.8mm. The selectivity curve for hook and line gear developed by Strachan-Fulton (1996) showed that *P. leopardus* as small as 230mm may be taken by the line gear, but with very low likelihood. The lower end of the size range taken by spear fishing in this study was as low as 108mm. It isn't known what proportion of fish less than 310mm were likely to be taken from a population by spear fishing, however the pilot study conducted for this study suggested that spear fishing under-sampled fish <200mm by approximately 25% (Welch, 1998). To better understand the changing selectivity with fish size, a more comprehensive study would be required to develop a selectivity curve for spear fishing. The difference in relative numbers of fish <310mm taken by spear and line fishing, however, emphasised the inability of line fishing with commercial grade gear to adequately sample smaller, and presumably younger fish.

There are several factors that contribute to such selectivity by line fishing. Hook and line fishers on the GBR generally use large hook sizes (Mustad 8/0) and large baits (whole pilchards). Both of these factors result in larger fish in the catch (Hook size: Koike *et al*, 1968, in Lokkeborg and Bjordal, 1992; Cortez-Zaragoza *et al*, 1989; Bait size: Lokkeborg and Bjordal, 1992) due to smaller mouth gape in smaller fish impeding the biting of large hooks and baits (Ralston, 1982, 1990). Competition for baits favouring larger fish (Hovgard and Riget, 1992) and larger home range areas (Samoilys, 1997; Zeller, 1997) also increase exposure of larger fish to capture by line fishing gear, given the gears' static nature. Spear fishing, as used in this study, is not as affected by these factors, as demonstrated by the much larger proportion of smaller fish in the catch. In fact, it is highly likely that spear fishing under-samples smaller fish due to the difficulty in sighting them and due to the smaller target they represent. Further, juvenile *P. leopardus* are somewhat cryptic after settlement, often occupying inaccessible habitats (Doherty *et al*, 1994), reducing the likelihood of them being speared.

Sampling gear effects across management zones

Fishing tends to take the larger fish from a population and therefore it is to be expected that the effects of fishing would be manifest in the size structure of a fished stock. The use of closed areas as fisheries management tools has only recently begun to receive serious attention and to date their effectiveness has been equivocal (Ayling and Ayling, 1986; Beinssen, 1989; Ayling *et al*, 1992; Ayling and Ayling, 1992; Ferreira and Russ, 1995; Polunin and Roberts, 1993; Davies, 1996; Fujita *et al*, 1998; Edgar and Barrett, 1999). The results here, also, were equivocal when spear and line mean sizes were compared. The difference in the mean size of *P. leopardus* between the spear and line samples was not consistent between management zones within regions.

In the Mackay region the MNP-B zone (closed to fishing) showed a significantly higher mean size than the GU-B zone (open to fishing) in both gear samples. This is not surprising, as Mackay is a region where fishing effort is one of the highest on the GBR (Mapstone *et al*, 1996a). More large fish being taken by both methods in the MNP-B zone influenced this. In the spear sample only, the higher mean size in MNP-B zones was also influenced by relatively fewer small fish (<310mm) in the MNP-B zone than in the GU-B zone. Higher densities of smaller juvenile *P. leopardus* on GU-B reefs relative to MNP-B reefs were also recorded by Ayling *et al* (1991). This observation considerably affected estimates of mean size. The authors postulated that the density difference may have arisen through cannibalism of small fish due to increased numbers of adult predators on protected reefs.

Storm Cay, also has very high levels of fishing pressure relative to other areas of the GBR (Mapstone *et al*, 1996a). The line caught size structures for the GU-B and MNP-B zones reflected this in that they were remarkably similar to the Mackay line caught size structures, and resulted in a significant difference in mean size between zones. In the spear sample however, a very large proportion of fish <310mm were caught in both the GU-B zone (39.74%) and MNP-B zone (36.13%) resulting in similar mean sizes. This may represent a strong recruitment pulse in this region because in spear samples from all other regions there were appreciably more fish <310mm in the GU-B zone. Alternatively, the Storm Cay region may have a more complex physical habitat to provide protection from predators and therefore enhance survivorship of smaller fish.

Fishing effort in the Lizard Island region is the lowest of all the regions sampled (Mapstone *et al*, 1996a). No zonal difference was found in the mean size and size structures for samples from both gears. The mean size of fish in the Townsville region was relatively high but a significant difference between zones in the spear sample was again mostly due to a large proportion of fish <310mm in the GU-B zone, which was twice the proportion of fish <310mm captured in the MNP-B zone. The difference was accentuated by more larger fish captured by spear fishing in the MNP-B zone, which was also evident in the line caught sample though to a lesser extent. In the line sample, no difference was observed in the mean size between zones, even though the MNP-B size distribution showed a shift to the right.

Sampling gear effects across regions

Regional differences in population size structure have been documented before for reef fishes (eg. Choat, 1991; Williams, 1991). With the large spatial scale of the GBR, and the heterogeneity of reef structures, different regions are subject to varying environmental conditions that may account for the difference in the observed size distributions from Townsville. Both sampling methods suggested that mean size in the Townsville region was significantly greater than some other regions, and the Lizard Island, Mackay and Storm Cay regions were all similar. There were noticeably less small fish in the Townsville region in both the spear and the line sample indicating that recruitment here is low relative to the other regions sampled. In fact, the modal size in the line sample was 460-490mm compared to 340-370mm in all other regions, representing an appreciable size difference. Apart from the <310mm size class, the spear sample showed a similar pattern. The Townsville region is more exposed to the oceanic waters of the Coral Sea than other regions in this study, and is characterised by steep reef edges, clear water and few off-reef structures such as bommies. Reefs in the other three regions are distinctly different and are characterised by more gentle slopes, more turbid waters and a more complex reef structure. These factors may account for the apparent lower levels of recruitment evident in the Townsville region.

Implications of sampling gear effects

The basis of size-based methods of fish stock assessment is the use of size as a proxy for age. Tropical fish species such as *P. leopardus*, exhibit very large variation in size-at-age (Ferreira and Russ, 1994) It is likely that parameter estimates derived from length-based methods will always be biased.

Smaller, younger fish usually dominate a population numerically, so the inability of line fishing to sample these fish representatively will always result in biased parameter estimates. Estimates of mean size from samples taken by line fishing are clearly positively biased when compared to the true population mean. In this scenario, using length-based parameter estimation methods would result in over-estimation of the potential yield in biomass of a stock. Setting catch quotas based on such estimates could very quickly result in over-harvesting of stocks (Hilborn and Walters, 1992). Total mortality rates calculated using mean size (Beverton and Holt, 1957) would be under-estimated if using a line caught sample. It is worth pointing out however that estimates derived using this method would normally only be considered an approximation anyway due to several obstinate assumptions (Hilborn and Walters, 1992). A more useful length-based method is the use of modes from a size frequency distribution where growth estimates are derived by assuming modes represent cohorts (modal progression) (Hilborn and Walters, 1992). Using age estimates for *Acanthopagrus butcheri*, Morison *et al* (1998) found growth to be much slower and longevity longer than estimates obtained by Kesteven and Serventy (1941) for the same species but using modal progression. On the GBR, Goeden (1978) estimated a maximum longevity of 5 years in *P. leopardus* and an estimate of mortality of 1.04, using length frequency data lacking in smaller fish. More recent work, including this study, have shown these estimates to be erroneous (Ferreira and Russ, 1994; Russ *et al*, 1998). By not effectively sampling fish less than 310mm, as seen in this study, line fishing catches could exclude several cohorts resulting in grossly inflated estimates of mean size-at-age and therefore growth.

Conclusions

In this study, spear fishing samples included a large proportion of *P. leopardus* that were less than 310mm while line fishing samples did not. This resulted in significantly higher estimates mean size of fish in the line caught samples. The biases between the two gears were not affected by sampling in regions of different physical and environmental characteristics. At a local scale the sampling gear biases were consistent between areas subjected to fishing and areas protected from fishing. The overall nature of the bias of line fishing, however, needs to be clarified further.

Chapter 4. The effect of sampling gear on fish age structures across management zones and regions of the Great Barrier Reef

Introduction

Age determination of fish has long been recognised as an almost necessary requirement of most fisheries stock assessment methods (Pauly, 1987; Hilborn and Walters, 1992). Basic information about growth, mortality and recruitment of fish populations are derived directly from size and age and age frequency data. Length-based methods can also be used to derive estimates of these parameters (discussed in Chapter 3), however there are many examples in coral reef fish of large variation in size-at-age (Bullock *et al*, 1992; Ferreira and Russ, 1992, 1995; Doherty and Fowler, 1994; Davies, 1996; Choat *et al*, 1996; Hart and Russ, 1996; Williams, 1997). This means that size frequencies will often not reflect age frequencies from a population and increases the importance of reliable estimates of age other than those derived from size. It is this variation that makes length-based methods relatively unreliable, particularly in longer lived species (Newman *et al*, 1996a). For example, Morison *et al* (1998) worked with age data to show that earlier length-based estimates of growth of *A. butcheri* were inflated (see Kesteven and Serventy, 1941). Morales-Nin and Ralston (1990) used several samples of *Lutjanus kasmira* to show that length-based growth parameter estimation was most unstable when compared to age-based estimation. Age structures also can be powerful tools for providing information about recruitment history (Jones, 1991; Doherty and Fowler, 1994). Russ *et al* (1996) showed one of the best demonstrations of this when a dominant year class of *P. leopardus* was tracked in age samples taken over four years. Horn (1997) presented a similar example for *Merluccius australis*. These studies all emphasise the importance of using age-based methods.

The age structures of fish populations can be useful in identifying differences in populations that come from different locations. They can reflect different biological characteristics of populations that may indicate discrete stocks (eg. Smith *et al*. 1998), or may also be indicators of different environmental or physical conditions. Regional differences in age structures may indicate a need for differences in management of harvested species. Fishing effects are often well reflected in age structures and mean ages as fishing most often impacts on the older fish in a population (Russ, 1991). This is a secondary effect of size selectivity in that larger fish tend to be older and fishing tends to take the larger fish. From a management perspective, age structures can be useful in evaluating management strategies such as area closures or reductions in catch or effort.

