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**Establishing a weight-length baseline for evaluating changes in  
yellowfin tuna (*Thunnus albacores*) body condition in the Western**

**Indian Ocean**

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## Abstract

Standard weight ( $W_s$ ) equations were established for yellowfin tuna (*Thunnus albacares*) in the Western Indian Ocean and used as a baseline for calculating relative weight ( $W_r$ ) indices. Length-weight data for yellowfin tuna were obtained from the Indian Ocean Tuna Commission (IOTC) for 1984 to 1991 and 2003 to 2013. Four quadratic standard weight equations were established (based on mean, median, first and third quartile statistics for each length class) using  $\log_{10}$ -transformed weight ( $W$ , in grams) and fork length (FL, in mm) data. The median  $W_s$  equation ( $\log_{10}(W) = -3.903 + 2.425(FL) + 0.103(FL)^2$ ) was the preferred baseline for the  $W_r$  analysis. Relative weight estimates for individual fish ranged from 92 to 110. Annual and monthly  $W_r$  estimates ranged from 99 to 101 and 99.9 to 100.5 respectively. A GLM was fitted to separate the effects of year, month and sex on the response variable  $W_r$ . Year, month, sex and the interaction terms Year:Sex and Month:Sex all contributed significantly to the variability in  $W_r$  explained. Correlations between environmental variability and yellowfin tuna condition were observed. Concentrations of suitable prey in 2003 and 2004 correlated to above average condition, although 2005 and 2006 were below average condition during similar prey availability and environmental conditions. Relative weight followed an increasing trend from 2008 to 2013 despite lower biological enrichment. Mechanisms such as a shallower thermocline and reduced fishing pressure are proposed explanations. This study provided a reference study for body condition studies of yellowfin tuna in the Indian Ocean. It also provided support for the application of the  $W_r$  index to other tuna species in the Indian Ocean managed by the IOTC.

## Introduction

Interactions between the El Niño Southern Oscillation, Asian monsoon and Indian Ocean Dipole (IOD) drive climatic variability in the Indian Ocean (Saji and Yamagata, 2003; Abram et al., 2008; Schott et al., 2009). Recent intensification of Indian Ocean climatic variability has been observed (Abram et al., 2008) with research predicting Indian Ocean climate variability considered to be in the early stages of development (Schott et al., 2009). The Indian Ocean Dipole (IOD) is the dominant climate pattern in the Indian Ocean (Behera and Yamagata, 2003; Meyers et al., 2007) and affects environmental conditions in both the eastern and western Indian Ocean. The Dipole Mode Index (DMI; Saji et al., 1999; Saji and Yamagata, 2003) is the global climate index that describes the IOD. Positive DMI

corresponds to a “warm” event and a positive IOD phase. During the positive IOD phase, sea surface temperature (SST) is anomalously cool in the east and warm in the western Indian Ocean (Vinayachandran et al., 2002). This anomalous SST drives changes in the mixed layer depth (MLD) (Feng and Meyers, 2003; Rao and Behera, 2005; Alory et al., 2007) and affects the habitat and abundance of commercially important species such as tuna (Marsac and Le Blanc, 1998; Marsac, 2001).

Anthropogenic pressures on marine resources act cumulatively with environmental variability in presenting challenges for the sustainable management of marine ecosystems (Halpern et al., 2008; Cheung et al., 2009; Doney et al., 2012). Commercial pelagic fisheries often target top predatory fish such as tuna and swordfish, with consequences through trophic cascading effects and food web alterations (Essington et al., 2002; Corbineau et al., 2008).

Environmental and climate variability exert bottom-up effects that can alter population and spatial dynamics of top predators, especially those that are dependent on food availability (Frank et al., 2006). Understanding the close links between pelagic fish population variability, fisheries activities and climate variability (Stenseth et al., 2004; Lehodey et al., 2006) are fundamental for management decisions.

As pointed out by Corbineau et al. (2008), noisy biological time series often integrate a mix of data on exploitation (targeting, strategy, fishing power), biological mechanisms (recruitment, growth, mortality, migration) and environmental forcing (local conditions or dominant climate patterns). These factors interact in a complex way and identifying the patterns of variability in fish population response is a fundamental challenge for the management of commercially important pelagic species (Corbineau et al., 2008).

Conventional methods applied to investigate associations between climate variability and population fluctuations involve time series analysis, with the aim of identifying time scale patterns of variability (Menard et al., 2007). These studies do not often identify the underlying mechanisms that link climate forcing and fish production. However physical and biological links can be established, which serve to inform ecosystem dynamics (Menard et al., 2007).

Environmental indicators provide a tool for addressing these challenges and have been used frequently in environmental assessment studies (Jackson et al., 2000; NRC, 2000; EEA, 2001) The application of environmental and ecological indicators in fisheries management

have proved valuable (Ndjaula et al., 2013) in measuring the influence of climate change (EEA, 2001; Niemeijer and de Groot, 2008; Link et al., 2010) assessing habitat health (Costanza and Mageau, 1999) and evaluating stock performance (Caddy, 2004; Cury and Christensen, 2005).

The premise for the effective use of indicators is that baselines be established from which environmental and ecosystem variability can be assessed (Ndjaula et al., 2013). In the context of fisheries management, a frequently used and widespread indicator of stock health is the length-weight relationship calculated from individual fish (Anderson and Neumann, 1996). The length-weight relationship for a particular species is a mathematical description oriented around the prediction of one variable from the other (LeCren, 1951). This mathematical description is usually based on a non-linear power function with weight being predicted from length (Blackwell et al., 2000; Ndjaula et al., 2013). Deviations of individual fish weight from the expected weight, generated by the L-W relationship, are used to indicate the fitness (body condition) of an individual. This is based on the assumption that heavier fish for a particular length, based on the length-weight relationship, are in better condition than average (Bolger and Conolly, 1989; Murphy et al. 1990). Through fish body condition analyses, the ecology and population dynamics of a fish species can be investigated through a quantifiable indicator (Blackwell et al., 2000; Ndjaula et al., 2013).

Blackwell et al. (2000) point out that establishing a L-W relationship may provide a useful tool for understanding the ecology of a species at both a population and community level. Through cautious interpretation, inferences about the state of an ecosystem in which that species occurs can be made (Murphy et al., 1990). In addition, L-W relationships allow for a statistically robust approach to comparing populations (Gerow et al., 2004; 2005) which is of particular interest to heavily exploited, large migratory species such as tuna.

Willis and Hobday (2008) emphasize the urgency and importance of tuna condition measures for management purposes. Similar trends in abundance, growth and condition have been noted in several tuna species, from different oceans (Polacheck et al., 2004; Pauly and Palomares, 2005; Golet et al., 2007) and the relationship between condition, survival and the environment is imperative for management purposes (Sinclair and Valdimarsson, 2003; King and McFarlane, 2006).

Several condition indices have been proposed for fish, such as the relative condition factor [ $K_n$ ], relative weight ( $W_r$ ), weight-length regression and residual analysis (Blackwell et al., 2000 and references therein). However many of these condition indices are length-dependent (assuming isometric growth) and therefore limited in comparative ability (Blackwell et al., 2000). Relative weight ( $W_r$ ) is the observed weight of an individual fish relative to the standard weight ( $W_s$ ) estimated from a length-weight regression equation, expressed as a percentage (Gerow et al., 2005; Ndjaula et al., 2013). This condition index has gained credibility by fisheries biologists (Wege and Anderson, 1978; Murphy et al., 1990; Blackwell et al., 2000; Gerow et al., 2005) and is receiving more support in its ability to inform management decisions for pelagic species (Ndjaula et al., 2013).

The  $W_r$  index can be considered ideal as it incorporates the desirable properties of a condition index laid out by Murphy et al. (1990). The  $W_r$  index is consistent (statistical properties and meaning are similar irrespective of species or length considered), tractable (applicable to standard statistical methods), efficient (reasonably precise estimates capable from a small sample size) and robust (unaffected by variation in data collection or analysis). In addition, the  $W_r$  index has gained credibility because it provides a reference point or benchmark from which condition can be assessed across all length ranges and between species (Blackwell et al., 2000).

Interpretations of relative weights are built on the premise that standard weight ( $W_s$ ) values, estimated from a standard weight equation, should describe the inherent shape of a fish in “average” condition (Ndjaula et al., 2013). In the current study “average” is regarded as the median standard weight value at a given length. The  $W_s$  baseline should be a fixed baseline (consistent over time) and be void of length-related biases which may affect  $W_r$  estimates. Relative weights calculated as below 100 indicate below average condition (below median) and estimates above 100 indicate above average condition (above median).  $W_r$  values close to 100 represent a fish of average median condition relative to the population under study.

Studies into fish body condition have highlighted its usefulness in informing management decisions for commercially exploited species (Marshall et al., 1999; Blackwell et al., 2000; Marshall et al., 2006; Marshall, 2009; Ndjaula et al., 2013). Although fish body condition is biologically and ecologically important to consider, it has often been overlooked in the management and exploitation of marine resources (Blackwell et al., 2000; Gerow et al., 2005;

Ndjaula et al., 2013). This is similarly the case for yellowfin tuna *Thunnus albacores* (hereafter referred to as yellowfin tuna) in the Indian Ocean, although many studies have assessed biological parameters such as length frequencies, length-weight relationships, growth parameters, spawning, natural mortality, food and feeding habits and size at first maturity (Somvanshi et al., 2002, Pillai and Satheeshkumar, 2012 and references therein).

This study will apply the standard length-weight method to yellowfin tuna from the Western Indian Ocean and analyse variation in  $W_r$  values over time. Yellowfin tuna are a cosmopolitan species that are predominantly distributed in the tropical and subtropical regions of the three major oceans (Atlantic, Pacific and Indian Ocean; IOTC, 2012). This species forms large schools with juveniles often forming mixed schools with skipjack tuna (*Katsuwonus pelamis*) and juvenile bigeye tuna (*Thunnus obesus*), two other commercially exploited tropical tuna species. Extensive studies into the feeding behaviour of yellowfin tuna indicate that they are largely opportunistic (Pillai and Satheeshkumar, 2012). Yellowfin tuna prey on a wide array of prey species and have been shown to dive to depths of 1000m to feed on mesopelagic prey. In addition, large yellowfin tuna also have the capacity to prey on very small fish, increasing the food availability to this species (Froese and Pauly, 2009).

Yellowfin tuna are widely exploited in the Indian Ocean through multiple fishing methods, with industrial purse seine vessels contributing to the majority of the catch. Fishing pressure has increased markedly since the 1950s and necessitated the formation of the Indian Ocean Tuna Commission (IOTC), which is mandated with the management of tuna and tuna-like species in the Indian Ocean. Annual total catches have fluctuated substantially over the past few decades, averaging 372200 t over the period of 2005 to 2009 (with very high catches during the period of 2003 to 2006). Total catches reached a peak at 523600 t in 2004 and have steadily declined since 2006, with 2009 recording the lowest catch (268192 t) since 1991 (IOTC, 2012; Pillai and Satheeshkumar, 2012). Total and spawning stock biomass from current estimates indicate continuous declines which are presumed to be the result of the 2003 to 2006 high catch rates (IOTC 2009). The Indian Ocean yellowfin tuna stock is considered close to overexploitation and several studies have highlighted management and conservation concerns (Pillai and Satheeshkumar, 2012; Juan-Jorda et al., 2013).

A number of studies have attributed much of the variability in yellowfin tuna catches and distribution to environmental and climate variability in the Indian Ocean (Nishida et al.,

2005; Menard et al., 2007; Corbineau et al., 2008; Marsac, 2008; 2012). Marsac (2012) in particular emphasizes the need to review trends in environmental factors in the Indian Ocean, such SST and sea surface chlorophyll (SSC), which are of most pertinent ecological relevance. The evidential influence of environmental variability on yellowfin tuna catches coupled with the uncertainty in recruitment and declining stock biomass highlight the need for evaluating population dynamics with an inclusive index such as condition.

The objectives of this study are to establish a length-weight baseline that will be used to evaluate body condition of yellowfin tuna in the Western Indian Ocean. Standard weight ( $W_s$ ) equations will be derived from a large dataset, which is assumed to include all possible condition scenarios of yellowfin occurring in the Western Indian Ocean. This study aims to enhance the current understanding of the effects of environmental variability and fishing pressure on yellowfin tuna stock dynamics in the Western Indian Ocean.

