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Diet of young southern bluefin tuna *Thunnus maccoyii* in the southwestern coastal waters of Australia in summer

オーストラリア南西沿岸海域における夏季のミナミマグロ *Thunnus maccoyii* 若齢魚の食性

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要約

豪州南西沿岸のミナミマグロ 1 歳魚（N=720）の胃内容物は魚類がほとんど（97.4 %容積）を占めた。マイワシ、ゴマサバ、マアジが主要な餌であり、マイワシは沿岸でのマアジは陸棚斜面付近での魚から多く出現した。エサの体長は 5 - 240 mm で 67%の個体は 30 － 50 mm の範囲であった。マイワシは大型餌の多く（130 － 190 mm の 84%）を占めたが、餌としての重要性は過去の報告より低かった。環境変動とミナミマグロ分布を関連付けるこれら主要エサ種の若齢期の分布を調査すべきである。

Summary

The diet of juvenile (predominantly age 1) southern bluefin tuna *Thunnus maccoyii* (SBT, N = 720), caught over 11 years of the recruitment monitoring survey off southern Western Australia during summer, consisted overwhelmingly of teleosts (97.4% by volume). Pilchard *Sardinops sagax* (27.4%V), blue mackerel *Scomber australasicus* (16.7%V), and jack mackerel *Trachurus declivis* (14.2%V) were the major taxa, with pilchard more abundant in coastal waters and jack mackerel more frequently encountered in fish caught closer to the shelf-edge. Prey size varied from 5 to 240 mm, with 67% of ingested items measuring between 30 and 50 mm. Pilchard dominated the prey size category 130–190 mm (84% by number), but the overall contribution of this species to the diet of juvenile SBT was much lower than previously reported. Future research in relation to the feeding ecology of juvenile SBT should focus on the biology and ecology of the young lifestages of the main prey species in this area and on prey distribution and dynamics as a key factor linking environmental change and SBT distribution.

We show the results of analysis for diet of young southern bluefin tuna *Thunnus maccoyii* in the southwestern coastal waters of Australia in summer based on the manuscript published in Fisheries Science (Vol. 73, pp337-344.) in 2011.

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Introduction

Southern bluefin tuna *Thunnus maccoyii* (SBT) has a broad distribution within waters of the Southern Hemisphere, where it is an important target species for various international fisheries, including the Japanese longline fishery and the Australian tuna farm fishery. Spawning takes place in the Indian Ocean, southeast of Java, Indonesia, after which juvenile SBT migrate south down the west coast of Australia [1]. Fish at age 1, around 50 cm in fork length (FL), are predominantly distributed in southwestern Australian coastal waters between October and March, while fish at age 2–5 migrate seasonally between southern Australian inshore waters and offshore regions [2–4]. After age 5, the SBT distribution extends over the southern circumpolar area throughout the Pacific, Indian, and Atlantic Oceans.

A collaboration between scientific institutions of several member countries of the Commission for the Conservation of Southern Bluefin Tuna (CCSBT), which is the Regional Fisheries Management Organization responsible for managing this species, resulted in the SBT Recruitment Monitoring Program that continues to provide crucial information for stock assessment. One of the projects, i.e., a line transect survey initiated and carried out by Japan since 1989, has focused on monitoring trends in the abundance of age-1 SBT off southern Western Australia by collecting sonar and trolling data during summer.

To evaluate survey design, various important parameters were independently investigated, including the distribution and behavior of age-1 individuals in the waters off Western

Australia [5–7]. These studies suggested the existence of two distinct distribution patterns of SBT in the area and, additionally, found evidence that changes in oceanographic structure affect residency and movement of SBT. They also stated the importance of understanding prey distribution and dynamics as a likely key factor linking oceanographic structure and SBT distribution.

This study is based on stomach contents analysis of SBT caught in the southwestern coastal waters of Australia during the recruitment monitoring survey and aims to provide an overview of the diet of juvenile SBT in the area and to identify key prey taxa and key geographical areas.