As with most sampling, it is vital that samples used to estimate age structures are as representative as possible of the population from which they came. Age structure will depend on the sampling regime and the selectivity of the gear used for collection of the sample. For example, samples of *P. leopardus* taken by fence nets were all relatively small and less than 2 years old while those taken by spear and line fishing were predominantly greater than two years old (Ferreira and Russ, 1994) although gear selectivity is primarily a function of fish size. Several studies have used spear fishing along with other collection methods to sample fish populations for age structure analysis (eg. Ferreira and Russ, 1994; Brown *et al*, 1996; Choat *et al*, 1996; Hart and Russ, 1996). On the GBR only one study has compared spear caught age structure with the age structure taken by a different sampling gear. Brown *et al* (1993) found that spear fishing caught more 1-3 year old fish relative to line fishing. This study was inconclusive, however, as the authors acknowledged in a later report (Brown *et al*, 1996) that these age estimates were strongly affected by reader bias.

In this study I examined the age structures of *P. leopardus* sampled by spear fishing and line fishing to estimate the effect of sampling gear on age, and to examine the consistency of such effects across different regions and different management zones of the GBR.

Methods

Age determination procedure

Speared samples

Otoliths from speared samples were removed through the ventral cranial surface on return to the laboratory at James Cook University. Otoliths were cleaned and weighed to the nearest 0.0001g using a Sartorius balance. Otoliths of *P. leopardus* show a pattern of translucent and opaque zones which have been identified as annuli (Ferreira and Russ, 1994). Otoliths from speared samples were generally read whole under a dissecting microscope at 40x magnification after being placed in a cavity filled with baby oil and illuminated by reflected light against a black background. Smaller otoliths were read under lower magnification (20x) with reduced light as this greatly enhanced identification of annuli. Also recorded for each otolith was information about the margin and the readability of the otolith. The margin was recorded as either opaque, < 50% translucent or > 50% translucent, based on the width of the last complete increment. The otolith was given a readability index from 1 – 3, with 1 = very clear to 3 = very poor.

Ferreira and Russ (1994) reported that whole readings of sagittae for *P. leopardus* underestimate age when compared to sectioned readings at ages above 6 years, and this underestimate tends to increase with age. Accordingly all whole otoliths with a count of 6 annuli or more were subsequently sectioned and re-read. Any other whole otoliths that had a readability index of 3 were also put aside for sectioning.

Otoliths to be sectioned were first embedded in epoxy resin and then sectioned transversely through the centrum using a Multi-drive low speed diamond saw. Sections were mounted on to slides using Crystal bond and polished using 800- and 1200-grade waterproof emery paper. All sectioned otoliths were then read in random order recording the same information as for whole otoliths. Annuli were counted on the distal surface in the posterior dorsal region of the sagittae. The sectioned age estimates then replaced the whole age estimates for those otoliths. The baseline age estimates from speared samples were therefore collected from the counts of whole otoliths of ages 5 years and less, and the counts of sectioned ages aged 6 or more or which had a whole otolith count with a readability of 3 (poor).

Whenever possible, the right sagitta was used in all steps of the age determination procedure for consistency. If the right sagitta was damaged or missing the left sagitta was then used. No difference has been found between right and left otoliths in either weight or age estimation for *P. leopardus* (Ferreira and Russ, 1994). All otoliths were read in random order without prior knowledge of the fish length or place of capture.

Precision of age counts

To determine the precision, or repeatability, of the otolith counts, 10 otoliths were selected at random from each of the age classes 1 to 10. All otoliths with counts greater than 10 years were pooled into an 11th class. This sub-sample of otoliths (n = 124) were then re-sorted in random order and read a second and third time. A minimum of two weeks elapsed between each reading and otoliths were re-randomised between readings. Given that there was a known number of samples for each age class, at each reading approximately one third of each of the sectioned and one third of the whole otoliths were read. This minimised the potential for prior knowledge of individual otoliths to cause bias in the age estimation procedure.

Precision was then calculated as the coefficient of variation (CV; Chang, 1982), the standard deviation of repeated counts divided by their mean.

Hook and line samples

Final ages for sagittal otoliths taken by line fishing were reached using a slightly different procedure that involved sectioning all otoliths and using multiple readers (see Mapstone *et al*, 1998a). To test for consistency in age estimates between samples, a random sample (n = 44, age range 1 - 13) was taken from the speared sample and read three times by both one of the main readers used to age fish from the line caught samples (AW), and the reader of the speared sample (DW). The CV was calculated for each reader and compared and percentage agreement between readers was also calculated. Percentage agreement is calculated simply as the number of age estimates agreed within a specified number of years between readers, and is expressed as a percentage of the total number of age estimates (Kennedy, 1970).

Data Analysis

Mean age

The mean age was calculated for each reef from both gear samples and was compared between methods among regions, zones and reefs by 4-way ANOVA. The factors were method (spear, line), region (LI, TVL, MCK, SC), and management zone (GU-B, MNP-B) as fixed, and reef as a random factor nested within region and zone. As with the size structure data, the primary questions of this thesis were concerned with the terms Method and it's interaction with Region and Zone.

Population age structure

A 4-way frequency analysis was used to develop a log-linear model of age structure taken by spear and line in different regions and management zones. Seven age classes were found to best achieve adequate cell frequencies while still retaining sufficient number of age classes to describe the population (SPSS Advanced Statistics 6.1; Tabachnick and Fidell, 1996). There were only four 1-year-old fish in the entire hook and line sample so it was necessary to pool all 1 and 2 year old fish into one age class (≤ 2 years). It was also necessary to pool fish of 8 years and older (≥ 8 years). A total of 112 cells were used with only nine cases having expected frequencies of <5. There was one '0' cell frequency which was retained in the analysis using a 'dummy' value as it did not influence the final model (SPSS Advanced Statistics 6.1; Tabachnick and Fidell, 1996).

Log-linear analyses of the age data were carried out initially fitting the fully saturated model to the data:

$$\ln(F_{ijkl}) = \mu + \lambda_i^M + \lambda_j^R + \lambda_k^Z + \lambda_l^A + \lambda_{ij}^{MR} + \lambda_{ik}^{MZ} + \lambda_{il}^{MA} + \lambda_{jk}^{RZ} + \lambda_{jl}^{RA} + \lambda_{kl}^{ZA} + \lambda_{ijk}^{MRZ} + \lambda_{ijl}^{MRA} + \lambda_{ikl}^{MZA} + \lambda_{jkl}^{RZA} + \lambda_{ijkl}^{MRZA}$$

Where:

μ = the average of the logs of the frequencies in all cells,

λ_i^M = the effect of the *i*th Method (spear, line),

λ_j^R = the effect of the *j*th Region (LI, TVL, MCK, SC),

λ_k^Z = the effect of the *k*th Zone (GU-B, MNP-B),

λ_l^A = the effect of the lth Age class (described above),

λ_{ij}^{MR}, λ_{ik}^{MZ}, λ_{il}^{MA}, λ_{jk}^{RZ}, λ_{jl}^{RA}, λ_{kl}^{ZA} = the effects of the 2nd-order interactions between factors,

λ_{ijk}^{MRZ}, λ_{ijl}^{MRA}, λ_{jkl}^{RZA}, λ_{ikl}^{MZA} = the effects of the 3rd-order interactions between factors, and

λ_{ijkl}^{MRZA} = the effect of the 4th-order interaction between factors.

The most parsimonious model, and the relative contribution of terms of interest to the model, was determined using the change in Likelihood-ratio (L-R) chi-square value (as discussed in Chapter 3). Again, the Method*Age term was of only limited interest in this study because a difference between methods was to be expected. As with the size data (Chapter 3) the terms of interest were Method*Region*Age, Method*Zone*Age and Method*Region*Zone*Age. In all tests an $\alpha \leq 0.05$ was used as the criterion for statistical significance.

Results

Precision of Age Determination

For the speared samples read multiple times the CV pooled across all age classes was calculated as 0.081. From the sub-sample taken to compare between-reader differences in age estimation, the spear reader (DW) had a CV of 0.06, and the hook and line reader had a CV of 0.05 (AW). Percentage agreement between DW and AW was 61.36% for exact agreement, and 90.90% within ± 1 year (Table 4.1). These values indicate a high degree of precision between readers (Chang, 1982).

	Reader (spear - DW)	**Reader (line - AW)**
CV	0.0630	0.0498
% exact agreement	61.36	
% agreement ± 1 yr	90.90	

Table 4.1: Co-efficient of variation (Chang, 1982) and % agreement for otolith counts between spear and line readings.

Mean age

The effects of Method*Region*Zone, Method*Region and Method*Zone were non-significant ($F_{0.05,3,8}$ = 1.21; p=0.367; $F_{0.05,3,8}$ = 3.75; p=0.060; $F_{0.05,1,8}$ = 0.039; p=0.849, respectively) (Table 4.2), suggesting that the any difference in mean age between the two methods was consistent across regions and management zones. The main effects Method and Zone did influence mean age (Method: $F_{0.05,1,8}$ = 143.88; p<<0.001; Zone: $F_{0.05,1,8}$ = 11.69; p=0.009) (Table 4.2). The mean age estimated from the spear sample (3.51 ± 0.046) was significantly lower than from the line sample (5.03 ± 0.038) (Table 4.3). The mean age estimated from the GU-B zone (3.85 ± 0.041) was also significantly lower than the mean age estimated from the MNP-B zone (4.78 ± 0.045).

Source	**SS**	**df**	**MS**	**F-ratio**	**p**
A (Method)	14.218	1	14.218	143.882	**<< 0.001**
B (Region)	1.767	3	0.589	0.772	0.541
C (Zone)	8.915	1	8.915	11.686	**0.009**
A*B	1.111	3	0.370	3.747	0.060
A*C	0.004	1	0.004	0.039	0.849
B*C	2.808	3	0.936	1.227	0.362
A*B*C	0.359	3	0.120	1.210	0.367
A*D(B*C)	0.791	8	0.099		
D (Reef) **(B*C)**	6.103	8	0.763		

***Table 4.2*:** ANOVA table for the analysis of mean age of *P. leopardus* taken by spear fishing and line fishing surveys from reefs across different regions and management zones. Significant p values are in bold.