Environmental variability in the Indian Ocean affects the forage distribution and food availability of species like yellowfin tuna (Marsac, 2008; 2012). It is hypothesized that environmental conditions that favour high food availability in the Western Indian Ocean, either through biological enrichment or concentration of forage species, will result in a positive body condition response of yellowfin tuna. Therefore yellowfin tuna body condition is expected to vary over time in relation to environmental conditions. Literature on yellowfin tuna body condition in the Indian Ocean is limited. While it is out of the scope of this study to analyse all factors that influence yellowfin tuna fish body condition, we propose a novel approach, the relative weight index ( $W_r$ ), for assessing yellowfin tuna condition in the Indian Ocean.

## Methods and materials

### *Study area*

The IOTC has identified Indian Ocean yellowfin tuna as a single stock and for assessment models, has demarcated the Indian Ocean into five areas (IOTC, 2012; Fig. 1). The Western Indian Ocean includes the area off Somalia (R2) and the Mozambique Channel (R3).

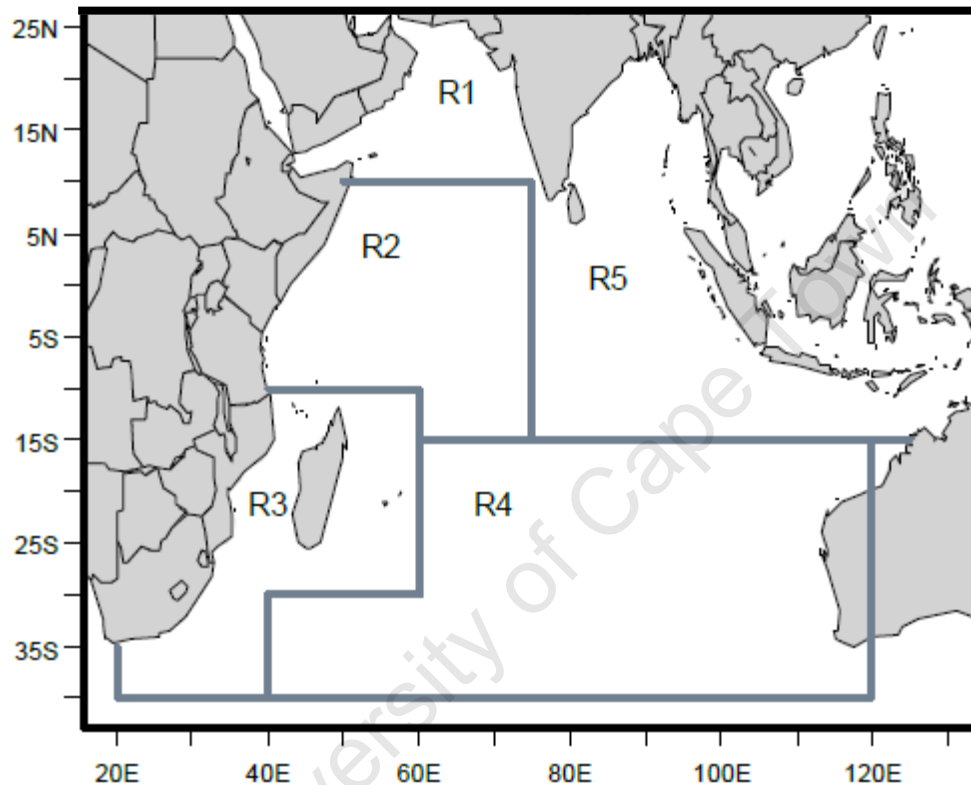


Fig. 1. Spatial stratification of the Indian Ocean for assessment models. Arabian Sea (R1); Off Somalia (R2); Mozambique Channel (R3); South Indian Ocean (R4); East Indian Ocean (R5) (adapted from IOTC, 2012).

### *Data collection and preparation*

Length and weight data for yellowfin tuna caught by purse seiners in the Western Indian Ocean were obtained from the IOTC. These biometric data were mostly collected at the cannery in the Seychelles 7.1° S, 52.8° E (Conserverie de l'Océan Indien, later renamed Indian Ocean Tuna Ltd. (IOT)) and by onboard observers on purse seine vessels. Four groups of data spanning 1984 to 1991 (excluding 1985) and 2003 to 2013 (excluding 2007) were used to establish the standard length-weight baseline. Data for the period 1992 to 2002 were

unavailable because of the enforcement of a restricted access rule which was later discontinued. Available data included:

- Measurements taken at sea by IRD (Institut de Recherche pour le Développement) observers in 1984 and by SFA (Seychelles Fishing Authority) onboard observers from May 1986 to October 1987.
- The first set of measurements taken at the cannery in Seychelles (Conserverie de l'Océan Indien) from August 1987 to January 1991.
- The second set of measurements resulting from 42 visits to the cannery in Seychelles (IOT Ltd) from October 2003 to July 2006.
- The third set of measurements made at the cannery (IOT Ltd.) taken over the period of 2008 to 2013.

Prior to sampling at tuna processing plant (IOT Ltd.) tuna are transhipped from fishing vessels and to a lesser extent unloaded frozen. Before processing, frozen tuna are thawed and, after entering the processing chain, fish are measured (FL rounded to the lowest cm), weighed (to the nearest 0.01kg) and sex is determined through gonad analysis. The date and location of capture of the fish are determined *a posteriori* through a detailed analysis of the purse seine logbooks (Marsac et al., 2006). Because of a paucity of location data, location was not included in further analyses in this study. Due to the single stock management of yellowfin tuna in the Indian Ocean and a paucity of location data, individual years were used to group the data.

For analysis, the datasets were merged and obvious erroneous measurements were removed as these were presumed to have arisen from measurement and recording errors. In addition, fish were excluded if length but not weight was recorded. Length-weight relationships were plotted separately for each dataset to identify individual outliers. Fish were judged as outliers if they weighed more than twice or less than half the mean weight for a given length.  $\text{Log}_{10}(L)$ - $\text{log}_{10}(W)$  linear regressions were fitted to each year to investigate the validity of each dataset and years with a coefficient of determination ( $R^2$ ) less than 0.9 (Bister et al. 2000) were excluded from further analyses. Sex (male or female) was not determined for all

fish used in this study and available sex data were filtered for obvious recording errors, such as recorded numbers instead of sex.

### *Establishing Standard Weight Equations*

The empirical percentile (EmP) method described in Gerow et al. (2005) was used to establish four standard weight ( $W_s$ ) equations for yellowfin tuna in the Western Indian Ocean. Each equation was based on one of four different statistics (mean, median, lower and upper quartile) of the distribution of mean weights for each length class, for length-weight data from all years. An Excel tool with macros designed for the EmP method was used (<http://www.sdafs.org/fmsafs/interactive-excel-tool-for-computing-assessing-and-using-emp-ws-equation/>). This tool was designed to use data input with units of millimetres (mm) and grams (g) and yellowfin tuna measurements of lengths and weights were adjusted accordingly. The Excel macro tool was applied to  $\log_{10}$ -transformed length-weight data in all applicable analyses.

Individual fish  $k$ , from each sample year  $i$  (fish from the same year) were placed into a length class  $L_j$  (2cm intervals) across the observed range of yellowfin lengths. The EmP method uses the mean weight of each length class as the basis for establishing the standard weight equations. Not all years contained fish in all length classes; the smallest sample size per analyzed year was 42 fish. The smallest and largest length classes contained the least fish and the length range was truncated for the calculation of the  $W_s$  equations.

Weight statistics  $[W]_j$  for each length class were calculated using the means of the respective length classes. A quadratic regression using  $\log$ -transformed length-weight data was fitted for each of the weight statistics. The quadratic regressions were weighted by the number of contributing years in each length class and used to calculate the standard weights for each respective length class ( $W_s(j)$ ):

$$\log_{10}W_{s(j)} = a + b\log_{10}L_j + c(\log_{10}L_j)^2 \quad (\text{Eq. 1})$$

where  $a$ ,  $b$  and  $c$  are constants in the quadratic regression.

The median standard weight equation was considered most appropriate for the purposes of establishing a fixed baseline for the evaluation of yellowfin tuna relative weights. Therefore this study only considered the median standard weight equation for further analysis. However the process for using the other standard weight equations is the same. The distribution of residuals for the median standard weight equation was evaluated across the length range to identify length related biases which could bias  $W_r$  estimates.

A bootstrap analysis was conducted to establish the precision of the  $W_s$  values obtained from Eq. 1. The bootstrap study consisted of 1000 replicates, whereby 16 length-weight datasets were selected randomly, with replacement, from the original 16 sample years. The median standard weight equation was applied to each of the 16 randomly collected bootstrap datasets. The relative margin of error (RMOE) was calculated for each length class used in the bootstrap analysis, calculated as twice the standard deviation among estimates divided by the average of the estimates. RMOE provided an easily interpretable measure of precision across the length range. When plotted across the length range it was used to make error distribution inferences and to set length confidence intervals for application of the median  $W_s$  equation.

The  $W_s$  equation (Eq.1) was plotted alongside the L-W relationship currently adopted by the IOTC for yellowfin tuna in the Indian Ocean (Marsac et al., 2006):

$$W(\text{kg}) = 1.8860\text{E-}05 (\text{FL}(\text{cm}))^{3.0195} \quad (\text{Eq. 2})$$

For comparing weight estimates, the differences between weights predicted from the  $W_s$  equation and the previous relationship were plotted in a bar graph.

### *Relative weight analysis*

Standard weights ( $W_{s(j)}$ ), generated for each length class ( $j$ ) and the observed weights ( $W_{(ijk)}$ ) for each individual fish ( $k$ ) in each length class ( $j$ ) in each year ( $i$ ), were used to estimate relative weight  $W_{r(ijk)}$ :

$$W_{r(ijk)} = 100 \times \frac{W_{(ijk)}}{W_{s(j)}} \quad (\text{Eq. 3})$$

A scatterplot of  $W_r$  against length and a frequency distribution were used to investigate length related bias in  $W_r$  estimates.

Trends in  $W_r$  were first analysed by plotting the mean  $W_r$  values over time, per month and per year. Similarly the mean  $W_r$  values for males and females were plotted per month and per year. Annual and monthly mean  $W_r$  values were investigated in terms of their respective sample size and the months of contributing data. This was an initial evaluation of the  $W_r$  estimates and the concern of confounding effects from year, month and sex.

#### *Modelling $W_r$ as a response variable*

$W_r$  estimates of yellowfin tuna represent a single predictor variable with candidate explanatory variables of year, month and sex. To separate the effects of year, month and sex on the  $W_r$  estimates, generalised linear models (GLM) of the form:

$$W_r = \beta_0 + \beta_1(\text{Year}) + \beta_2(\text{Month}) + \beta_3(\text{Sex}) + \varepsilon'$$

were applied using R 3.0.1 (R Development Core Team, 2013) (second-degree interactions not shown here). Only fish in which sex had been determined were used in the GLM framework.

Gaussian GLMs with an identity-link function were used in the modelling framework. Residual plots and a quantile-quantile plot were plotted for the final GLM to test for violation of the assumed Gaussian distribution. Explanatory variables and interaction terms were first evaluated based on minimizations of model deviance and Akaike's Information Criterion (AIC; Akaike, 1973) using a forward stepwise selection procedure (Swartzman et al., 1992; Ortiz and Arocha, 2004). An analysis of variance was applied to the GLMs and the 'F' statistic and its p-value were used to test significance of the variation explained compared to the preceding GLM model.

Annual  $W_r$  estimates were standardized by fixing month and sex to a vector of standardized values. Similarly, monthly  $W_r$  estimates were standardized by fixing year and sex to a vector of standardized values. The final GLM was applied to the standardized vectors to predict the annual and monthly  $W_r$  trends over time, corrected for other all other effects.

### *Environmental Data*

Environmental data for the West Equatorial area was adapted from Marsac (2012), which provided an outline of the climate and oceanographic conditions in the Indian Ocean over the period 2002 to 2012. The value assigned to each year  $y$  is an average of December<sub>(y-1)</sub> to February<sub>(y)</sub>. Sea surface temperature (SST), sea surface chlorophyll (SSC) and mixed layer depth (MLD) were used to assess if there were any plausible environmental driving forces behind body condition variability in the Western Indian Ocean. SSC was used as a proxy for biological enrichment in the Indian Ocean because it has been linked to increased food availability for species such as yellowfin tuna (Nishida et al., 2005; Marsac, 2012).

### **Results**

Length-weight data from 1991 were disqualified from the final dataset based on a coefficient of determination ( $R^2$ ) below 0.9. The final dataset used in the  $W_r$  analysis consisted of 9650 yellowfin tuna with a length range of 33 to 165cm (mean= 109cm) and a weight range of 0.7 to 95kg (mean= 31kg). A total of 9643 fish was used to establish  $W_s$  (Table 1A) after truncating the length range to 33 to 161cm for the EmP tool. The length distribution of the 9643 individual yellowfin tuna used to calculate the  $W_s$  equations, as well as the number of contributing years to each length class are summarized in Table 1. The frequency distribution of the individual fish lengths (Fig. 2) followed a bimodal distribution with peaks for small and large length classes.