Materials and methods

Stomachs were collected from SBT captured by trolling in and in transit to and from the recruitment monitoring survey from December to March in each of the years 1997–2003 and 2007–2010 (Table 1). All samples were collected off southern Western Australia between 117°E and 125°E ($N = 720$) (Fig. 1).

Table 1 Number of *Thunnus maccoyii* stomachs analyzed by survey (summarized for each Australian summer period)

Survey	December (py)	January	February	March	Total
1997		3	41		44
1998		24	64		88
1999		38	139	17	194
2000		10	28	6	44
2001		26	108	41	175
2002		1	13		14
2003	28	30			58
2007		37			37
2008		14			14
2009	2	8			10
2010		36	6		42
Total	227	399	64	30	720

py previous year

Time of catch and position were recorded, and each fish was measured for fork length to the nearest 1 cm and weighed to the nearest 0.1 kg. Stomachs were immediately removed and frozen.

In the laboratory, stomachs were thawed and opened. Prey items were identified to the lowest possible taxon, counted, measured in terms of volume, measured for total length (if possible), and assigned a state of digestion according to five categories (1 = fresh and body intact, 3 = half digested with parts of body missing, 5 = digested with only some hard parts remaining).

The proportion of each prey taxa was expressed in three ways: percentage of total number of prey (%*N*), percentage of total volume (%*V*), and percentage frequency of occurrence (%*O*). The relationship between SBT fork length and prey size was investigated using the Kruskal–Wallis rank-sum test carried out using R version 2-8-1 software (R Development Core Team 2008).

Results

Outline of SBT samples

SBT individuals measured 33–86 cm FL (mean 53.1 cm) (Fig. 2). Most fish measured around 50 cm FL and were assigned to age 1, with a small proportion of fish over 70 cm FL assigned to age 2 [3]. Figure 1 depicts the catch locations of all sampled SBT for each year. In the survey area, the continental shelf is typically found at a depth of 40–100 m and extends 30–80 km out from the coast, at which point the seabed sharply drops away from 200 m to more than 500 m

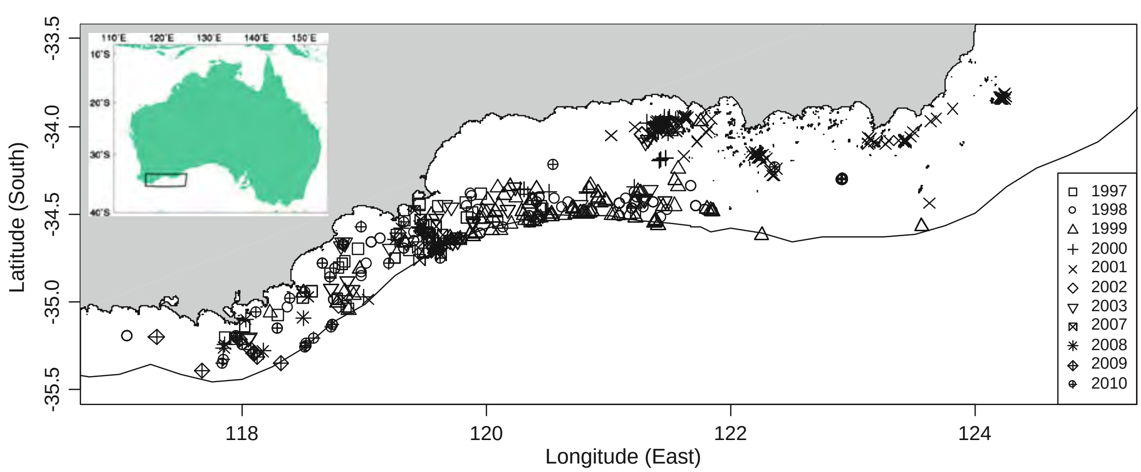


Fig. 1 Locations of catch of *Thunnus maccoyii* whose stomach contents was analyzed, by survey year. Year *y* includes December of $y - 1$. *Solid line* is the 200 m isobath