	Spear mean age	Line mean age	Spear age range	Line age range
Lizard Island	*3.63*	*5.06*	*1-16*	*1-16*
GU-B	3.09	4.67	1-9	1-15
MNP-B	4.25	5.55	1-16	2-16
Townsville	*3.45*	*4.76*	*1-11*	*1-11*
GU-B	2.93	3.88	1-8	1-9
MNP-B	4.29	5.34	1-11	1-11
Mackay	*3.06*	*4.82*	*1-11*	*2-13*
GU-B	2.64	4.37	1-10	2-10
MNP-B	3.50	5.09	1-11	2-13
Storm Cay	*3.83*	*5.30*	*1-16*	*1-15*
GU-B	3.78	4.89	1-16	2-15
MNP-B	3.87	5.58	1-14	1-13
TOTAL	**3.51**	**5.03**	**1-16**	**1-16**

***Table 4.3*:** Summary table of mean ages and the age range of samples taken by spear and line fishing for all regions and management zones in each region.

Population age structure

The best-fit log-linear model to describe the age data contained the 3rd-order interaction terms Method*Region*Age, Method*Region*Zone, and Region*Zone*Age (L-R $\chi^2_{,24}$= 22.925, p = 0.524). The 4th-order interaction term had a negligible effect on the expected frequencies in the model so no further analyses of this term were done. The terms Method*Region*Zone and Region*Zone*Age were not relevant to the questions asked in this study so were not investigated further here.

The significant 3rd-order interaction term Method*Region*Age (L-R $\chi^2_{,18}$= 49.964, p < 0.001), however, was of interest because it indicated potential differences in age frequencies that depended on method in at least one region. When considered separately by region all regions showed significant effects of method on age class frequencies (M*A: LI, $\chi^2_{,6}$ = 210.168; TVL, $\chi^2_{,6}$ = 85.252; MCK, $\chi^2_{,6}$ = 453.265; SC, $\chi^2_{,6}$ = 328.817; All regions p < 0.001). In the Lizard Island region (Figure 4.1a), by removing the <3, 3 and 6 year age classes, the agreement between the age class frequencies for each method was greatly improved ($\chi^2_{,3}$= 6.964, p = 0.073). A similar result was found in both the Mackay and

Storm Cay regions except the 7-year-olds and ≥ 7-year olds respectively were also removed before counts from the two methods were similar (MCK: $\chi^2_{,2}$ = 2.727, p = 0.256; SC: $\chi^2_{,2}$ = 5.999, p = 0.050) (Figures 4.1c & 4.1d). The difference between samples for the older age classes was not as large in the Townsville region and a better fit to the data was obtained by removing only the <3 and 3 year olds ($\chi^2_{,4}$ = 6.162, p = 0.187) (Figure 4.1b).

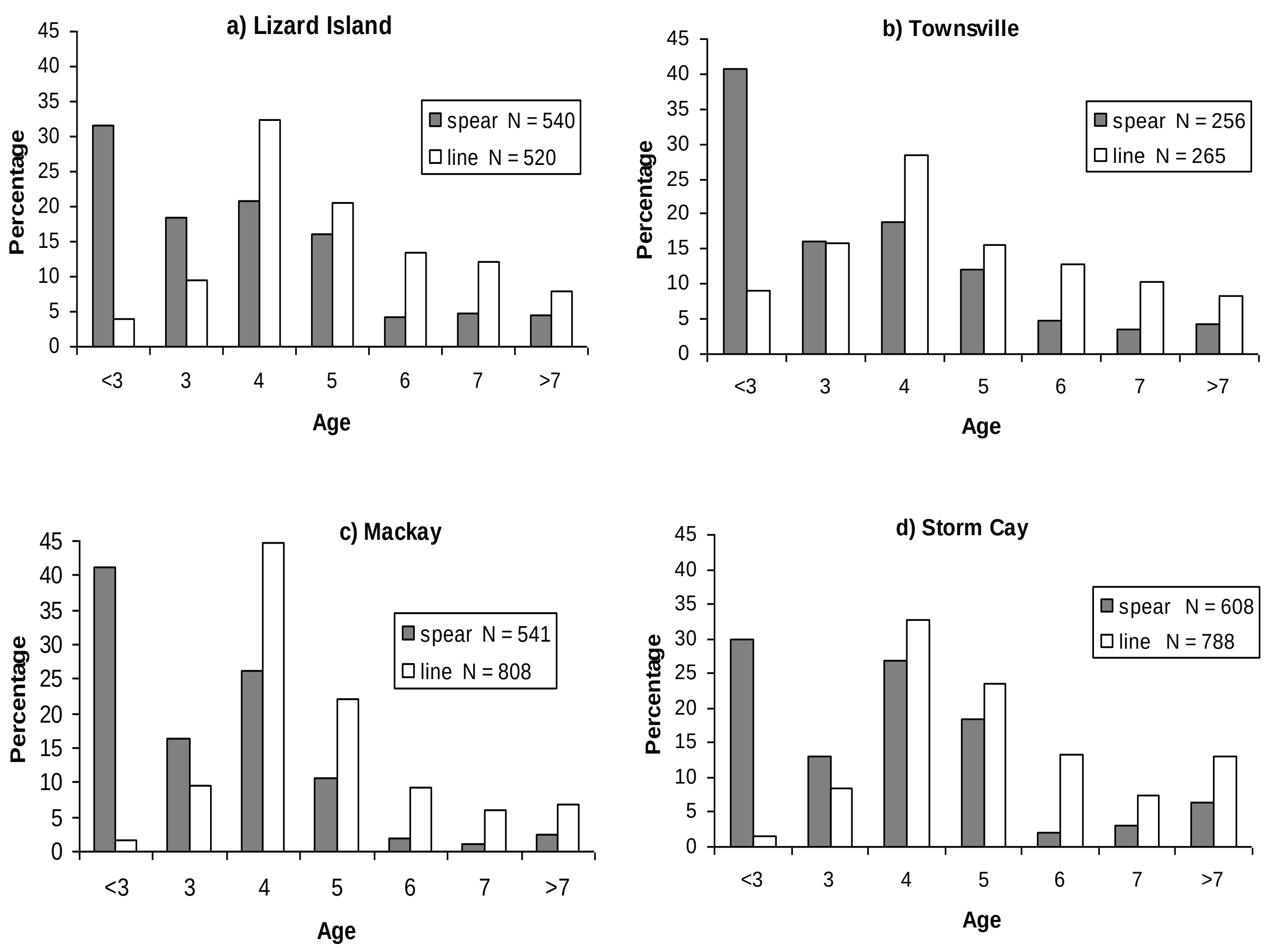


Figure 4.2: Relative frequency (%) of *P. leopardus* for each age class for each of the speared sample (dark bars) and the line sample (light bars) from the Lizard Island (a), Townsville (b), Mackay (c) and Storm Cay (d) regions.

In all regions the 1-2 year old age class explained the vast majority of the variation between methods, with significantly more of these fish in the speared sample than in the line sample. In all regions, most of the remaining variation was due to more 3-year-olds in the speared sample and more ≥ 6-year-olds in the line sample (see Figures 4.1a – d).

Discussion

Sampling gear effects

The difference in age structure and mean age between the two sampling methods followed the same general pattern across both management zones but varied among regions. The most notable and consistent difference between samples in this study was that 1 and 2 year old fish made up the majority of the speared catch while they were the least represented in the line catch. This was also noted by Brown *et al* (1993) in the only other study on the GBR that has compared age structures of speared and line caught *P. leopardus*. The other main feature was that line fishing took more old fish (≥ 6 years) than did spear fishing. A possible explanation for this was that sampling by line fishing was able to fish in depths to 30 metres while spear fishing was restricted to 10 metres. Larger and therefore older fish of populations are often found in deeper water (Ayling, 1983; Morales-Nin and Ralston, 1990; Wigley and Serchuk, 1992). Cautious behaviour of larger fish may make them harder for divers to approach underwater. It is also possible that larger fish are disproportionably sampled by line fishing due to competition for baits. The author has observed on several occasions on the GBR larger *P. leopardus* individuals chase smaller individuals away from baits. Further, the use of large hook and/or bait sizes in the GBR hook and line fishery may select for larger fish. In the Brown *et al* (1993) study there was a hint of this difference in the older age classes, but sample sizes were very low. Clearly, the lack of young fish and the higher proportion of old fish in the line catch has also led to the higher mean age observed consistently in the line caught samples.

Another feature of the age distributions was that samples from both gears, in all regions and zones, had a very strong mode at age 4 years. The age distributions from the speared samples however were consistently bi-modal at 1 year and 4 years of age. Although spear fishing was obviously able to take 1-year-old fish much more effectively than line fishing, it is not possible here to determine whether the 1-year age class was fully recruited to the gear. Further work would be required to determine the age of full recruitment to spear fishing gear and the age-specific selectivity of spear fishing.

The second mode in the speared sample at the 4-year age class, along with the very strong mode at this age in the line sample, suggests that it represented an unusually strong year class. Large variation in year to year recruitment is widely documented for tropical coral reef fish (eg. Victor, 1983; Doherty and Williams, 1988). It has been noted in recent work on the GBR that this variation strongly influences population structure and abundance of *P. leopardus* (Ferreira and Russ, 1995; Brown *et al*, 1996; Russ *et al*, 1996). The hypothesis that the strong 4-year-old cohort in both spear and line samples is recruitment driven was supported by the high catches of larval *P. leopardus* in the Cairns region reported by Doherty (1996) in light traps in the 1991/92 season relative to other years. Furthermore, Ayling (19##) recorded a strong recruitment pulse from observations of recruits on reefs near Townsville in early 1992. If the recruitment hypothesis is correct, then the interesting observation in this study is that it is evident over a very large area of the GBR (7^{o} latitude). For the purpose intended here however, the important point is that both gears demonstrated the strong age class. It is unlikely though that strong year classes below 4 years of age would be evident in samples taken by line fishing, whereas spear fishing would be more likely to show strong year classes down to 1 year old fish.

Line fishing caught relatively more 4-year-old fish than spear fishing but the difference was greater in the GU-B zone from three of the four regions. Again this was because of the influence of the high number of 1-3 year old fish in the speared sample and when omitted from both samples the relative frequencies of 4-year-olds were a lot closer. No effect of zone was observed on this strong year class which would indicate that these fish were not yet fully vulnerable to fishing, or that fishing pressure was insufficient to noticeably reduce the proportion in the population.