Table 1. Summary of yellowfin tuna length-weight data used for calculating the standard weight equations (Eq. 1). A) Number of individual fish and contributing years to each fork length category. The midpoint is the middle of the length interval (34 = 33 to 35cm FL). B) Number of contributing months and individual fish for each year (for entire dataset). C) Number of contributing years and individual fish for each month of the year for the entire dataset. D) Years sampled for sex (male/female) with contributing number of individual fish. E) Months sampled for sex with contributing years and number of individuals.

A					
Fork Length midpoint (cm)	Number of contributing datasets	Total number of individuals	Fork Length midpoint (cm)	Number of contributing datasets	Total number of individuals
34	3	10	98	12	160
36	4	18	100	14	289
38	4	23	102	14	292
40	1	32	104	14	330
42	3	57	106	15	320
44	2	59	108	15	326
46	4	96	110	14	353
48	4	70	112	12	296
50	5	55	114	12	310
52	5	71	116	13	321
54	5	137	118	15	253
56	6	176	120	13	299
58	6	177	122	15	307
60	5	158	124	15	396
62	6	93	126	15	446
64	5	53	128	13	380
66	5	43	130	14	412
68	5	35	132	15	317
70	6	15	134	13	244
72	7	22	136	13	247
74	6	27	138	13	248
76	6	44	140	13	194
78	7	28	142	13	166
80	6	52	144	12	134
82	7	52	146	12	113
84	8	37	148	13	80
86	10	46	150	10	75
88	10	60	152	12	58
90	9	69	154	8	44
92	11	102	156	6	19
94	12	134	158	8	13
96	11	140	160	3	8

B			C			
Year	Number of contributing months	Total number of individuals	Month	Number of years month sampled in	Total number of individuals	
1984	2	241	1	7	904	
1986	2	92	2	10	990	
1987	9	827	3	9	965	
1988	11	948	4	10	641	
1989	9	524	5	7	577	
1990	8	870	6	8	1004	
2003	3	305	7	11	1345	
2004	5	1051	8	7	517	
2005	4	981	9	5	646	
2006	4	1015	10	8	741	
2008	2	42	11	8	890	
2009	8	608	12	8	430	
2010	9	274				
2011	9	921				
2012	11	852				
2013	2	99				
D		$\Sigma = 9650$	E		$\Sigma = 9650$	
Sex	Year	Number of contributing fish	Month (Jan =1)	Number of years month sampled in	Number of contributing fish	
Male (N=3061)	2003	127	1	5	407	
	2004	571	2	6	362	
	2005	409	3	4	322	
	2006	436	4	4	163	
	2008	17	5	3	223	
	2009	292	6	4	278	
	2010	154	7	7	448	
	2011	501	8	3	95	
	2012	501	9	2	81	
	2013	53	10	5	139	
				11	6	392
				12	6	151
Female (N=2652)	2003	91	1	5	301	
	2004	433	2	7	293	
	2005	414	3	3	219	
	2006	499	4	4	139	
	2008	24	5	3	220	
	2009	294	6	5	336	
	2010	114	7	6	411	
	2011	397	8	3	57	
	2012	340	9	2	59	
	2013	46	10	5	119	
				11	6	351
				12	6	147

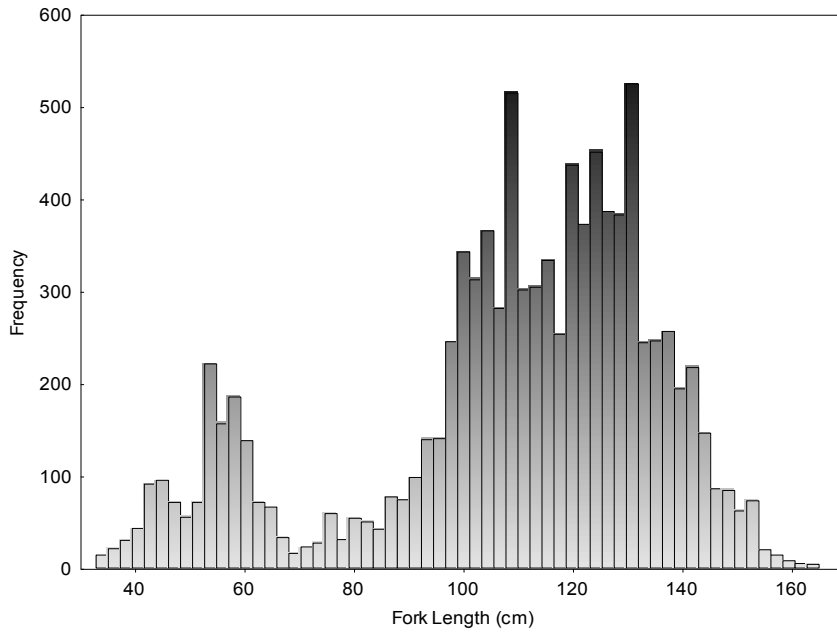


Fig. 2. Frequency distribution of individual yellowfin tuna in length classes from all years used in this study (N = 9650)

The four quadratic regressions (Table 2) produced reasonable fits to the  $\log_{10}$  length-weight data and the median weight relationship closely matched those for the individual years (Fig. 3.), with only one year (1986) deviating from the median standard weight equation.

Table 2. Parameters of the four standard weight quadratic regression equations (Eq. 1) for yellowfin tuna (*Thunnus albacores*) in the Western Indian Ocean. Standard error of the quadratic parameter  $c$  is given and denotes the error associated with the curvature of the quadratic regression curve.

Log-log standard weight regression parameters				
	a(Intercept, g)	b(Linear, $\text{g}\cdot\text{mm}^{-1}$ )	c(Quadratic, $\text{g}\cdot\text{mm}^{-2}$ )	SE of c
1st quartile	-3.951	2.447	0.099	0.045
Median	-3.903	2.425	0.103	0.048
3rd quartile	-3.091	1.929	0.180	0.052
Mean	-3.692	2.313	0.117	0.039

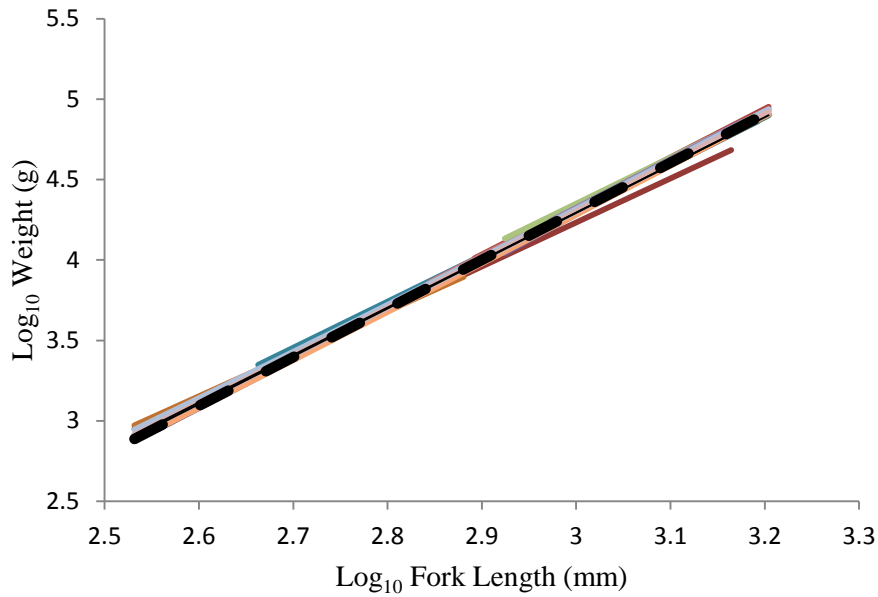


Figure 3. Median standard weight ( $W_s$ ) equation calculated using the EmP method for yellowfin tuna (*Thunnus albacores*) from the Western Indian Ocean (black dashed line). Lines in colour are the 16 weight-length relationships on a log-log scale for all years used in the analysis (N= 9650).

The residuals from the regression analysis of the median standard weight equation were normally distributed (Fig. 4A) and indicated homoscedasticity (Fig. 4B), although there was slightly higher variance for small weights. Therefore the assumptions of the regression analysis were satisfied and no length related bias was observed in the median  $W_s$  equation.

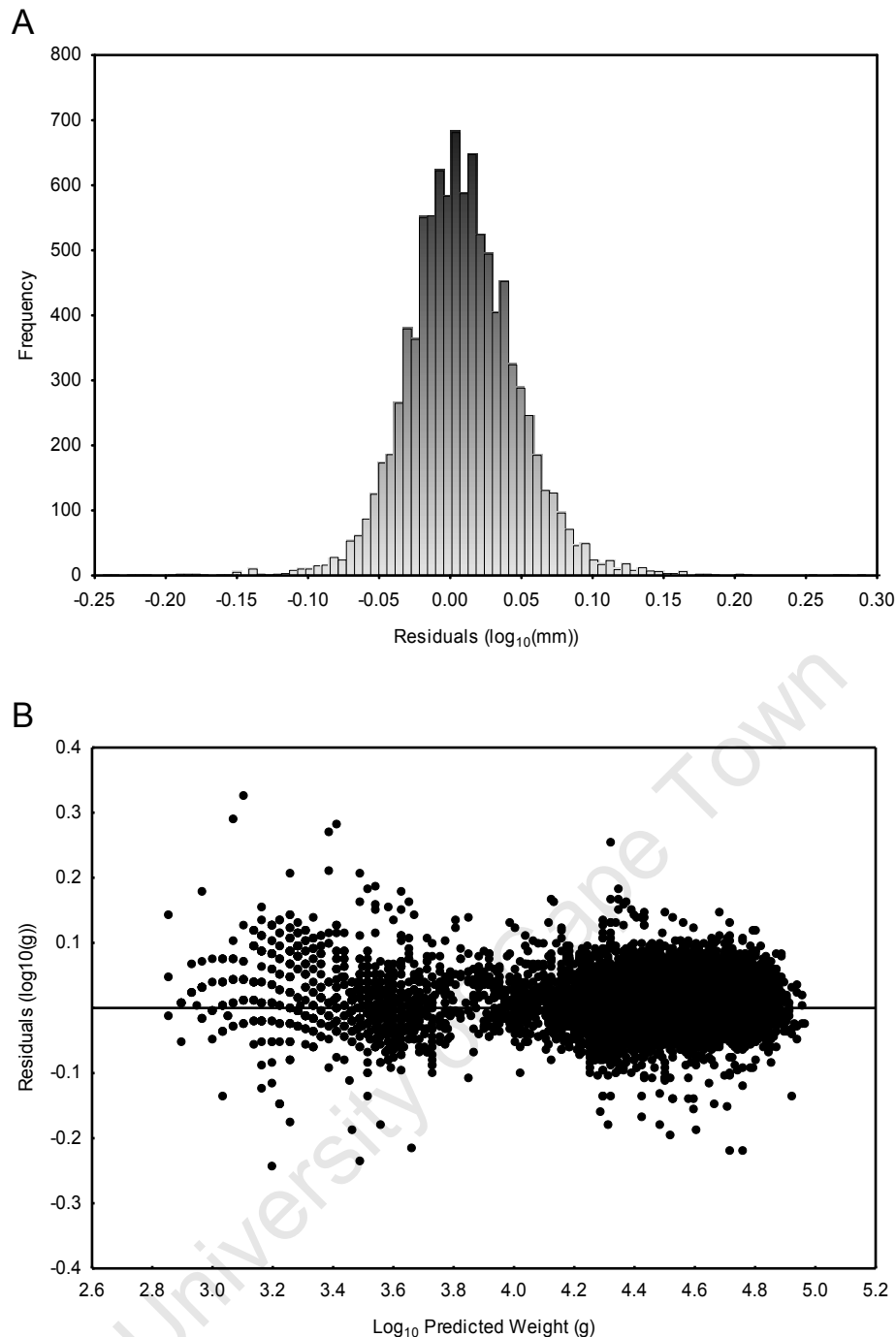


Fig. 4. Regression analysis results of median standard weight equation (Eq. 1) with  $\log_{10}$ -transformed median yellowfin weights as a function of  $\log_{10}$  fork length. A) Frequency distribution of residuals from regression analysis. B) Plot of residual values against predicted standard weights.