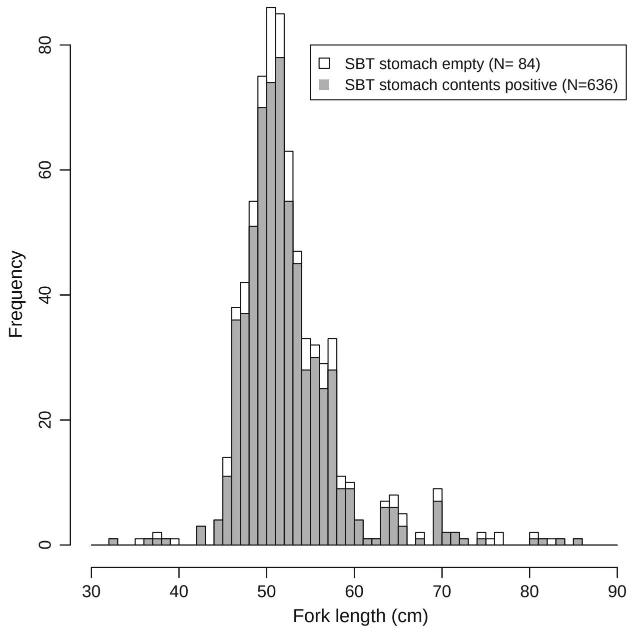


Fig. 2 Fork length frequency of *Thunnus maccoyii* whose stomach contents was analyzed

depth within ca. 4 km. SBT were almost exclusively caught in the area between the coast and the shelf-edge, with very few caught beyond the edge throughout the entire duration of the survey period. The majority of samples were collected within the boundaries of the line transect survey (118.6–121.5°E, south of 34.4°S), with a smaller proportion of samples caught opportunistically outside the line transect survey area during the normal survey period.

Prey composition

Prey taxa were encountered in 636 out of 720 stomachs and consisted overwhelmingly of teleosts (92.8%*N*, 97.4%*V*), with crustaceans (6.5%*N*, 0.5%*V*) and cephalopods (0.7%*N*, 2.1%*V*) constituting a very small proportion of the diet of juvenile SBT (Table 2). At a lower taxonomic level, the major prey taxa ($\%V > 5\%$) were represented by: Clupeidae (18.1%*N*, 22.2%*O*, 31.4%*V*) including pilchard *Sardinops sagax* (9.9%*N*, 18.1%*O*, 27.4%*V*) and anchovy *Engraulis australis* (8.4%*N*, 10.6%*O*, 8.2%*V*), Scombridae as represented by blue mackerel *Scomber australasicus* (21.5%*N*, 30.0%*O*, 16.7%*V*), and Carangidae as represented by jack mackerel *Trachurus declivis* (3.7%*N*, 13.3%*O*, 14.2%*V*). (Note that all individuals belonging to the genera *Sardinops*, *Trachurus*, and *Scomber* identified down to species level were consistently identified as the three species mentioned, after which all individuals identified down to the same genera were deemed to represent that species.)

There was considerable interannual variation in the occurrence of all major prey taxa (Table 3). Pilchard, blue mackerel, and jack mackerel were encountered during most years, whereas anchovy, in contrast, was of importance in only a few years, including 2001, when anchovy and pilchard were both major prey taxa. Note that during the survey of 2001 the majority of SBT were caught in coastal waters east of 121°E, considerably further inshore than the line transect survey area (Fig. 1).

A preliminary map analysis of prey occurrence suggested concentrated occurrence of blue mackerel and jack mackerel near the shelf-edge. When SBT samples were divided into groups on the basis of catch location in relation to the shelf-edge (as represented by the 200 m isobath) in 5 km blocks, the results suggested a difference in prey composition between the area within 20 km from the shelf-edge and the coastal area further inshore (Fig. 3). In general terms, it appeared that the main occurrence of pilchard was in coastal waters while that of jack mackerel was closer to the shelf-edge. Blue mackerel was encountered in both areas, but perhaps more prevalent further offshore.