Implications of sampling effects

The greater ability of spear fishing to sample 1-3 year old fish relative to line fishing, means that spear estimates of mean age will be consistently lower. This indicates that estimates of mean age from line fishing samples of *P. leopardus* on the GBR will be over-estimated. Samples from spear fishing also provide much greater ability to identify strong or weak year classes before they become vulnerable to the fishery. This type of information can be important in forecasting good or poor fishing years (Russ *et al*, 1996). Underwater visual survey (UVS) methods can also be useful in predicting good or poor fishing years by counting the 0+ fish. However, UVS is unable to give estimates of age or determine sex for fish older than the newly recruited juveniles. Spear fishing provides not only a clear picture of recruitment history of a population but also will provide for more accurate estimates of mortality. With more accurate parameter estimates, the uncertainty in management decision-making will be reduced and the predictive ability of models will be improved.

Conclusions

Line fishing is very ineffective at sampling the 1-3 year old fish from populations of *P. leopardus*. These younger age classes represent a very large proportion of *P. leopardus* populations and therefore provide a vast amount of information about recruitment history and early life history growth and mortality. Accordingly, the use of mean age and age distributions from hook and line samples can be misleading. Spear fishing is able to provide samples that include these younger age classes as well as older fish. Spear samples are therefore more representative of populations of *P. leopardus* than line fishing. The age-specific selectivity of spear fishing is poorly understood however.

Chapter 5. The effect of sampling gear on estimates of growth and mortality across management zones and regions of the Great Barrier Reef

Introduction

The estimation of population parameters is fundamental to fisheries stock assessment. From such parameters we can get important information such as stock size, potential yield and productivity. Using catch-at-age data that is biased due to size selection imposed by the fishing gear will yield inaccurate estimates of population parameters such as growth indices (L_∞ , K and t_0) and mortality rates. This usually arises when samples lack smaller, younger fish or larger, older fish, or both. Since almost all fishing gears are size selective, this is a common occurrence.

Different gears also exhibit different selective characteristics. Ferreira and Russ (1994) found that samples of *P. leopardus* taken by spear and line fishing combined lacked 1-year-old fish, resulting in biased growth parameter estimates. They demonstrated this by complementing the sample with 1-year old fish taken using fence-nets. Mulligan and Leaman (1992) presented results of a model for an exploited population of *Sebastes alutus*, a species that shows negative growth at older ages, that gave inflated estimates of L_∞ due to a lack of small, older fish. Biased estimates of abundance and population biomass also result if selectivity is not constant over all ages in the population (Bence *et al*, 1993: Sampson, 1993). Also different types of the same gear (eg. different hook sizes or mesh sizes) show different selective characteristics. For example, Goodyear (1995) used computer simulations to demonstrate two different growth schedules for *Epinephelus morio* when comparing samples from commercial hook and line and recreational hook and line fishers. The difference was because recreational anglers in general tended to take the faster growing fish in a given year class because they are the first to be recruited to the gear (Miranda *et al*, 1987). This results in an overestimate in mean length per year-class, and therefore growth rate, because the smaller fish of an age-class tend to be captured less frequently than the larger ones (Ricker, 1969). Estimates of rates of mortality will depend largely on the age at which full recruitment to the fishing gear occurs, and also whether selectivity is constant across recruited ages. This can vary depending on variability in size at age for a species and the type of fishing gear.

There are two ways one can attempt to overcome biased parameter estimation from using selective fishing gears: 1) Use a fishing gear that is not size selective to sample from fish populations representatively, or 2) gain an understanding of the selective nature of the fishing gear in question and account for this bias in the estimation of parameters. The first option is fairly difficult to achieve, if not impossible (Miranda *et al*, 1987; Hovgard and Riget, 1992). The second option is achieved by i) comparing variations of the same gear type, such as different mesh sizes (eg. Hamley, 1975: Ralston, 1990) or ii) by comparing different fishing gears (eg. Leclerc and Power, 1980) that are expected to have different selective properties.

In this chapter I investigate the bias of population parameter estimates derived from hook and line samples by comparison with samples taken by spear. To do this I compared total mortality rates and von Bertalanffy growth function (VBGF) parameters estimated from samples taken using hook and line gear with those taken by spear fishing, which is expected to be selective over a greater range of age and size. Implications for stock assessment are discussed using yield-per-recruit analyses as an example.

Methods

Growth parameters

Ferreira and Russ (1994) determined that the most appropriate growth model to describe the growth of *P. leopardus* was the VBGF. The von Bertalanffy growth equation for length is given by:

$$L_t = L_\infty(1 - e^{-K(t-t_0)})$$

where L_t is the length at age t; L_∞ is the mean maximum length; K is the rate at which L_∞ is approached; and t_o is the theoretical age at size 0. This function was fitted to the size-at-age data for samples taken by each gear from each reef.

For all reefs I constrained the curves to more biologically realistic parameter estimates by selecting a y-intercept that corresponded to a size at age 0, or size at hatching, of 1.62mm (see Masuma *et al*, 1993).

Growth parameter comparison

Although several methods for comparing growth parameters and curves have been suggested (eg. Kimura, 1980; Misra, 1980; Bernard, 1981; Cerrato, 1990; Chen et al, 1992; Zivkov, 1999), none of these are multi-factorial tests and none allow for the use of hierarchical analyses. This results in problems when interpreting multiple tests and adjusting significance levels to account for compounding Type I errors. Since I was primarily interested in the effect of the sampling gear on the estimated parameters, I examined the difference (*d*) in the parameters estimated from the data for each of the two gears. For example, for each reef separate estimates of K were obtained using the spear and line data (K_s and K_l). The difference between the estimates (K_s - K_l) became the test variable (K_d). The same approach was used for L_∞. The third VBGF parameter, t_o, was omitted from this procedure, as it had been constrained in the original parameter estimation and consequently was the same for all data sets.

The principal analysis for effects of region or management zone on *d*, for each of K and L_∞, involved a 3-way ANOVA with the factors Region, Zone and Reef nested within Region*Zone, and K_d and L_d as the dependent variables. Region and Zone were fixed orthogonal factors, and reef was a random factor that provided the error variance for tests of Region, Zone and Region*Zone.

To test whether *d* for each of L_∞ and K was in fact significantly greater than zero, I did a two-tailed paired sample t-test. Here, the t statistic is calculated by:

$$t = \frac{\bar{d}}{s_{\bar{d}}} \ ,$$

where $\bar{d}$ is the sample mean difference, and $s_{\bar{d}}$ is the sample standard error of the difference. The degrees of freedom v, is equal to $n - 1$ (Zar, 1984).

Mortality rate comparison

The instantaneous rate of total mortality (Z) was estimated for both spear and hook and line samples for each of the reefs sampled using age-based catch curves (Pauly, 1984). Catch curves were plotted as the natural log (ln) of the frequency for each age class. Catch curves were plotted up to and including age classes that were represented by at least one sample. Age classes were included until there were at least two age classes in a row that did not contain samples.

From examination of line caught age frequency plots a strong mode at 4 years of age was evident on nearly all sixteen reefs. The age of full recruitment to the line fishing gear was therefore assumed to occur at 4 years of age and, accordingly, catch curves were fitted starting at this age class. As was demonstrated in the previous chapter, spear fishing gear was able to sample coral trout in the 1 to 3 year old classes much more effectively. As the 1-year age class was a common mode amongst the spear age samples, this age was treated as the age of full recruitment to the spear fishing gear. However, almost all of the age frequency plots for the spear samples were bi-modal, predominantly in the 1-year and 4-year age classes. This suggests variable levels of recruitment which would violate the key assumption of fitting catch curves (Pauly, 1984). In order to assess the possible impact on the analysis of the data of a recruitment pulse at the 4-year age class, I re-fitted catch curves to the spear data with the 4-year age class omitted, and to the line data beginning at the 5-year age class. These data were then analysed separately to the samples with 4-year olds included to compare the results. To minimise the use of spurious estimates of Z in the analysis, the criterion used for inclusion was that a minimum of 4 age classes were required in the fitted catch curves.

For consistency the mortality data were compared between spear and hook and line gear in a similar fashion to the growth parameters. That is, I examined the difference (*d*) in the estimates of mortality derived from the data from the two sampling gears. Therefore, the test variable was the difference in Z estimates obtained using the spear and line data ($Z_s - Z_l = Z_d$). Again, to test for the effects of region or management zone on Z_d, and therefore method, I used a 3-way ANOVA with the factors Region, Zone and Reef nested within Region*Zone, and Z_d as the dependent variable. Region and Zone were fixed orthogonal factors, and reef was a random factor that provided the error variance for tests of Region, Zone and Region*Zone.

Yield-per-recruit analyses

Yield-per-recruit (YPR) curves were first developed in the 1950's by Beverton and Holt (1957) and are useful in predicting future yields at different levels of fishing effort (F). They are therefore useful in assessing different management strategies such as increasing or decreasing the number of fishing licences, or changing the minimum legal size. It is important to note that YPR curves used on their own have severe limitations. For example, they don't take into account recruitment or stock size so predictions of harvested biomass or economic value of the catch are not possible (Hilborn and Walters, 1992; Sparre, 1992). I use YPR curves here simply to demonstrate possible implications of gear selectivity for projected yield at different levels of F.

YPR curves were calculated using data from both the spear and line samples to demonstrate possible implications of gear selectivity for projected yield at different levels of F. Estimates of natural mortality (M) were derived from estimates of Z from the MNP-B zones under the assumption that F = 0 in these zones. YPR curves were calculated using models derived by Gabriel *et al* (1989). These models used the growth parameters derived from the VBGF model to calculate mean length-at-age (l_t). Lengths were converted to mean weight-at-age using the equation of Ferreira and Russ (1994):

$$TW = 0.0079 \times FL^{3.157}$$

where TW is Total Weight (g) and FL is Fork Length (cm). YPR in weight (g) is then calculated by the equation:

$$YPR = \sum N_t . W_t . \frac{F}{F+M}(1 - e^{-F-M})$$

where, N_t = the proportion alive at age t; W_t = weight (g) at age t; F = instantaneous rate of fishing mortality; and M = instantaneous rate of natural mortality. The length-at-first-capture (l_c) was set at 36cm FL, which approximates the legal minimum length of capture of *P. leopardus* (38cm TL) on the GBR (Mapstone and Davies, unpublished data). YPR was calculated for all ages t such that $l_t \geq l_c$, over a range of F from 0 – 3.0.