The RMoE that resulted from the bootstrap analysis (1000 replicates) ranged from approximately 1.5%, fish ranging between 46cm and 136cm, to 3.5%, for the smallest (33 to 43cm) and largest (139 to 159cm) fish in the analysis (Fig. 5). Therefore the median  $W_s$  equation was able to predict reasonably precise weight at length values across the range of yellowfin tuna lengths.

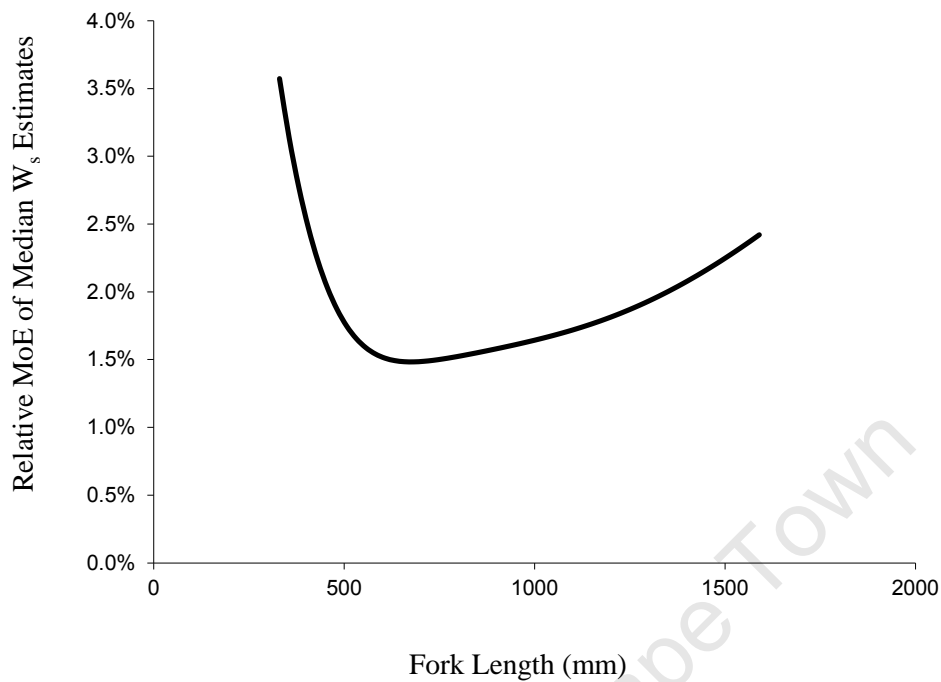


Fig. 5. Relative margin of error (RMoE) from bootstrap analysis (1000 replicates) of median standard weight equation

The median  $W_s$  relationship established in this study consistently estimated lower weights at length than the current IOTC yellowfin tuna L-W relationship (Marsac et al., 2006) (Fig. 6A and B). The difference in weight estimates were low for small length classes and increased with length, with a maximum difference of approximately 1.2kg for fish of 145cm.

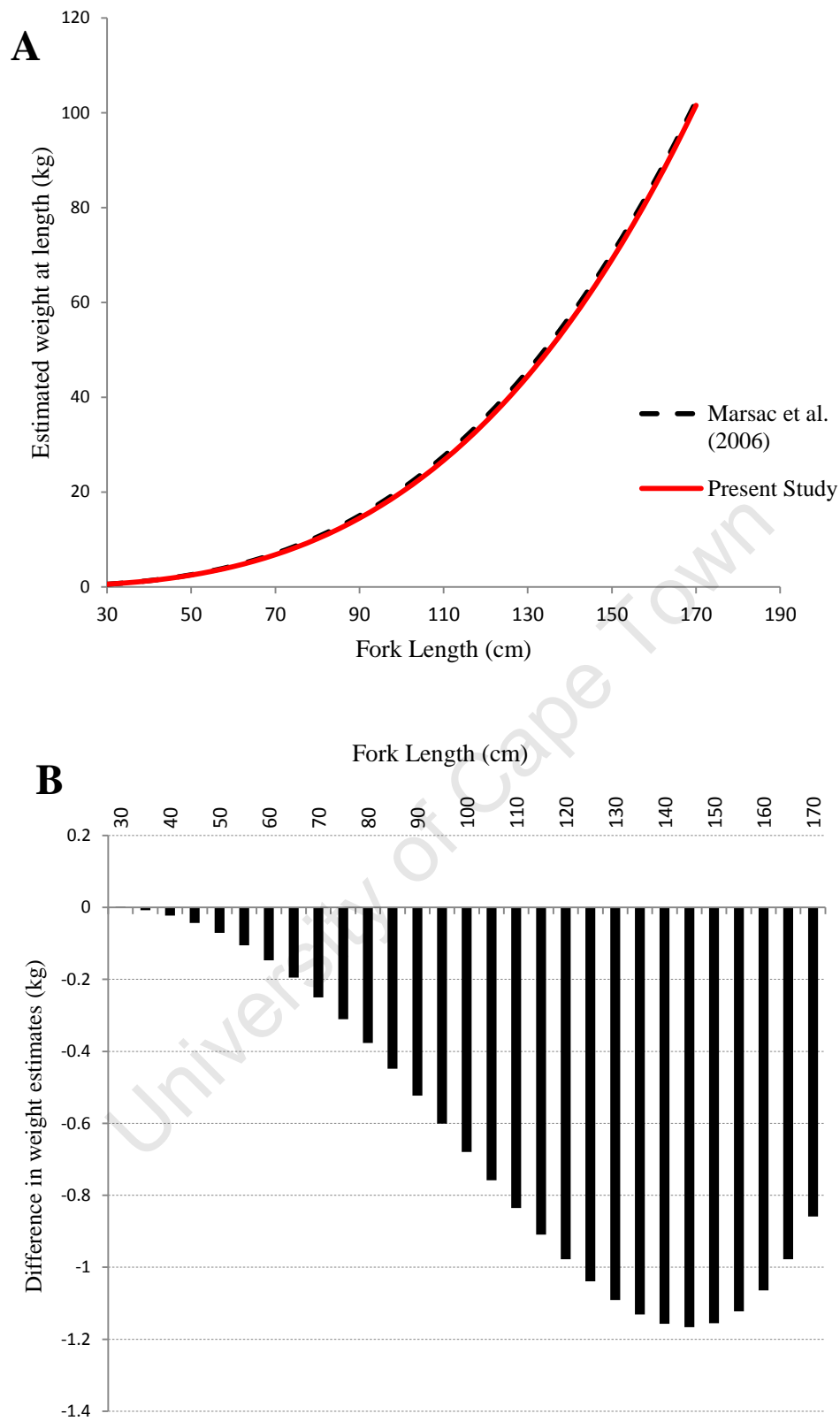


Fig. 6. Comparison between the median standard length-weight relationship developed in this study (Eq. 1) and the current IOTC yellowfin tuna L-W relationship (Eq. 2; Marsac et al., 2006). A) IOTC L-W relationship (dashed line) plotted with the median  $W_s$  relationship (solid line). B) Difference between the two relationships using the median  $W_s$  relationship as a reference point.

### Relative Weight ( $W_r$ ) Analysis

Relative weights calculated for individual yellowfin tuna displayed no systematic trend in terms of increases or decreases with fish length (Fig. 7.), but there was increased variability observed for small fish between 33 and 70cm. Relative weights followed a symmetrical frequency distribution and had a central tendency (Fig. 8), further indicating no bias in  $W_r$  estimates.  $W_r$  values for individual fish smaller than 62cm ranged between 92 and 110. Fish larger than 62cm exhibited a narrower range of  $W_r$  values from 95 to 102 (Fig. 7).

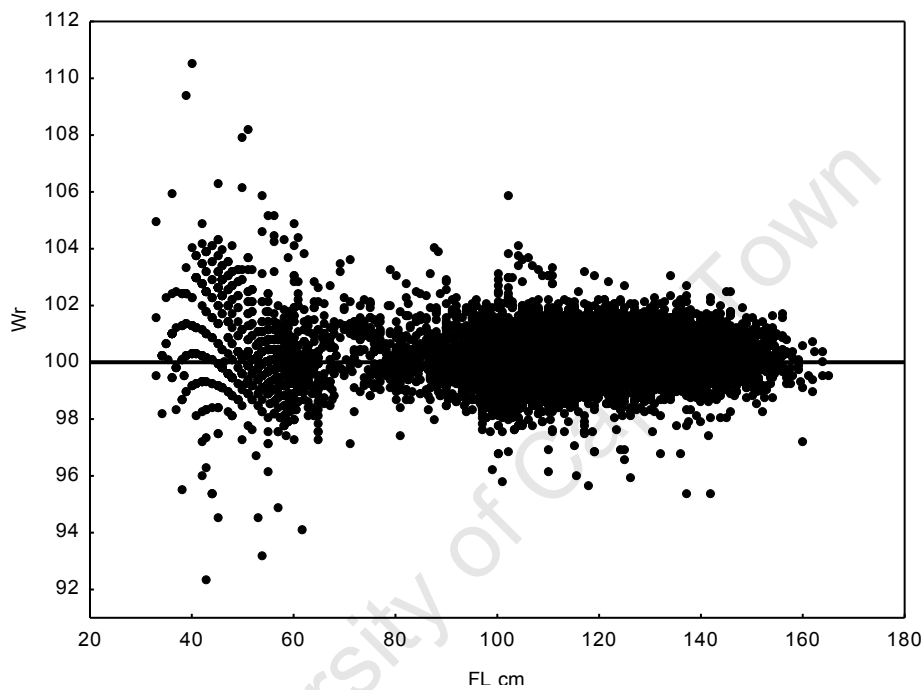


Fig. 7. Scatterplot of relative weights of yellowfin tuna ( $N = 9650$ ) calculated from the median standard weight equation.

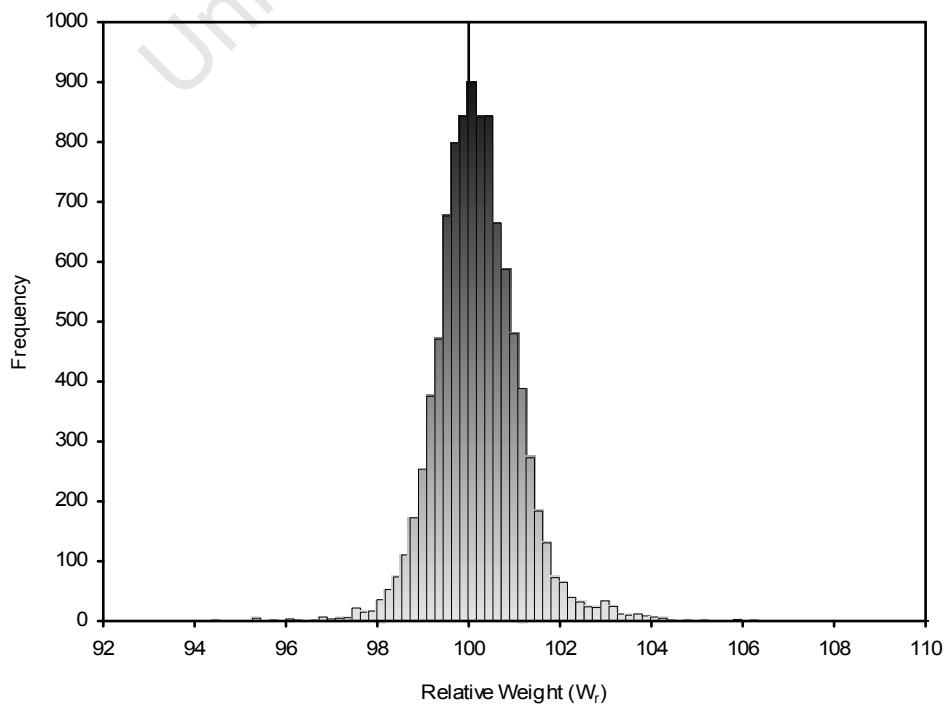


Fig. 8. Frequency distribution of  $W_r$  values for individual yellowfin tuna calculated from the median standard weight equation.

*Preliminary analysis of  $W_r$  estimates*

Annual mean relative weights of all fish had a narrow range of approximately 99 to 101 (Fig. 9), as did the mean monthly  $W_r$  values which ranged from 99.9 to 100.5 (Fig. 10). The sample size for the study years were of little concern (Table 1), except for 1986 (92 fish sampled) and 2008 (42 fish sampled) which accounted for the large standard error for these two years. Annual mean  $W_r$  values indicate that yellowfin tuna in the Western Indian Ocean were in a condition below that of the median standard weight from 1984 to 1988, followed by two years of above average condition (1989 and 1990) (Fig. 9). In 2003 and 2004 yellowfin tuna were in above average condition followed by below average condition for 2005 and 2006. From 2008 onwards, yellowfin tuna body condition was above average and displayed an increasing trend across time.

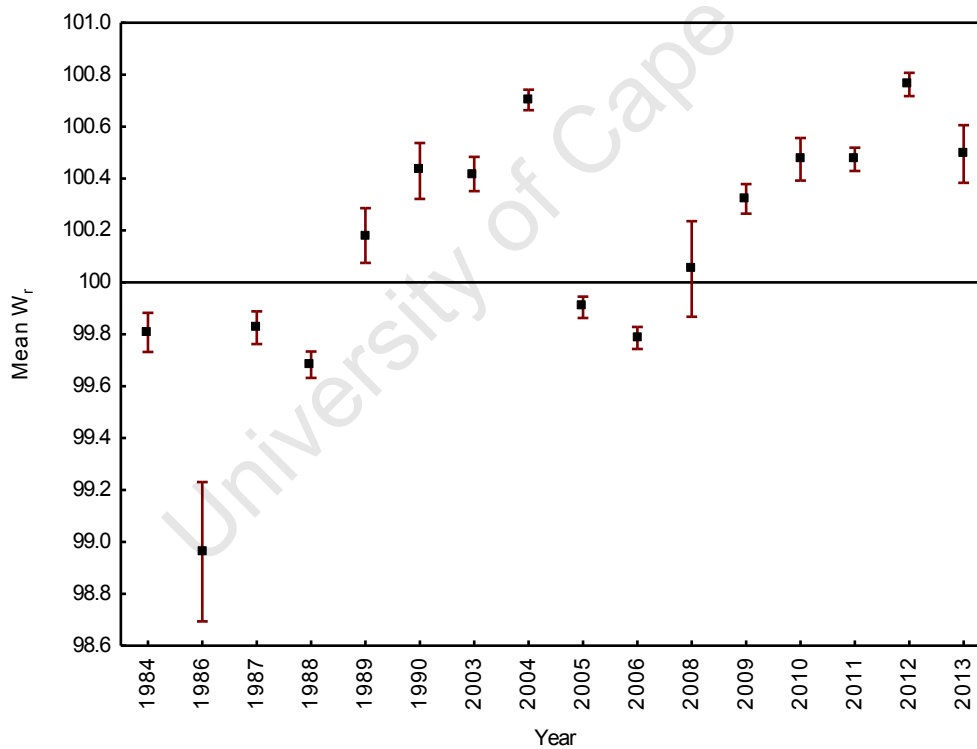


Fig. 9. Annual mean relative weight values ( $\pm$ se) for yellowfin tuna in the Western Indian Ocean from 1984 to 1990 and 2003 to 2013. Solid line indicates the baseline median standard weight.

The highest monthly mean  $W_r$  values occurred in August and October (Fig. 10). January to April displayed a decreasing trend in body condition with time, although the condition was still above median. An increasing trend in condition was observed from May to August, starting below average condition in May. September had below average condition with October to December characterized by above average condition, with a decreasing trend with time. Although sample size was not a concern for the calculation of monthly mean  $W_r$  (Table 1C), there was a large standard error observed. This suggested that monthly mean  $W_r$  values were confounded by differences among years and the unequal representation from each year, as not all months were sampled in each year.

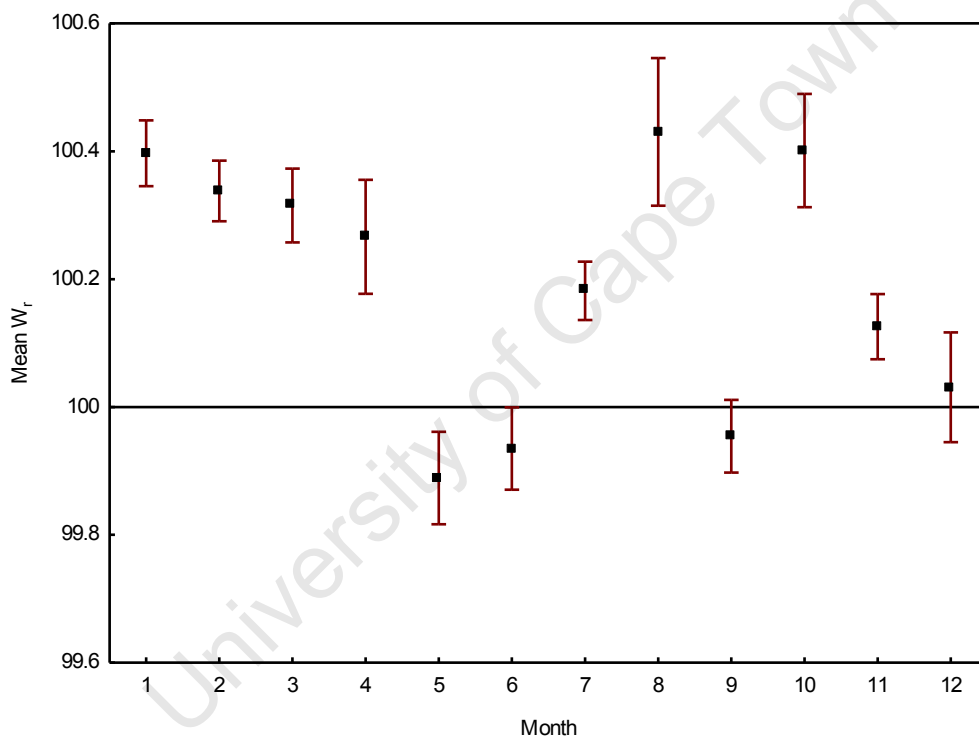


Fig. 10. Monthly mean relative weight ( $\pm$  se) from January (1) to December (12). Solid line indicates the baseline median standard weight.

The analysis of relative weight for yellowfin tuna males and females consisted of 3061 male and 2652 female fish, for the period 2003 to 2013 (excluding 2007) (Table 1D). Mean annual relative weights for both male and female yellowfin tuna followed the same temporal trends across the period 2003 to 2013. Male and female annual mean  $W_r$  values had a narrow range of 99.9 to 100.8 and 99.7 to 100.8 respectively (Fig. 11). Mean  $W_r$  values for males were consistently higher than females across the sample years, except in 2010 and 2013. The years 2005 and 2006 were characterized by below median condition with all other years above

median condition. There was a consistently increasing trend in condition from 2005 to 2013. Standard error for annual mean  $W_r$  for both males and females (Fig. 10) was higher as compared to the annual mean  $W_r$  (Fig. 9) over the same period. This indicated male and female annual means were confounded by year and month effects, as males and females were sampled unequally from different month in the sample years. The difference in males and female annual mean  $W_r$  values suggested that there was an interaction between the effects of year and sex on  $W_r$  estimates.

Monthly mean  $W_r$  values for male and female yellowfin ranged from 100 to 100.9 and 99.9 to 100.6 respectively. Male monthly mean  $W_r$  values were consistently higher than female means, except for December. However both sexes followed the same temporal trends across all months. January to April was characterized by above-average condition with an increasing trend. Mean  $W_r$  showed an increasing trend from May (approx. average condition) to August (above condition), followed by a decreasing trend in condition from August to December (approx. average condition). The difference in male and female monthly mean  $W_r$  values suggested that there was an interaction between the effects of month and sex on  $W_r$  estimates.

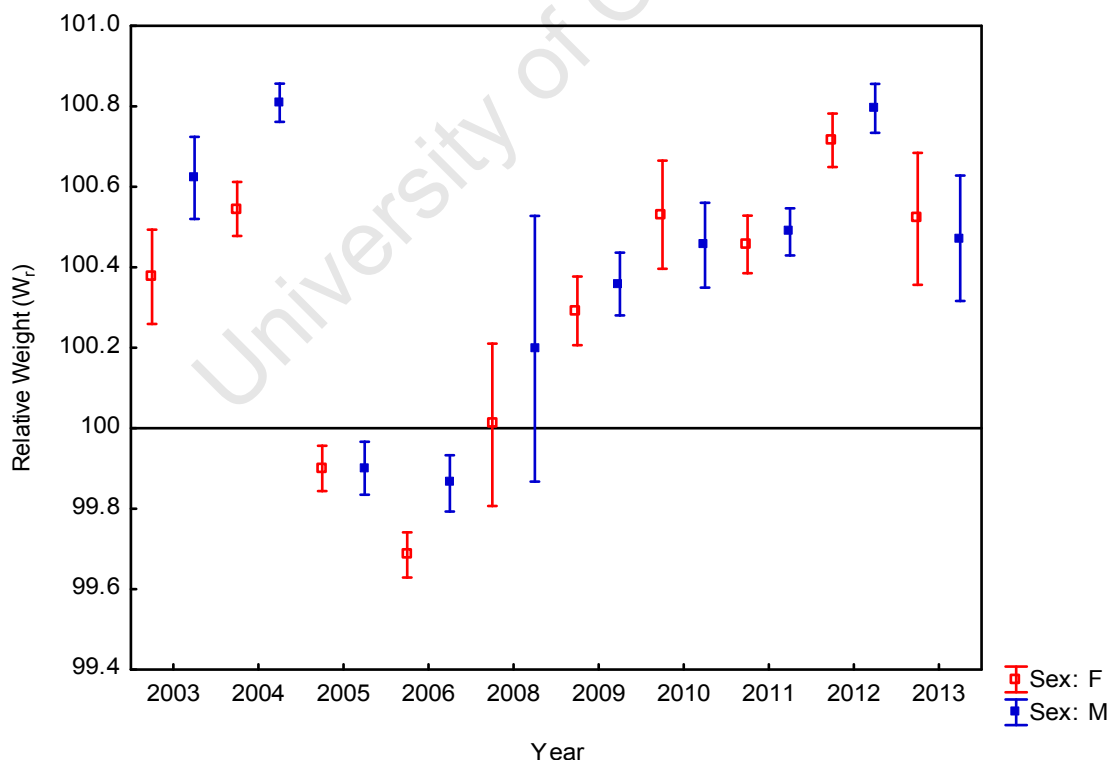


Fig. 11. Annual mean ( $\pm$ se) relative weights for male (solid marker) and female (open marker) yellowfin for the period 2003 to 2013 (excluding 2007). Solid line indicates the baseline median standard weight.

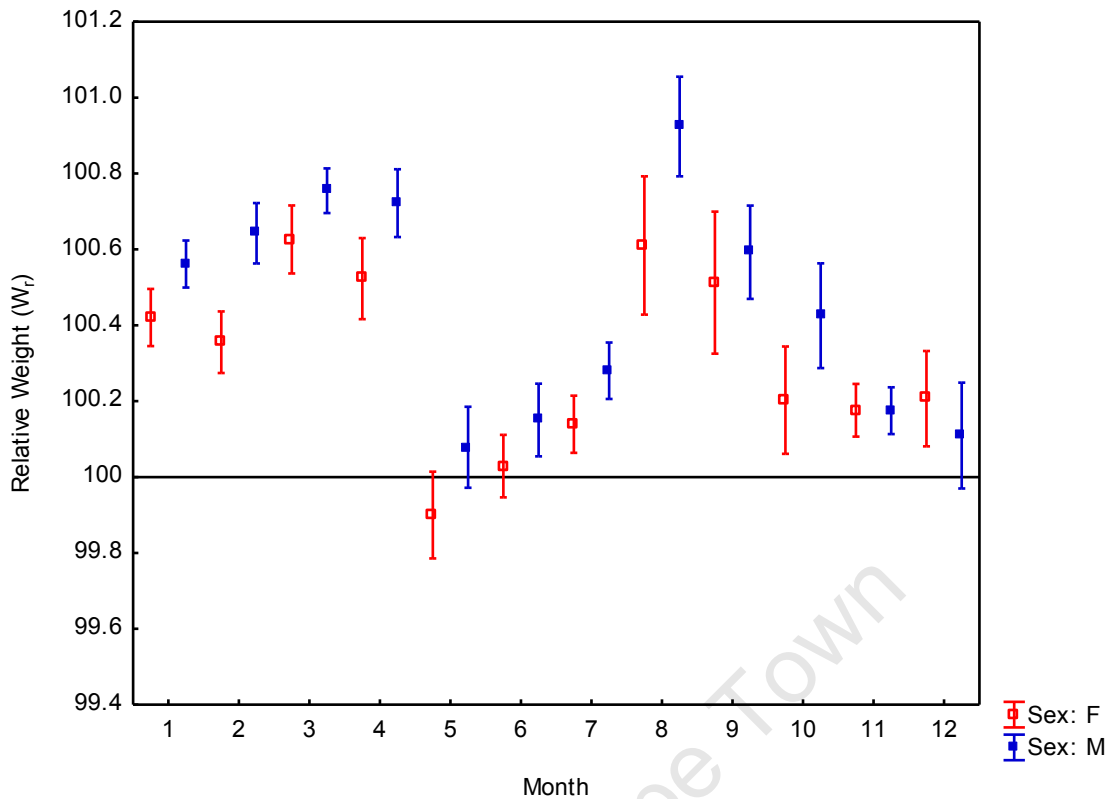


Fig. 11. Monthly mean ( $\pm$ se) relative weights for male (solid marker) and female (open marker) yellowfin for the period of 2003 to 2013 (excluding 2007). Solid line indicated the baseline median standard weight.