Results

Growth parameters

Constraining t_o affected the mean growth parameter estimates from both the spear and line samples. The change in the estimate from the overall line sample however was far more pronounced than for the speared sample. By fitting the raw spear data, the overall mean estimates for L_∞ and K were 562.42 and 0.24 respectively, and after forcing the curves through the selected y-intercept the estimates became L_∞ = 454.71 and K = 0.50. For the line data however, overall mean estimates derived from the raw data were L_∞ = 1685.42 and K = 0.13, but became L_∞ = 501.58 and K = 0.40 when t_o was constrained to 1.62mm. The obvious trends in the VBGF parameters were that L_∞ was consistently lower in the speared samples and K was consistently lower in the line samples (Table 5.1). Only one reef out of sixteen, Knife Reef, did not follow this pattern. This exception may have arisen because the line caught sample from Knife Reef contained only one fish older than 5 years, and the total sample size was unusually small.

The mean size of fish taken by line fishing in each age class was larger than that of speared fish at the very young ages, with the difference decreasing with age. For example, the overall mean sizes at age for 1-3 year olds respectively were 206.8, 283.95, 335.31mm (spear), and 309.33, 322.97, 352.60mm (line). These data indicate that for each of these age classes, line fishing tended to take the larger, and therefore faster growing, individuals (see Figure 5.1).

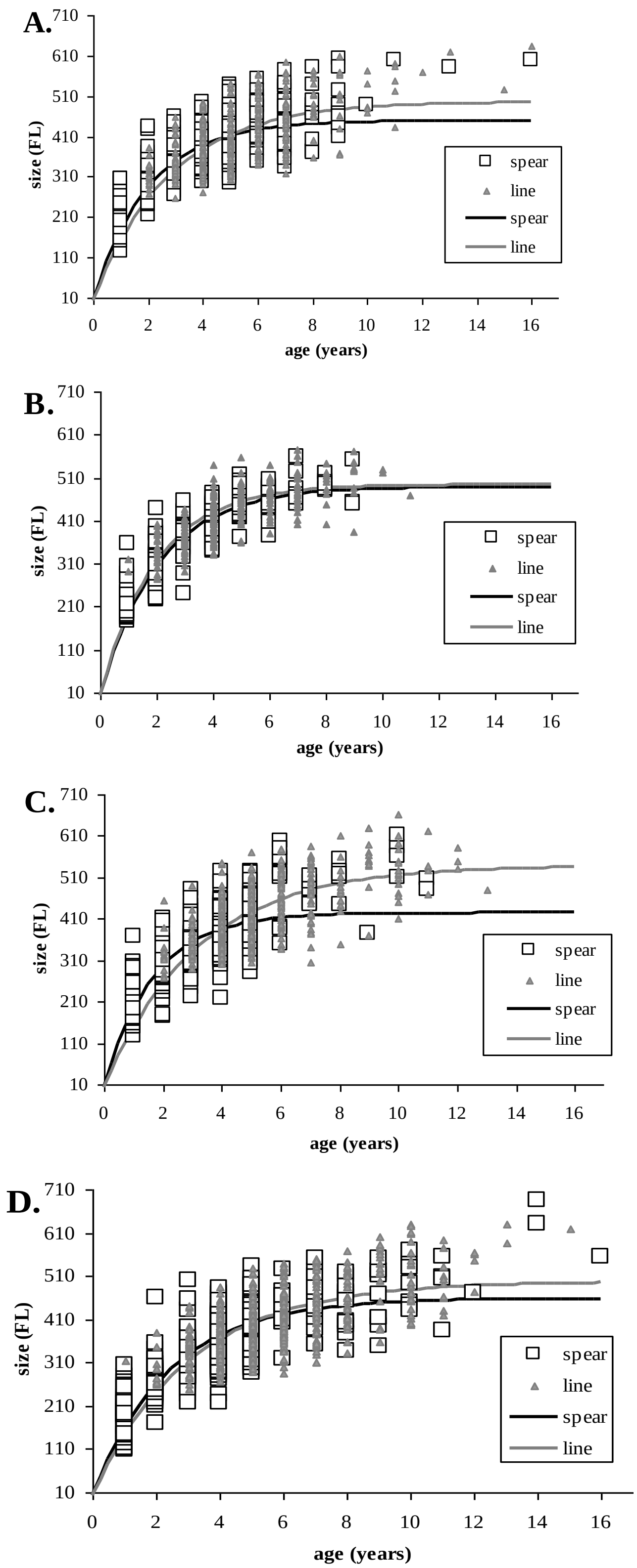


Figure 5.1**:** von Bertalanffy growth curves fitted to size and age data for *P. leopardus* collected by spear and line for each of the regions a. LI, b. TVL, c. MCK, and d. SC. The TVL region showed lower variability in size at age than the other regions.

Reef	L_∞		K	
	Spear	**Line**	**Spear**	**Line**
14-133	433.474	507.812	0.546	0.345
Rocky B	449.654	468.926	0.539	0.480
Eyrie	489.964	654.436	0.379	0.177
Rocky A	456.985	488.127	0.428	0.337
Lizard Island (pooled)	448.839	495.566	0.497	0.357
Fork	473.461	517.642	0.524	0.452
Knife	501.766	436.889	0.429	0.796
Faraday	503.161	517.603	0.418	0.410
Yankee	475.719	478.189	0.550	0.548
Townsville (pooled)	487.995	493.553	0.482	0.502
Boulton	361.817	462.685	0.807	0.403
Liff	385.174	450.690	0.757	0.415
20-136	431.639	554.573	0.525	0.304
Bax	481.066	542.500	0.512	0.344
Mackay (pooled)	424.032	538.018	0.592	0.313
21-124	425.269	428.466	0.431	0.385
21-139	489.226	518.408	0.356	0.305
21-130	466.603	478.121	0.449	0.393
21-133	450.319	520.189	0.428	0.313
Storm Cay (pooled)	458.404	496.884	0.412	0.327
OVERALL (pooled)	446.966	498.953	0.497	0.362

***Table 5.1*:** Estimates of VBGF parameters (L_∞ and K) derived from the spear and hook and line samples for each reef, and pooled for each region and method (t_o constrained).

Comparison of growth parameters

The L_∞ and K data conformed to both the assumption of normality and homogeneity of variance so the raw difference (*d*) values were used in the analysis. For L_∞, ANOVA results indicated that neither region nor zone affected *d.* (Table 5.2).

Source	**SS**	**DF**	**MS**	**F-ratio**	**p**
Region	19757.392	3	6585.797	2.511	0.132
Zone	2667.464	1	2667.464	1.017	0.343
Region*Zone	968.389	3	322.796	0.123	0.944
Reef(Region*Zone) (error)	20980.040	8	2622.505		

***Table 5.2*:** Three-way ANOVA to test the effect of region and zone on the difference data of L_∞ taken from the spear and hook and line samples.

A paired t-test on the overall mean difference found that L_∞ estimates derived from the pooled spear and line samples were significantly different ($t_{0.05\ (2),\ 15} = 2.131$, $p = 0.002$), with the line estimate of L_∞ significantly greater than the speared estimate. This is best demonstrated by examination of the fit of the VBGF's to the pooled data for each of the spear and line samples (Figure 5.2). There was no effect of zone on *d* for the K parameter estimates, but there was a significant regional effect (Table 5.3).

Source	**SS**	**DF**	**MS**	**F-ratio**	**p**
Region	0.26200	3	0.08742	5.942	**0.020**
Zone	0.00019	1	0.00019	0.013	0.913
Region*Zone	0.05657	3	0.01886	1.282	0.345
Reef(Region*Zone) (error)	0.11800	8	0.01471		

***Table 5.3*:** Three-way ANOVA to test the effect of region and zone on the difference data of K taken from the spear and hook and line samples. Significant p values are in bold.

To further examine the significant regional effect on K, a paired t-test on the difference data was carried out for each region. Estimates of K derived from the spear and line samples were significantly different in the Lizard Island ($t_{0.05\ (2),\ 3} = 3.182$, $p = 0.034$), Mackay ($t_{0.05\ (2),\ 3} = 3.182$, $p = 0.014$), and Storm Cay ($t_{0.05\ (2),\ 3} = 3.182$, $p = 0.025$) regions (Figure 5.3). In each region the spear estimate of K was significantly greater than the line estimate. In the Townsville region there was no difference in estimates of K between the two gears ($t_{0.05\ (2),\ 3} = 3.182$, $p = 0.527$). The von Bertalanffy growth curves for each region are shown in Figure 5.1.

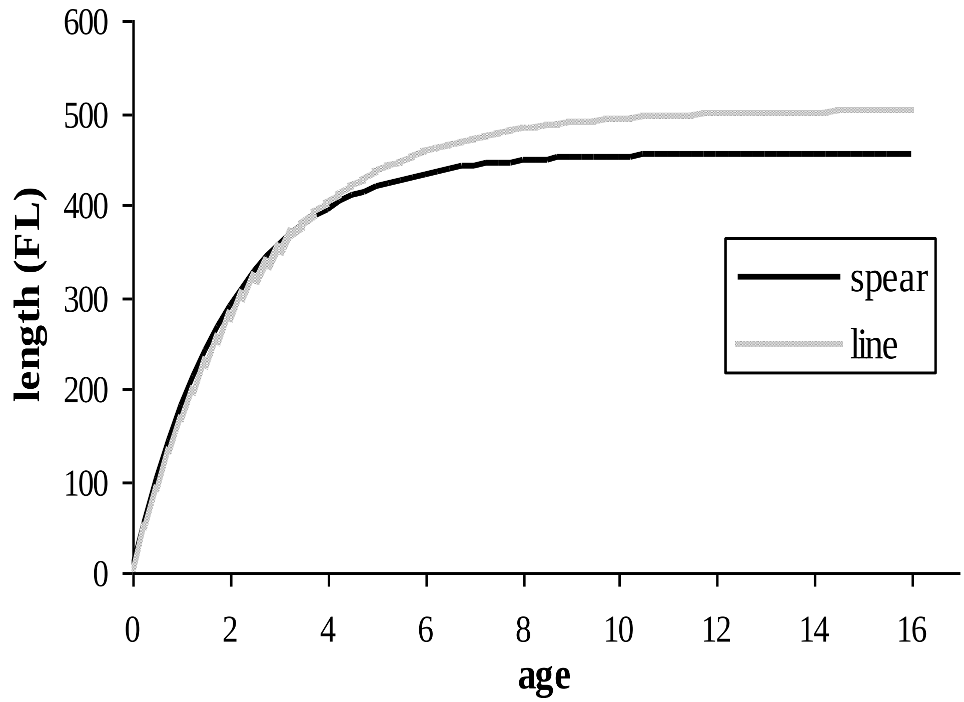


***Figure 5.2*:** von Bertalanffy growth curves fitted to the pooled spear and line data demonstrating the higher estimate of L∞ from the line sample.