The narrow range in  $W_r$  observed for the annual and monthly means suggested that deductions about body condition (as above average or below average condition) should be approached with caution. In addition, potential confounding effects of year, month and sex, identified in the preliminary analysis, necessitated the investigation of  $W_r$  estimates as a response variable through a GLM modelling framework.

#### *GLM model framework*

Table 3 summarizes the results of GLMs fitted to the subset of sexed yellowfin tuna ( $N = 5713$ ) from 2003 to 2013. The forward stepwise selection procedure found that all explanatory variables and interaction terms explained a significant amount of variation in the data ( $\text{Year} > \text{Month} > \text{Year:Sex} > \text{Sex} > \text{Month:Sex}$ ), and resulted in reductions of AIC. (Table 3).

Table 3. Summary statistics of Gaussian GLMS (link = identity) fitted to yellowfin tuna  $W_r$  estimates from the Western Indian Ocean.  $\Delta$  AIC is the difference in the AIC compared to the preceding model.  $\Delta$  Deviance is the difference in deviance explained compared to the preceding model.

Model structure	d.f.	AIC	$\Delta$ AIC	Residual Deviance	$\Delta$ Deviance	% explained	Cumulative % explained	$F$	$P$ value
Null	2	13118		3321.1					
+Year	11	11614	-1503	2544.7	-776.4	23.38	23.38	202.20	<0.001
+Month	22	11440	-174	2458.9	-85.8	3.37	26.75	18.29	<0.001
+Sex	23	11412	-28	2445.8	-13.1	0.53	27.28	30.67	<0.001
+Year:Sex	32	11394	-18	2430.4	-15.4	0.63	27.91	4.01	<0.001
+Month:Sex	43	11391	-3	2419.6	-10.8	0.44	28.36	2.29	0.0087

The GLM with the lowest AIC and highest deviance explained was used to standardize the effects of year, month and sex:

$$W_r = \beta_0 + \beta_1(\text{Year}) + \beta_2(\text{Month}) + \beta_3(\text{Sex}) + \beta_4(\text{Year:Sex}) + \beta_5(\text{Month:Sex})$$

Residual plots and quantile-quantile plots indicated no violation of the assumed Gaussian error model (Fig. 12), although the quantile-quantile plot deviated at the lower and upper theoretical quantiles.

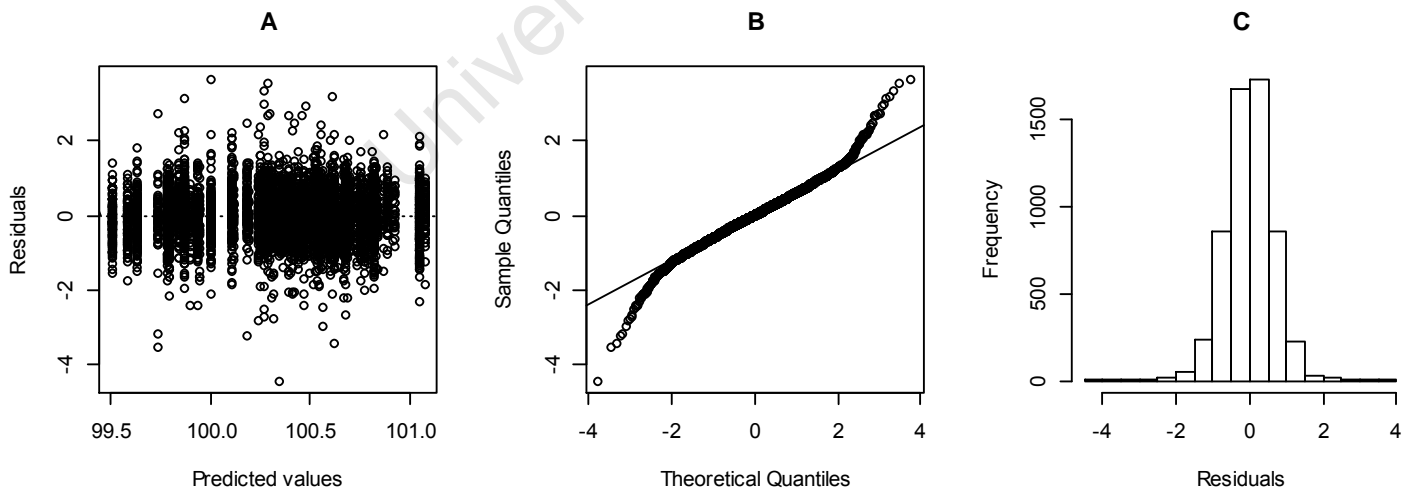


Fig. 12. Residual scatterplot (A), quantile-quantile plot (B) and frequency distribution (C) of Gaussian GLM fitted to relative weight estimates of yellowfin tuna in the Western Indian Ocean.

The final GLM incorporated 2003 (Year), January (Month) and females (Sex) into the intercept. Table 4 provides a summary of the final GLM results and indicates the significance levels of the estimates calculated for explanatory variables. Standardized annual mean  $W_r$  followed the same trend over time for both males and females (Fig. 13) and had a range of 99.71 to 100.70 and 99.62 to 100.61 for males and females respectively. Males had a significantly higher annual mean  $W_r$  compared to females ( $p < 0.01$ ), except for 2004 and 2006. The mean  $W_r$  estimates for 2003 and 2004 were above average, followed by below average condition for 2005 and 2006. Thereafter there was an increasing trend in condition over time from 2008 to 2013. Standardized annual mean  $W_r$  therefore followed the same trend across time, for 2003 to 2013, as in the preliminary analysis, when the effects of month and sex were not corrected for. However the range of annual mean  $W_r$  values was smaller when the effects of month and sex were standardized.

All months, except for April and May, were statistically different from the intercept ( $p < 0.05$ ; Table 4). Standardized monthly mean  $W_r$  values for males and females ranged from 100.41 to 100.79 and 100.31 to 100.70 respectively. Male and female yellowfin tuna followed the same trend in standardized monthly mean  $W_r$  over time (Fig. 14). Monthly mean  $W_r$ , for both sexes, followed a trend of decreasing condition from February to May, increasing condition from May to August and a decreasing trend in condition from August to December. The ranges of standardized monthly mean  $W_r$  values for both sexes were smaller than the means not corrected for the year effect.

The significance of the interaction term between month and sex indicates that there are significant monthly differences in male and female yellowfin tuna condition. However only November and December for the month:sex interaction term were found to be significantly different from the intercept ( $p < 0.05$ ).

Table 4. Summary results of final GLM (family = Gaussian, link = identity) fitted to  $W_r$  estimates. The table summarizes the estimates for different levels of the explanatory variables and their level of significance. Significance codes for p values: <0.001 ‘\*\*\*’, 0.001 ‘\*\*’, 0.01 ‘\*’, 0.05 ‘.’

	Estimate	t value	P value	Sig. Level
Intercept	100.160	1097.45	< 0.001	***
Year				
2004	0.185	2.02	0.0431	*
2005	-0.496	-6.34	< 0.001	***
2006	-0.648	-7.38	< 0.001	***
2008	-0.361	-2.37	0.0176	.
2009	-0.096	-1.14	0.2544	
2010	0.234	2.46	0.0141	.
2011	0.128	1.47	0.1422	
2012	0.402	4.59	< 0.001	***
2013	0.310	2.37	0.0179	.
Month (Jan = 1)				
2	0.330	5.69	< 0.001	***
3	0.282	4.50	< 0.001	***
4	0.128	1.84	0.0661	
5	-0.003	-0.05	0.9632	
6	0.123	2.03	0.0423	.
7	0.270	4.71	< 0.001	***
8	0.313	3.18	0.0015	*
9	0.356	3.44	0.0006	***
10	0.209	2.54	0.0111	.
11	0.209	3.24	0.0012	*
12	0.238	3.14	0.0017	*
Sex (Male = M)				
M	0.466	3.79	<0.001	***
Year:Sex				
2004:M	-0.131	-1.06	0.2874	
2005:M	-0.264	-2.47	0.0134	.
2006:M	-0.246	-2.04	0.0410	.
2008:M	-0.071	-0.31	0.7568	
2009:M	-0.284	-2.49	0.0129	.
2010:M	-0.415	-3.26	0.0011	*
2011:M	-0.354	-2.99	0.0028	*
2012:M	-0.350	-2.96	0.0031	*
2013:M	-0.577	-3.25	0.0011	*
Month:Sex				
2:M	0.046	0.59	0.5523	
3:M	-0.138	-1.69	0.0904	
4:M	-0.049	-0.53	0.5995	
5:M	-0.145	-1.64	0.1007	

6:M	-0.064	-0.76	0.4480	
7:M	-0.131	-1.74	0.0827	
8:M	0.085	0.68	0.4977	
9:M	-0.110	-0.81	0.4205	
10:M	-0.134	-1.18	0.2378	
11:M	-0.209	-2.41	0.0161	.
12:M	-0.370	-3.54	< 0.001	***

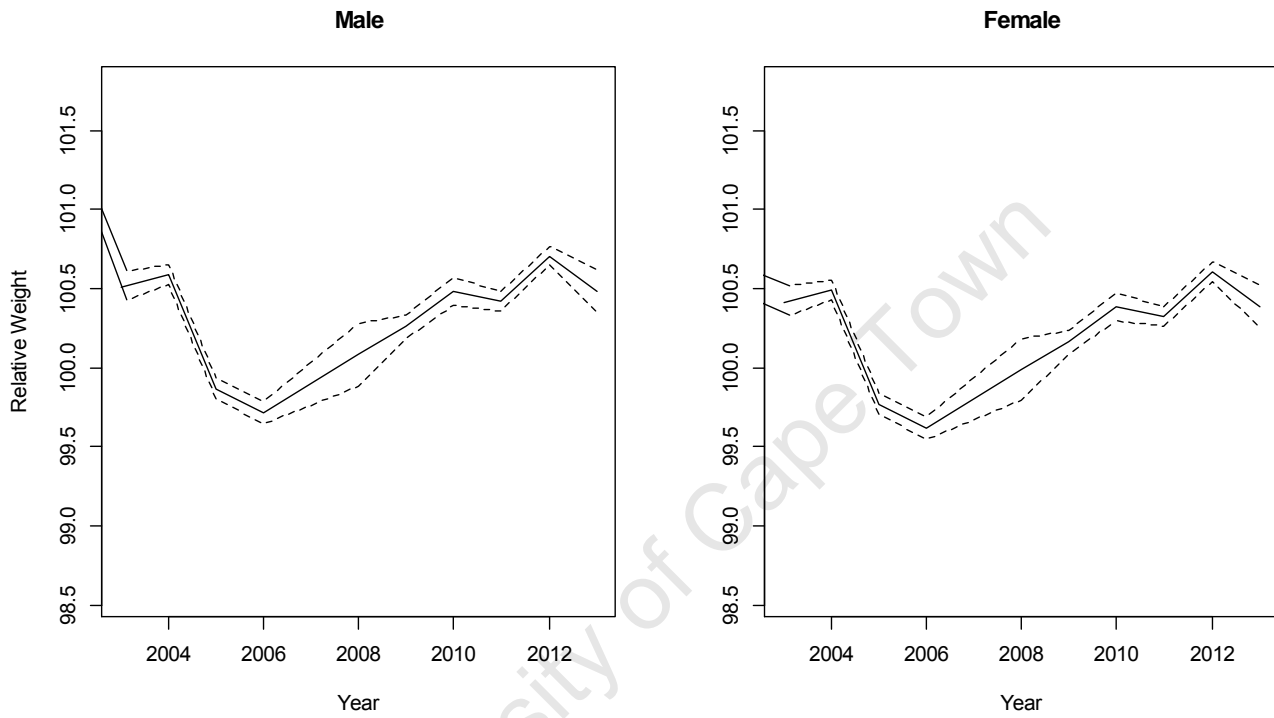


Fig. 13. Annual mean relative weight ( $\pm$ se), corrected for the effect of month, for male and female yellowfin tuna in the Western Indian Ocean.

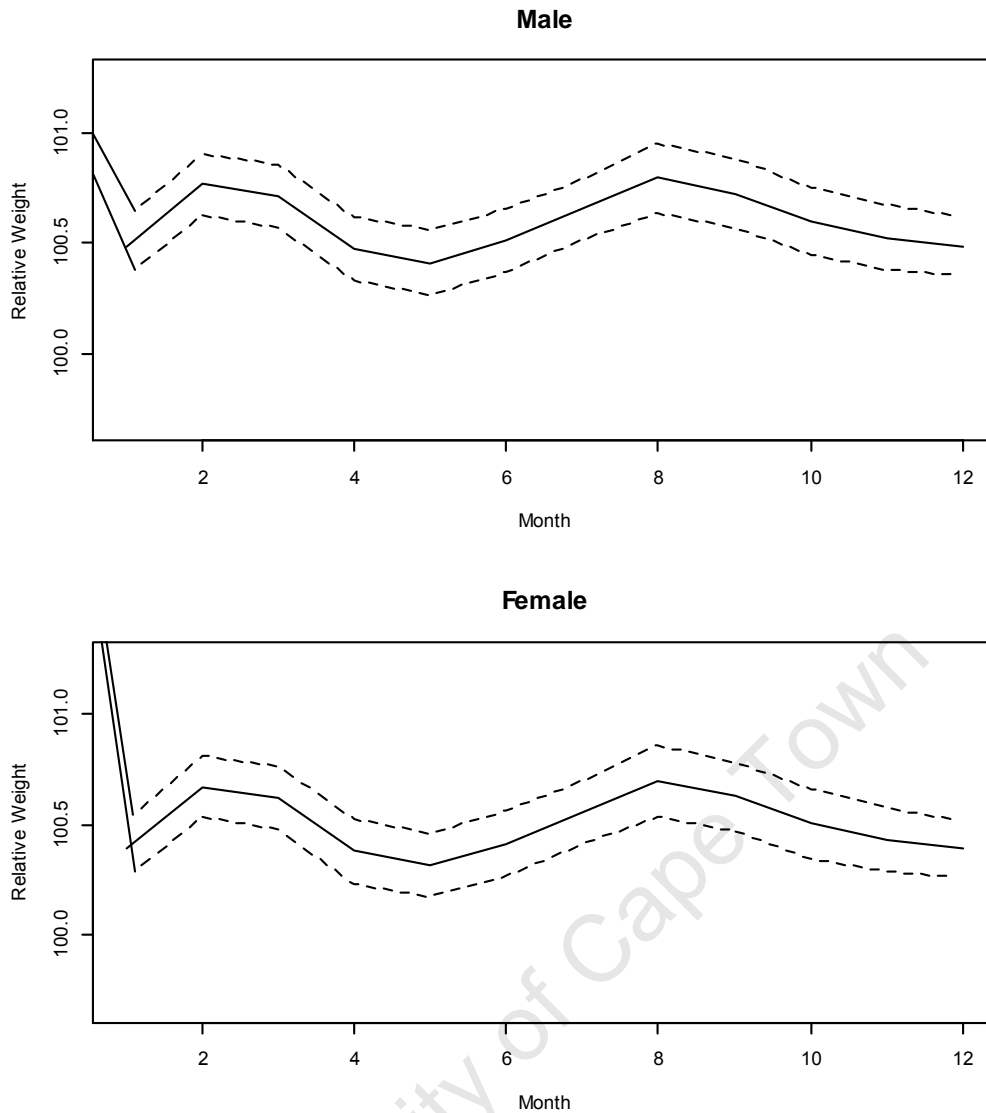


Fig. 14. Monthly mean relative weights ( $\pm$ se), corrected for the effect of year, for male and female yellowfin tuna in the Western Indian Ocean.

### *Environmental Data*

Two phases in SST anomalies occurred over the period 2002 to 2012 in the West Equatorial area of the Indian Ocean (Fig. 13A). There was a warmer period from 2002 to 2007 followed by a cooler period from 2008 to 2012. The peak in temperature that occurred in 2007 matched an El Nino/positive dipole event in the Indian Ocean). MLD anomalies during this period are characterized by a shoaling thermocline/shallower MLD (except for 2007 which experienced a deep thermocline). Maximum productivity was observed for 2003 and 2004 (+18.5% above the 2002 to 2012 mean) with a declining trend thereafter. The lowest productivity occurred in during 2009 to 2010 (-17%) and 2011 to 2013 (-23%).

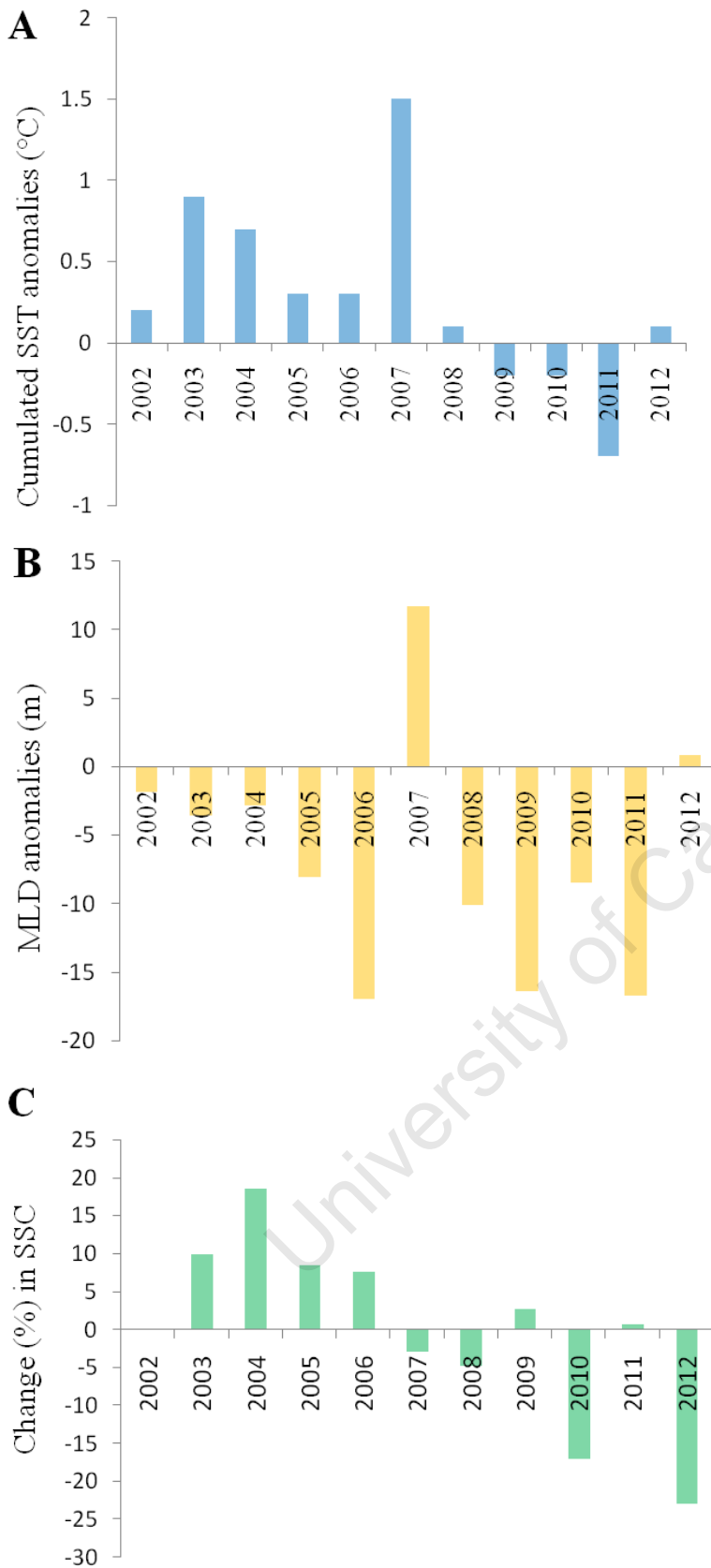


Fig.15. (A) SST (B) MLD and (C) SSC trends in the West Equatorial area of the Indian Ocean from the core north-west monsoon (December to February). SST is cumulated over the season and SSC is calculated as the change relative to the 2002-2012 seasonal average. Negative MLD anomalies correspond to a shallower thermocline (Graphs adapted from Marsac (2012)).

## Discussion

### *Establishment of the weight-length baseline*

The evaluation of environmental indicators requires the establishment of baselines in order to interpret and causally link ecological status to environmental variability (Niemeijer and de Groot, 2008; ICES, 2010). The  $W_s$  equation established in this study provides a benchmark from which changes such as resultant  $W_r$  of yellowfin tuna in the Indian Ocean can be interpreted. Analysis of the statistical properties of the observed and predicted length-weight residuals indicated no length-related bias. Results of the residual analyses imply that variability observed in  $W_r$  can be attributed to changes in biological and environmental conditions (Ndjaula et al. 2013).

The length-weight data used in the current study spanned a substantial time period (years from 1984 to 2013) in which numerous environmental phenomena were observed in the Indian Ocean (Nishida et al., 2005; Marsac, 2008; 2012). In addition, yellowfin tuna caught from both fish aggregating devices as well as free schools were included in the dataset. Therefore a range of length-weight scenarios can be assumed to have been included in the establishment of the standard weight baseline.

Length-weight data from 1991 was excluded during the dataset validation process. This is because sampling at the cannery (IOT Ltd.) was stopped in January of 1991 resulting in a paucity of data for this year, from only one month. The coefficient of determination ( $R^2$ ) criteria (Bister et al., 2000) was therefore appropriate for validating the length-weight datasets. The analysis of the length-weight relationships indicated that the median standard weight equation provided a good fit to all years, except 1986. Although an adequate number of fish were sampled for the year 1986, fish were only sampled from two months. This is a plausible explanation for the deviation from  $W_s$  as well as the large standard error around the mean  $W_r$  for this year.

Bias in the prediction of weights from the  $W_s$  equation will subsequently bias  $W_r$  estimates (Blackwell et al., 2000; Ndjaula et al., 2013). Therefore, assessing the precision of the  $W_s$  equation was fundamental to the interpretation of  $W_r$  variability. The standard weight equation developed in this study is compatible over a wide range of yellowfin tuna lengths. The bootstrap analysis conducted on the median standard weight equation indicated that the largest RMoE was observed for the smallest and largest fish in the dataset. Although

yellowfin tuna processed at the cannery (IOT Ltd.) have been frozen in brine (Marsac et al., 2006), the drying effect is considered minimal (Caveriviere, 1976; Bard, 1983) and accurate measurements are likely to offset potential freezing related weight bias (Marsac et al., 2006). Errors associated with small and large yellowfin tuna length classes can therefore be attributed to a paucity of fish in these length classes. For large yellowfin tuna, the likelihood of measurement errors when dealing with large fish may have contributed to the observed error.

RMoE over the length range was considered small (<3.5%) and because the residuals were normally distributed, alternative fitting methods were not necessary (Kimmerer et al., 2005; Robertis and Williams, 2008). An RMoE of <2% was considered acceptable (Ndjaula et al., 2013) when the EmP method was applied to another pelagic species, sardine (*Sardinops sagax*). Based on the RMoE plot, the appropriate length range for the application of the  $W_s$  baseline is suggested as 40 to 160cm FL for yellowfin tuna in the Western Indian Ocean.

A substantial number of studies have established length-weight relationships for yellowfin tuna in the Indian Ocean, from numerous sources of fisheries data and for different sectors of the Indian Ocean (Morita, 1973; Pillai et al., 1993; John, 1995; Dissanayake et al., 2008; Ghosh et al., 2012). These relationships are summarized by Somvanshi (2002). The  $W_s$  equation established in the current study incorporated substantially more fish than previous studies, over a larger time period but only incorporated purse seine caught yellowfin tuna. De Montaudoin et al. (1991) identified minor but significantly different parameters between male and female L-W relationships for yellowfin tuna in the Western Indian Ocean. However Marsac et al. (2006) pointed out that that sex cannot be identified externally and a composite curve is more appropriate for yellowfin tuna.