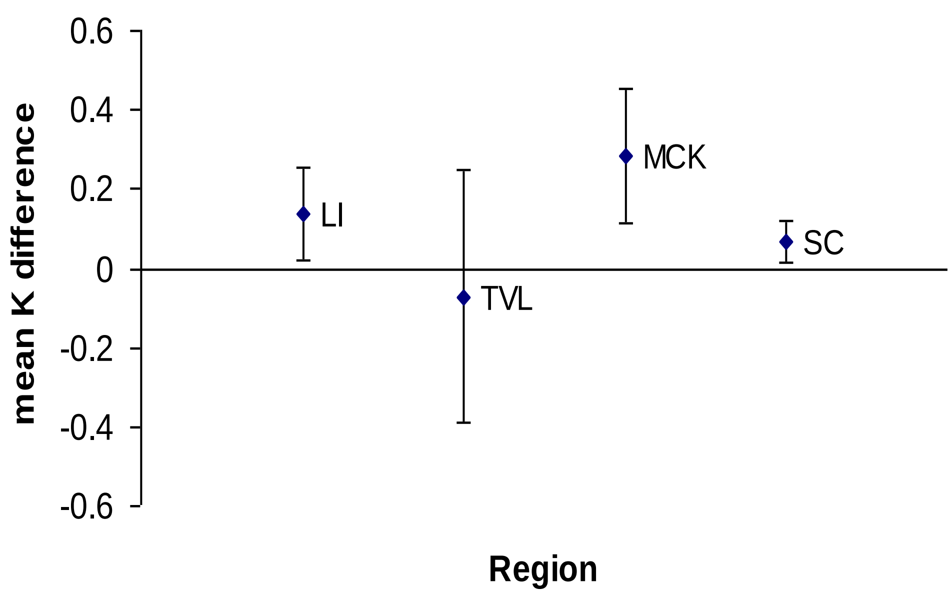


***Figure 5.3*:** Mean difference in K estimates between sampling gears among regions. This shows that the difference in estimates of K between samples was not consistent among different regions. Error bars represent 95% confidence intervals.

Comparison of mortality rates

After fitting catch curves to both the spear and hook and line data it was found that some reefs from both the Townsville and Mackay regions contained less than four age classes. Both these regions were subsequently omitted from the analyses. Unfortunately, this restricted comparisons of mortality rates between spear and line to the Lizard Island and Storm Cay regions only (Table 5.4).

Region	**Reef**	**Zone**	**SPEAR**	**LINE**
			Z (se)	**Z (se)**
LI	14-133	GU-B	0.386 (0.04)	0.513 (0.09)
LI	Rocky-B	GU-B	0.440 (0.14)	0.718 (0.13)
LI	Eyrie	MNP-B	0.256 (0.07)	0.398 (0.06)
LI	Rocky-A	MNP-B	0.278 (0.08)	0.526 (0.08)
SC	21-124	GU-B	0.319 (0.07)	0.570 (0.10)
SC	21-139	GU-B	0.357 (0.07)	0.393 (0.05)
SC	21-130	MNP-B	0.333 (0.05)	0.467 (0.05)
SC	21-133	MNP-B	0.336 (0.05)	0.366 (0.04)

***Table 5.4*:** Estimates of total mortality (Z) with standard error (SE) for the reefs from the Lizard Island (LI) and Storm Cay (SC) regions. These reefs were used in the ANOVA.

There was no difference in the results of ANOVA between the data set that included the 4-year age class and the data set with the 4-year class omitted. Both ANOVA results indicated that neither region nor zone affected *d*. (4-year age class included: Table 5.5; 4-year age class omitted: Table 5.6).

Source	**SS**	**DF**	**MS**	**F-ratio**	**p**
Region	0.0149	1	0.0149	1.313	0.316
Zone	0.0023	1	0.0023	0.207	0.673
Region*Zone	0.0014	1	0.0014	0.126	0.740
Reef(Region*Zone) (error)	0.0453	4	0.0113		

***Table 5.5*:** Three-way ANOVA to test the effect of region and zone on the difference data of Z derived from the spear and hook and line samples. Here the 4-year age class was included in the estimation of Z. The Townsville and Mackay regions were omitted from the ANOVA due to insufficient age classes for Z estimation.

Source	SS	DF	MS	F-ratio	p
Region	0.0152	1	0.0152	0.863	0.406
Zone	0.0006	1	0.0006	0.036	0.859
Region*Zone	0.0064	1	0.0064	0.365	0.578
Reef(Region*Zone) (error)	0.0706	4	0.0177		

***Table 5.6*:** Three-way ANOVA to test the effect of region and zone on the difference data of Z derived from the spear and hook and line samples. Here the 4-year age class was omitted in the estimation of Z. The Townsville and Mackay regions were omitted from the ANOVA due to insufficient age classes for Z estimation.

Similar results for the ANOVA tests indicated that if the 4-year age class did in fact represent a strong recruitment pulse, it was a) not sufficient enough to affect the estimates of Z from the spear and line samples, or b) affected both the spear and line samples equally. Therefore the analysis of the data which included the 4-year class formed the basis of discussions of the data hereafter.

The ANOVA results indicated that the effect of method on estimates of Z was consistent among regions and management zones. A paired t-test on the overall mean difference found that Z estimates derived from the pooled spear (0.338 ± 0.021) and line (0.494 ± 0.041) samples from Lizard Island and Storm Cay were significantly different ($t_{0.05\ (2),\ 7} = 2.365$, $p = 0.002$). The line estimate of Z was significantly greater than the speared estimate.

Yield-per-recruit analyses

Estimates of Z were re-calculated by pooling data to zones within regions. This enabled estimates of M (MNP-B zone Z estimates) to be derived for use in the YPR calculations. It also enabled estimates of Z to be made for all regions as pooling reefs provided adequate age ranges (≥ 4 age classes) when fitting catch curves. Estimates of F for each region could also be calculated as the difference in Z between zones ($Z_{GU\text{-}B} - Z_{MNP\text{-}B}$) (Table 5.7).

Region/Zone	SPEAR			LINE		
	Z (se)	**n**	**Age range**	**Z (se)**	**n**	**Age range**
LI GU-B	0.47 (0.06)	291	1-9	0.62 (0.08)	221	4-12
LI MNP-B	0.36 (0.06)	248	1-13	0.50 (0.05)	227	4-13
TVL GU-B	0.49 (0.15)	158	1-8	0.67 (0.14)	63	4-9
TVL MNP-B	0.23 (0.06)	98	1-11	0.52 (0.07)	136	4-11
MCK GU-B	0.68 (0.19)	272	1-7	0.77 (0.07)	261	4-10
MCK MNP-B	0.41 (0.07)	267	1-11	0.53 (0.04)	456	4-13
SC GU-B	0.36 (0.08)	297	1-11	0.48 (0.05)	276	4-15
SC MNP-B	0.36 (0.04)	309	1-14	0.50 (0.05)	434	4-13

Table 5.7: Spear and line estimates of total mortality rates (Z) with standard error (SE), sample size (n), and the range of ages that curves were fitted, for management zones within each region.

For the YPR calculations, the Townsville and Mackay data were used as examples. Mackay was chosen because growth differences between methods were greatest in this region, and Townsville was chosen because the difference in estimates of M between methods was greatest here. The parameters used to calculate the YPR curves for both the Mackay and Townsville regions are summarised in Table 5.8.

Parameter	MACKAY		TOWNSVILLE	
	Spear	**Line**	**Spear**	**Line**
L_∞	424.032	538.018	487.995	493.553
K	0.592	0.313	0.482	0.502
M	0.41	0.53	0.23	0.52

Table 5.8: Spear and line parameter estimates used to calculate the YPR curves for the Mackay and Townsville regions. The estimate of natural mortality (M) is simply the MNP-B estimate of Z from each region.

Curves of YPR over different levels of F for the Mackay spear and line samples are shown in Figure 5.4a. The general shapes of each curve were very similar. The YPR curves for both samples rose sharply and began to asymptote at approximately F = 0.5. Over the range of F used here, both curves did not reach a maximum yield-per-recruit. Also, the relative increase in YPR with increasing F suggested that the amount of fishing effort required to maximise the gain in YPR (optimal F) would be the same regardless of which sample was used (Table 5.9). The only difference in the curves was that, even at low levels of F, the predicted YPR from the spear sample was almost twice that predicted by the line sample (Figure 5.4a).

Change in F	Relative (%) increase in YPR			
	MACKAY		TOWNSVILLE	
	Spear	Line	Spear	Line
0.10 – 0.20	64.50	65.24	31.05	66.01
0.20 – 0.50	61.46	61.52	28.45	62.66
0.50 – 0.75	15.28	14.94	3.65	15.12
0.75 – 1.00	8.11	7.82	0.94	7.84
1.00 – 1.50	8.73	8.39	0.16	8.28
1.50 – 2.00	4.61	4.56	-0.04*	4.42

Table 5.9**:** Relative increases in YPR with increasing F for both spear and line samples from the Mackay and Townsville regions. (* Maximum YPR was reached at F = 1.3).

In the Townsville region the YPR curves of each method differed more noticeably (Figure 5.4b). The line YPR curve was similar to that of Mackay with the relative gain in YPR suggesting that the optimal fishing effort could be as high as F = 1.5, depending on management objectives. The YPR curve from the spear sample reached a maximum at F = 1.3. However, the shape of the curve suggested that the optimal value of F was 0.5 as further gains in YPR were minimal above this value (Figure 5.4b; Table 5.9). Further, predicted YPR using the spear sample was between approximately 2.5 – 5 times that of the line sample (Figure 5.4b).

The general shapes of the curves are influenced more by the estimates of natural mortality than by the growth parameter estimates K and L_∞. Despite the higher estimate of L_∞ from the line sample in both regions, and therefore the greater yield potential, the higher estimate of natural mortality from the line sample means that much of this growth is not realised before death by natural causes occurs. This is more obvious in the Townsville region where the difference in natural mortality estimates between samples is greater.

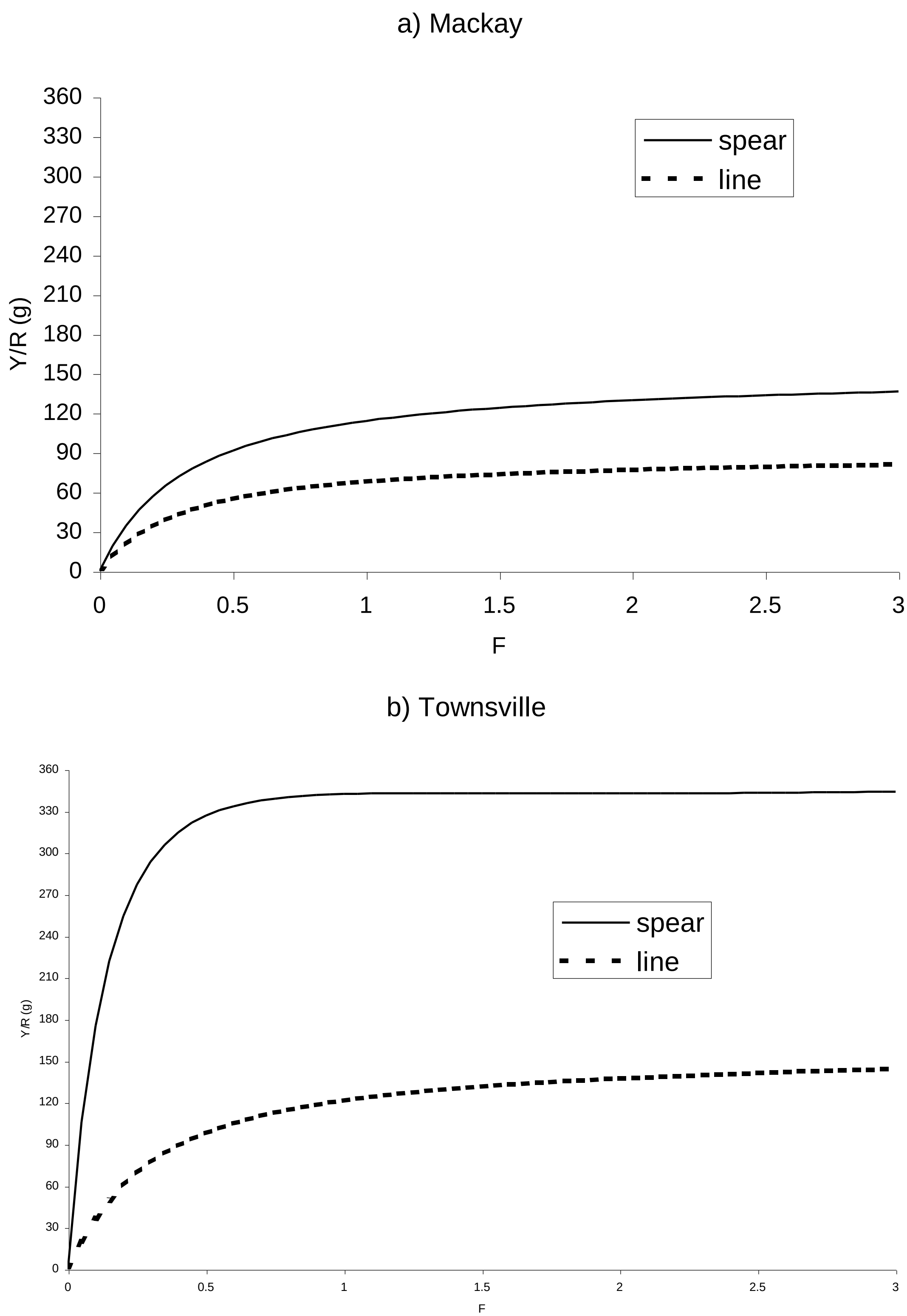


Figure 5.5: Yield-per-recruit (YPR) curves for A) the Mackay region, and B) the Townsville region. Curves from the spear data are indicated by the solid lines and the line curves are represented by dotted lines.

Discussion

Growth parameters

The difference in estimates of K and L_∞ between the spear and line caught samples were consistent, with spear K greater than line and spear L_∞ smaller than line. Results of analyses indicated that the magnitude of the difference in L_∞ between samples was similar across all management zones and regions. Since the parameters K and L_∞ are highly correlated (Misra, 1980; Moreau, 1987; Cerrato, 1990), a similar result would have been expected in the analysis of the difference in K between samples. This was not the case as a regional effect was detected. As was noted earlier, there is no robust method for the comparison of multiple non-linear curves in a hierarchical fashion with multiple factors and levels. Given the number of tests involved for individual pairwise comparisons the chance of Type I error would be high (Zar, 1984). The ANOVA method used here provides one approach to this problem. However, by averaging estimates over different levels, such as zones and regions, rather than pooling data and re-fitting curves, information on best fit is potentially lost. This may have occurred here as the regional L_∞ difference data from the averaged parameter estimates used in the ANOVA differed markedly from the re-fitted parameter estimates derived from the pooled data. Furthermore, it is likely that the averaged estimates were unduly influenced by the growth parameter estimates from Knife reef (see Table 1), perhaps causing the regional effect detected.

The magnitude of the difference in L_∞ between gears was significant, as was the difference in K in the LI, MCK and SC regions. The difference in K was not significant in the TVL region however. Examination of the size-at-age data for this region showed that, unlike the other three regions, no very large fish (>600mm) were captured and no fish older than 11 years were captured by either gear. Furthermore, the size range at each age class was uniformly narrow relative to other regions. I can only speculate about possible explanations for the size-at-age range patterns observed in the TVL region. Descriptions of habitat differences between regions were discussed previously (Chapter 3). It is possible that the TVL region provides a less productive and more constant environment resulting in less variability in growth than in other regions. The reefs sampled in this region are much closer to the edge of the continental shelf than other regions sampled in this study. Productivity levels are very low in offshore environments and differences in cross-shelf fish population dynamics have been documented for the GBR previously (Williams, 1991; Hart and Russ, 1996; Newman and Williams, 1996; Mapstone *et al*, 1998b).

The main difference in the samples taken by each gear was in the younger age classes. One-year old fish were well represented in the spear samples but were absent in the vast majority of line caught samples. Also, the mean size of fish taken by line fishing in each age class was much larger at the very young ages, with the difference decreasing with age. It is widely acknowledged that selective sampling gears that under-sample younger fish, or that take the faster growing fish in a given age class, will result in growth parameters that are biased (Knight, 1968; Ricker, 1969; Miranda *et al*, 1987; Mulligan and Leaman, 1992; Goodyear, 1995; Horn, 1997). Knight (1968) argued that using data lacking in older fish to fit a VBGF, results in L_∞ estimates that are too high. A similar result will occur when data are lacking in younger fish or when faster growing individuals are selectively captured (Miranda *et al*, 1987; Mulligan and Leaman, 1992). Craig *et al* (1997) found that estimates of K and L_∞ were highly dependent on the range of ages used to fit growth models. The very young age classes (1 – 3 years) in particular, had the most influence on parameter estimates. This is not surprising as it represents the years where most growth occurs in coral reef fish (Ferreira and Russ, 1994; Newman *et al*, 1996a; Craig *et al*, 1997). In this study older, larger fish were in slightly higher numbers in the line caught sample (see Chapter 4), however, the upper limit of size and age ranges of data to which curves were fitted were similar for each gear. The resulting overall effect was that von Bertalanffy growth curves fitted to spear data generally showed more curvature due largely to the presence of 1-year-olds but also due to smaller mean sizes in younger ages (1–3 years).

The practice of constraining the y-intercept when fitting a VBGF is fairly uncommon in the literature. Given that many data sets lack smaller, younger fish this often results in growth parameters that lack any biological sense. Newman *et al* (1996b) found that the fit of the VBGF to length-at-age data for *Lutjanus adetti* was greatly improved by constraining the y-intercept to a length-at-birth estimate for the species. By constraining the y-intercept in this study, the influence of 1-year old fish in particular on the curves from each sample was greatly reduced. Despite this, however, significant differences in parameter estimates were still observed between the spear and line samples.

Mortality comparison

In fitting age-based catch curves it is assumed that the samples are representative of the populations from which they came (Hilborn and Walters, 1992). It is also assumed that mortality is constant among age classes and therefore the age range shouldn't affect estimates of Z. In this study the only difference between methods when fitting the catch curves was the range of ages over which curves were fitted. However, estimates of total mortality (Z) for the line caught samples were higher than the spear caught samples and the difference in Z between the methods was consistent across both regions analysed and management zones within those regions. One possible explanation for the difference is that 1-year old fish are not fully recruited to the spear gear. It is more likely that the difference in Z between gears is because the gears exhibit different age/size-specific selectivity. Although the analysis only included the Lizard Island and Storm Cay regions, reefs from the Townsville and Mackay regions with sufficient age classes to fit catch curves showed a similar pattern to those analysed.

Another assumption in fitting catch curves is that of constant recruitment. This assumption also is rarely satisfied (Hilborn and Walters, 1992), resulting in unreliable estimates of Z from single sample catch curves (Horn, 1997). There is some evidence to suggest that the 4-year class in this study may represent an unusually high recruitment year (see Chapter 4). Wankowski *et al* (1988) reported very high estimates of Z for jackass morwong due to the presence of a strong year class. In this study, if the 4-year age class did represent a strong year class, it didn't influence the comparison of the estimates of Z between the spear and line samples. One way to avoid the assumption of constant recruitment levels is to fit catch curves to a cohort over several years. This is logistically a large exercise as it would require sampling over many years to obtain the data necessary for realistic parameter estimates. Russ *et al* (1998) fitted catch curves to a cohort of *P. leopardus* sampled on the GBR by line fishing, and estimated mortality on MNP-B reefs as 0.147. Although this cohort was followed over four years it was from age 6 – 9 years so did not take into account rates of mortality for younger ages. Further sampling by spear in other years would provide information to more accurately estimate age-specific mortality by such a method, especially because spear fishing is able to sample the younger age classes.