The L-W relationship (Marsac et al., 2006) currently adopted by the IOTC was the most pertinent to consider for this study. Marsac et al.'s (2006) L-W relationship was established using a non-linear power regression. The same yellowfin tuna length-weight data, from 1984 to 1991 (excluding 1985) and 2003 to 2006, were used in Marsac et al. (2006) and the current study. The Marsac et al. (2006) relationship consistently predicted higher weight at length with an increasing difference with length. This is related to the differences in the fundamental shape of the respective L-W relationship curves as described by Gerow et al. (2005). It is not in the scope of this study to evaluate the mathematical properties of the EmP method in

relation to the current yellowfin tuna relationship. However a larger scope of environmental variability and fishing pressures can be assumed to have been included in  $W_s$  compared to the current IOTC L-W relationship. For the purposes of evaluating  $W_r$  variability in relation to changes in environmental conditions and fishing pressure over time, the  $W_s$  equation was considered more appropriate as it incorporated substantially more fish, sampled over a longer time period compared to the current IOTC relationship.

### *Relative weight analysis and application to yellowfin tuna in the Indian Ocean*

The current study provided a novel approach for assessing yellowfin tuna body condition in the Western Indian Ocean in relation to fishing pressure and environmental variability over time. Yellowfin tuna condition were shown to significantly vary among years, months and between sexes. Time series of yellowfin tuna catch and CPUE reveal complex interactions among biological mechanisms, fishing strategies and environmental variability on different scales (Menard et al., 2007; Corbineau et al., 2008). Therefore yellowfin tuna body condition was hypothesized to reflect favourable environmental conditions and food availability.

The preliminary analysis of mean  $W_r$  values and the contributing data indicated that there were potential confounding effects between year, month and sex on the  $W_r$  estimates calculated in this study. Evaluation of the contributing data showed that there was unequal sampled representation from each year as well as between sexes. This necessitated the separation of the year, month and sex effects on  $W_r$  estimates. The standardized trends in annual and monthly mean  $W_r$  displayed a narrower range of  $W_r$  estimates, compared to the mean  $W_r$  values that were not standardized for the effects of year, month and sex. This further emphasized that interpretation of  $W_r$  values as above or below median condition should be approached with caution, and the standardized trends were used for interpretations of yellowfin tuna condition.

The main mechanism used to explain the very high catches of yellowfin tuna in the Indian Ocean for 2003 to 2006 (peaking at 523 745 t in 2004) was increased catchability caused by their aggregation across a reduced area and depth range (IOTC, 2012). It has been observed that, when food availability is scarce, tunas adopt a wandering strategy in small schools as opposed to large schools when food is abundant (Roger, 1994). Favourable oceanographic conditions resulted in large concentrations of suitable prey and, therefore, the aggregation of large yellowfin tuna shoals.

Favourable oceanographic conditions corresponded to a shallower mixed layer depth (MLD), increased biological enrichment (measured as increased SSC) and warmer sea surface temperatures (SST) (Marsac, 2008; 2012). Data and model results indicated that an increase in recruitment in preceding years was unlikely the cause of the high catches, but this has not been completely ruled out (IOTC, 2012).

The observed increase in food availability coincides with the above average condition observed in 2003 and 2004 but contradicts the below average condition observed for 2005 and 2006. The MLDs for 2005 and 2006 were shallower than those of 2003 and 2004, although the SST and SSC were slightly lower and therefore environmental conditions are considered to be similar among these years. Sample size is not a concern for 2005 and 2006 and standard error was relatively small, although only four months per year were sampled.

Yellowfin tuna catches in 2003 and 2004 exceeded all estimates of MSY (Pillai and Satheeshkumar, 2012) and might have altered population structure and consequently affected yellowfin tuna condition. However reductions in biomass should have resulted in higher food availability for remaining fish

Condition has been linked to growth rate, reproductive state and potential, recruitment biomass ratios, prey abundance, population density, stock structural indices and environmental variables (Guy and Willis, 1991; Liao et al., 1995; Marwitz and Hubert, 1997; Blackwell et al., 2000; Marshall, 2009). Therefore determining the exact cause of the low condition in 2005 and 2006 is a challenge as multiple factors may have affected condition. Yellowfin tuna catches in 2003 and 2004 exceeded all estimates of MSY (Pillai and Satheeshkumar, 2012) and might have altered population structure and consequently affected yellowfin tuna condition. However in terms of condition relating to prey abundance and population density, reduced biomass should have resulted in more food availability and increased condition.

The increasing trends in relative weights for the period of 2008 to 2013 correspond to cooler SST, lower SSC and shallower MLD (Marsac, 2012). SSC was consistently low over this period and food availability for large pelagic species like yellowfin tuna is assumed to have

been lower. If food availability is low, yellowfin tuna would have to expend more energy in search of prey (Golet et al., 2007), shift their diet to less energetic prey (the junk food hypothesis; Piatt and Anderson, 1996; Golet et al., 2002) or migrate to regions with greater food availability (Anderson and Piatt, 1999). These scenarios are expected to reduce yellowfin tuna condition. Catches of yellowfin tuna from 2008 to 2013 were lower than previous years and estimated total and spawning stock biomass declined, presumably a result of the high catches in 2003 to 2006.

Despite the reduced biological enrichment and potential impact of high catches from previous years, condition steadily increased. I suggest several mechanisms to explain the increasing trend in body condition from 2008 to 2013:

- In the case of a deepening thermocline and reduced biological productivity, foraging conditions are unfavourable for yellowfin. Forage disperses in deeper layers and subsequently tuna do not form free schools at the surface (Marsac 2008). This was the case during the 1997 – 1998 dipole event in which an eastward shift of the purse seine fishing grounds occurred. The period of 2008 to 2013 was characterized by shallower MLD. A shallower thermocline may have improved foraging conditions for species like yellowfin tuna by concentrating suitable prey near the surface. If this is the case, thermocline depth plays an integral role in the food availability to species like yellowfin tuna, despite low biological enrichment.
- High catches of 2003 to 2006, which reduced the stock biomass (Pillai and Satheeshkumar, 2012), may have reduced competition for food resources which would strongly suggest density dependence as an underlying mechanism for the increased condition.
- Reductions in fishing pressure over this period, from management regulations as well as the withdrawal of fishing fleets due to piracy has resulted in the Indian Ocean yellowfin tuna stock changing from a overfished status ( $F_{\text{year}} / F_{\text{MSY}} > 1$  and  $SB_{\text{year}} / SB_{\text{MSY}} < 1$ ) in 2008 to a status considered not over fished ( $F_{\text{year}} / F_{\text{MSY}} \leq 1$  and  $SB_{\text{year}} / SB_{\text{MSY}} \geq 1$ ) in 2012 (IOTC, 2012). Improvement in stock structural indices might explain the improving yellowfin tuna condition over this period.

Mean annual  $W_r$  for males and females (2003 to 2013) displayed the same trend in condition over time as the means plotted for all fish. Almost all fish sampled from 2003 to 2013 were sexed. Therefore the similarities between trends can be expected as approximately the same fish contributed to the calculation of the respective means.

The West Equatorial Indian Ocean is a major spawning ground for yellowfin tuna (Marsac, 2012) and spawning mainly occurs from December to March (IOTC 2012). Zhu et al. (2008) found that gonadosomatic index (GSI) for yellowfin tuna in the west-central Indian Ocean was significantly different between months. Monthly mean relative weight displayed comparable trends to the monthly GSI trends (Zhu et al., 2008) of yellowfin tuna. Body condition for yellowfin tuna is expected to resemble reproduction cycle, as is the case with bluefin tuna (*T. thynnus*; Golet et al., 2007). In the case of bluefin tuna, feeding periods are presumed to put individuals into a positive lipid balance, and create energy stores for gonadal development and metabolism (Medina et al., 2002; Carruthers et al., 2005; Golet et al., 2007) and corresponded to increased condition. The significant differences in male and female yellowfin monthly condition can be attributed to differential investment in reproduction (Zhu et al., 2008). Therefore the monthly condition observed for males and females corresponds to current understanding of yellowfin tuna reproduction in the Indian Ocean.

This study observed increased variance in the  $W_r$  estimates of smaller yellowfin tuna. Graham et al. (2007) found that juvenile yellowfin tuna in Hawaii exhibit a rapid ontogenetic shift in diet. Yellowfin tuna significantly changed their diet between 45 and 50 cm forklength (ca. 1.5kg). Fish of smaller length classes fed predominantly on planktonic organisms and it is suggested that at a threshold of 45cm FL, yellowfin tuna have the endothermic capacity to access deeper dwelling prey, in colder water. Therefore larger yellowfin tuna are able to opportunistically feed on a wider range of prey species and are less susceptible to fluctuations in food availability, compared to juvenile yellowfin tuna. This is a plausible explanation for higher variability in  $W_r$  estimates for smaller fish. Murphy et al. (1991) suggested that  $W_s$  equation should be established for juvenile fish, which would allow for more robust hypothesis testing, compared to the current study, of juvenile yellowfin tuna body condition.

Two condition indices have been applied to tuna in the Indian Ocean in previous studies. Plumpness, measured through the thorax girth, and bioelectrical impedance (called

Bioelectrical Impedance Analysis –BIA) were applied to skipjack tuna (*Katsuwonus pelamis*) in the Indian Ocean to assess the difference in condition between tuna caught off fish aggregating devices (FAD) and free schools of tuna. Plumpness is analysed by developing a relationship (assumed to be linear) between the response variable thorax girth (TG) and the predictor variable fork length (FL) (Hallier and Gaertner, 2008; Robert et al., 2010). Deviations from this relationship are interpreted as an indicator of fish well-being or condition. BIA involves the passing of an alternating electrical current at high frequency (50 kHz) and low intensity (800  $\mu$ A) through an organism. BIA analysis assesses the changes in cell membrane integrity which relate to the nutritional state of an organism (Wirth and Miklis, 2005; Robert et al., 2010).

The study by Robert et al. (2010) highlighted several important issues surrounding tuna condition studies, which the  $W_r$  index overcomes. There is a need for better understanding in the thorax girth and BIA condition indices in terms of what they represent. It is pointed out that reference points are limited in the literature for those particular indices and therefore further comparisons across a temporal and spatial scale are restricted. This emphasizes the need for baselines when using environmental indicators to assess changes in ecological and environmental conditions. In the case of the  $W_r$  index, the standard weight equation incorporated fish from a large temporal scale. It was assumed to have included all possible condition variability experienced from fluctuations in ecological and environmental conditions. Therefore the  $W_s$  baseline is applicable to a range of condition studies such as temporal and spatial studies of yellowfin tuna condition or FAD-free school studies such as Robert et al. (2010).

Robert et al. (2010) highlighted the usefulness of chemical testing of fat content in white muscle tissue of tuna to establish the time evolution of condition when the quality or quantity of diet changes. This point is pertinent to this study as well as there is a need to understand how condition varies over time after ecological or environmental changes occur. This emphasizes the need for caution when interpreting  $W_r$  values across time as the condition in one year may represent a lag from ecological and environmental variability experienced previously.

Relative weight target ranges (95 to 105) have been suggested in previous studies on other fish species. However Willis et al. (1991) reinforced the idea that universal target ranges are

inappropriate in most situations. Therefore expectations of  $W_r$  values should be related to the specific management objective being pursued, with seasonal variation in condition considered (Blackwell et al., 2000).

Current recruitment is considered lower than average (Pillai and Satheeshkumar, 2012) and the Working Party for Tropical Tuna (WPTT) has expressed uncertainty surrounding recruitment models and regional recruitment estimates. Marshall et al. (2006, 2009) propose that the condition index be used as a proxy of stock bioenergetics status in the context of management decisions as it may improve stock-recruitment relationships. This is particularly pertinent to the current management needs of the IOTC and emphasizes the importance of assessing yellowfin tuna body condition in the Indian Ocean.

Ndjaula et al. (2013) conducted a  $W_r$  analysis on a small pelagic species in the Southern Benguela ecosystem, sardine (*Sardinops sagax*), and observed a large range in  $W_r$  values of 50 to 150 for individual fish. In comparison, the range of  $W_r$  values found for yellowfin tuna in the Western Indian Ocean are substantially narrower. There is uncertainty surrounding the inter-species comparability of  $W_r$  values (Cade et al., 2008; Gerow 2010).  $W_r$  analyses should be conducted on yellowfin stocks in the Atlantic and Pacific Oceans, as well as in other regions of the Indian Ocean, to determine an appropriate target range for yellowfin tuna. In addition,  $W_r$  analyses of other tropical tuna species, such as skipjack and bigeye tuna, may provide insight into target ranges of  $W_r$  values for yellowfin tuna in the Indian Ocean.

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This study presented a novel approach to assessing yellowfin tuna body condition in the Western Indian Ocean. The significant variation in condition among years provided insight into current mechanisms used to explain variation in the tuna fishery, as well as identified new potential underlying mechanisms. The ability to link variability in the tuna fishery to

environmental variability and fishing pressure is fundamental to management decisions with condition providing an integrated response of biological information.

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