From other studies for *P. leopardus* on the GBR the majority of estimates of total mortality using static age structures, range from 0.12 – 0.31 on MNP-B reefs and 0.12 – 0.42 on GU-B reefs (see Russ *et al*, 1998 for a review). They are all appreciably lower than estimates derived from both gears in this study (MNP-B: 0.23 – 0.53, GU-B: 0.36 – 0.77).

Yield-per-recruit analyses

Although rates of growth (K) are important in YPR analyses (Hilborn and Walters, 1992), in the examples provided to assess differences in gears, it was the rates of natural mortality that influenced the shapes of the curves the most. With higher levels of natural mortality there is the incentive to fish a stock before they die of natural causes, to maximise the YPR from the population (Hilborn and Walters, 1992). This scenario was reflected in both curves from the Mackay region and the line example from the Townsville region. In these examples, the losses due to natural mortality quickly exceeded the gains in biomass from growth. Predicted optimal values of F were all relatively high in these examples in order to catch the fish before they died due to natural causes. The difference in estimates of natural mortality between the two gears in the Mackay region was not great enough for us to see differences in the shape of the curves. However, at the lower level of natural mortality, as estimated by the spear data from the Townsville region, the predicted optimal level of fishing effort was much lower than the line estimate. Use of the line data in this case could lead management to recommend levels of fishing effort that are 3x greater than those estimated by the spear data to maximise YPR. This type of decision could very quickly lead to growth overfishing of the stock.

In both the Mackay and Townsville YPR curves, the spear data predicted estimates of YPR that were at least 2x that of the line data. On it's own this information doesn't tell us very much. However, used in conjunction with recruitment data and the use of forecasting techniques that can predict good, average or poor fishing years (see Coleman *et al*, 19??; Russ *et al*, 1996), the difference in levels of YPR becomes important. This information can give estimates of predicted yield (biomass) and may therefore influence predicted optimal fishing effort. For example, if using a system that limits fishing days (effort) the effort allowed per boat/licence would be related to the predicted total yield.

The use of high estimates of natural mortality resulted in relatively low yields and very high levels of fishing to maximise this yield, regardless of the growth characteristics of the population. Setting high levels of F under such circumstances could ultimately lead to the collapse of the stock, depending on other factors such as management controls (eg. minimum size limits). Further, although lower rates of natural mortality will give relatively much higher yields over a range of F, the level of yield will depend on the growth parameters used (Hilborn and Walters, 1992). Since it is assumed that the spear samples are more representative of *P. leopardus* populations, line caught samples are likely to result in the prediction of inflated levels of F to optimise YPR. Line data would also under-estimate YPR and if used to predict yield or stock productivity it could cost jobs and livelihoods by under-valuing the fishery. The positive from a biological viewpoint is that line samples will give conservative estimates of YPR.

Conclusions

Line fishing under-samples smaller, younger *P. leopardus*, which represents the ages of fastest growth. Consequently, this study demonstrates that by using line caught samples, estimates of growth parameters are likely to be biased, even if growth curves are constrained through a realistic y-intercept. In comparison to spear fishing, line fishing samples give higher estimates of L_∞ and lower estimates K and would appear to do so consistently in all regions and management zones of the GBR. Line fishing also consistently gives estimates of total mortality that are greater than those estimated by spear fishing. Again the driving influence of this appears to be the younger age classes lacking in the line samples. Although the differences in parameter estimates between the two sampling gears are found consistently in the regions and management zones analysed, their significance to management will be manifest in stock assessments. Two YPR examples were given using data from two of the regions sampled in this study. To maximise YPR from the line data one would predict levels of fishing effort up to 3x greater than that predicted by spear fishing. In addition the line data predicts YPR levels that are up to 80% lower than the spear data. This suggests that with the use of line data to predict optimal levels of fishing, the stock may be fished at unsustainable levels. From the YPR examples used here, it can be seen that line fishing selectivity can lead, ultimately, to assessments of stocks that are biased since line fishing is recognised as being a selective fishing gear (Ralston, 1990). Importantly, this knowledge will make the task of inferring the bias in line caught samples a much simpler and more reliable task in future work. Using the gear comparisons made in this study, the magnitude of the resulting bias in parameter estimates can be better accounted for in future samples taken by hook and line gear, particularly for the GBR line fishery.

Chapter 6. Summary and Conclusions

No study of *P. leopardus* has been able to sample the size and age range attained here using the one sampling method. This vindicated the choice of spear fishing as the best method against which to compare line fishing, assuming that spear fishing sampled *P. leopardus* populations more representatively than other methods. The pilot study for this actually suggested that spear fishing under-samples fish less than 200mm, though, by how much is questionable given the sample size of the pilot study (Welch, 1998). As a sampling gear, spear fishing could be useful for certain coral reef fish species to obtain more accurate estimates of growth and mortality. Although the development of a selectivity curve for spear fishing gear would improve the known selection characteristics of hook and line gear, a comprehensive comparison of the size selectivity of different hook sizes using line fishing would also be a very effective way to more fully understand line fishing biases.

The magnitude in the difference in relative numbers taken by spear and line in fish less than 310mm in particular, emphasises the inability of line fishing to adequately sample smaller, younger fish. Despite large variability in the size-at-age estimates for *P. leopardus* (Ferreira and Russ, 1994), a similar result was also reflected in the age samples. Line fishing under-sampled 1-3 year old fish, particularly 1-year-olds. Furthermore, the greater sampling capability of spear fishing demonstrated some possible indirect effects of fishing that were not observed in the line caught samples: in GU-B (fished) zones, more small, young fish were captured than in the MNP-B (un-fished) zones. Spear fishing slightly under-sampled larger, older fish relative to line fishing however, and line fishing samples are likely to be more representative of populations of *P. leopardus* in ages greater than 5 years. However, as a consequence of severely under-sampling the smaller, younger fish, line fishing over-estimated mean size and mean age.

By excluding younger ages when fitting VBGF's, estimates of K are likely to be under-estimated, while estimates of L_∞ are likely to be over-estimated (Mulligan and Leaman, 1992; Ferreira and Russ, 1994). Not surprisingly then in this study, von Bertalanffy growth curves fitted to the line fishing data consistently showed this pattern, even after constraining curves through an estimated size-at-hatching for *P.leopardus*. Line fishing also selectively caught the faster-growing individuals, particularly in the younger age classes, further contributing to biased growth parameter estimates. The overall patterns in the differences in growth parameter estimates from the two methods were evident in all management zones and most regions sampled. In regions such as Townsville in this study, where variability in size-at-age is small relative to the other regions, the selective nature of line fishing may not be as apparent in growth parameter estimates. Although sample sizes from both sampling methods were low in this region, this may simply demonstrate cross-shelf differences in population structure and/or size of the common coral trout on the GBR.

Estimates of total mortality rates were also found to be consistently higher from the line data for the two regions analysed. Despite similar overall patterns of differences in parameter estimates between gears, changes in the magnitude of the difference can influence stock assessments. In the YPR curve examples used, the estimates of natural mortality in particular, influenced the shapes of the curves. It is the shape of the YPR curve that determines the predicted fishing mortality that will maximise yield-per-recruit. By consistently giving higher estimates of Z, line fishing data are likely to predict higher levels of fishing effort. As shown in Chapter 5 this may be as much as 3x the optimal value of F estimated using parameters from spear samples. This result would present the greatest concern to a manager. Increasing fishing effort may increase the catch in the short term, however, the long term effects would be a reduction in catch and a possible fishery collapse due to recruitment failure. On a regional basis the difference in predicted F may vary and may lead to localised depletion of stock through overfishing. The line data was also shown to underestimate the YPR by up to 80%. Optimal fishing effort is deduced by a combination of factors other than biological ones, such as social and economic circumstances (Hilborn and Walters, 1992). This suggests that with the use of line data, under-valuing the fishery could compromise livelihoods. In the GBR hook and line fishery, this would possibly mean reductions in the number of licences, reductions in fishing days, or perhaps even closing more areas of the GBR to fishing. From a biological perspective however, estimates of YPR from line data are likely to be conservative.

The major differences in size and age samples between methods were to be expected. An important observation in this study was that those differences were consistent in all regions and management zones that were sampled on the GBR. This knowledge will greatly improve the interpretation of line caught samples of *P. leopardus,* anywhere on the GBR. Growth and mortality parameter estimates are key requirements of many stock assessment models and as such, it is vital that they be as accurate as possible, as the examples provided demonstrates. Using the gear comparisons made in this study, the magnitude of the bias in parameter estimates can be better accounted for in future samples taken by hook and line gear, particularly for the GBR line fishery. As this method is by far the most practical and cost-effective method for collecting samples from the GBR line fishery, the results here will be particularly relevant to the development of models to evaluate different management strategies.

To date, selectivity of hook and line gear has been poorly understood (Ralston, 1982; Ralston, 1990). This study represents the first comparison using the two sampling gears, spear and line. It also represents the only example known to the author of gear comparisons over large spatial scales. This study however, was based on the use of only one hook size. It is possible that changes in hook size would alter the nature of the bias. This would need to be quantified experimentally using different hook sizes and large sample sizes would need to be collected per age class (Punt *et al,* 1996). Such a study would further improve our understanding of hook and line gear as a fish sampling method.

It is highly unlikely that samples from fish populations will be unbiased (Miranda *et al* 1987; Hovgard and Riget 1992; Pope *et al,* 1975). The results presented in the preceding chapters demonstrate this for line fishing. The attention of fisheries researchers must therefore focus on how gear selectivity affects the samples collected from fish populations. By better understanding the selective nature of fishing gears the biases can then be accounted for in how we use such samples, eg. population parameter estimation. The significant benefit would be derived from improved performance of fisheries models used for management. Such research has evolved only slowly, particularly for hook and line gear. In this study a better understanding of the bias of line fishing on the GBR is provided. This will help ensure that stock assessment models are more reliable, enhancing the notion of sustainable fishing for the GBR line fishery.

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