Prey size

Prey species were often represented by numerous individuals within the same stomach. Where individuals of the same prey species were of similar size, in the same digested state, and encountered within the same stomach they were deemed to form a prey group. After selecting and measuring several representative individuals, all individuals of the prey group were then assigned the same total length as the representative individuals selected from the group to be measured. The total body lengths of a total of 10,336 prey items (87% of all prey) from 1,098 prey groups were recorded. Prey length varied in size from 5 to 240 mm, ranging from 30 to 50 mm for 67% of all ingested individuals (Fig. 4). Among 30 taxa found in stomachs, 30 were present in the <70 mm category. Only 11 taxa, including a few key species such as pilchard, anchovy, blue mackerel, and jack mackerel, were additionally present in size categories >70 mm. Importantly, pilchard formed 84% of prey individuals ranging in length from 130 to 190 mm.

The prey size range varied widely in relation to SBT fork length and was notably broad for SBT between 45 and 60 cm fork length (Fig. 5). The prey size range for SBT with >60 cm FL was much smaller, most likely due to the small sample size for SBT of this size. The majority of anomalously large prey was formed by pilchard (Fig. 4). Prey size did not differ with SBT size, so that there was no significant relationship between SBT fork length and prey body length (median by SBT fork length in 1-cm bins) (Kruskal–Wallis rank-sum test, $\chi^2 = 26.65$, $df = 19$, $p = 0.1132$).

Table 2 Prey items identified from stomach contents of *Thunnus maccoyii* with proportions presented by number (%*N*), occurrence (%*O*), and volume (%*V*)

Class order	Family	Species	Other	%*N*	%*O*	%*V*
Teleostei						
Clupeiformes	Clupeidae	*Sardinops sagax*		9.90	18.14	27.39
Clupeiformes	Clupeidae	*Spratelloides robustus*		7.82	3.15	3.02
Clupeiformes	Clupeidae			0.42	0.95	0.95
Clupeiformes	Engraulididae	*Engraulis australis*		8.37	10.57	8.16
Clupeiformes				0.03	0.32	0.38
Gonorynchiformes	Gonorynchidae	*Gonorynchus greyi*		1.31	7.73	1.30
Myctophiformes	Myctophidae			1.21	1.89	0.26
Beloniformes	Scomberesocidae	*Scomberesox saurus*		0.06	0.47	0.51
Beloniformes	Hemiramphidae	*Hyporhamphus melanochir*		0.01	0.16	0.01
Syngnathiformes	Centriscidae	*Macroramphosus scolopax*		0.05	0.79	0.04
Syngnathiformes	Syngnathidae			0.01	0.16	0.01
Zeiformes	Caproidae	*Antigonia rhomboidea*		0.01	0.16	0.01
Zeiformes	Zeidae			0.01	0.16	0.01
Perciformes	Carangidae	*Pseudocaranx dentex*		4.80	18.14	4.20
Perciformes	Carangidae	*Trachurus declivis*		3.65	13.25	14.22
Perciformes	Carangidae			3.24	7.10	0.60
Perciformes	Gerreidae	*Parequula melbournensis*		0.02	0.47	0.02
Perciformes	Mullidae	*Upeneichthys stotti*		3.98	4.89	1.90
Perciformes	Pentacerotidae	*Paristiopterus gallipavo*		0.02	0.16	0.10
Perciformes	Arripidae	*Arripis georgianus*		4.30	9.78	3.36
Perciformes	Cheilodactylidae	*Nemadactylus macropterus*		0.01	0.16	0.10
Perciformes	Scaridae			0.02	0.16	0.36
Perciformes	Scombridae	*Scomber australasicus*		21.48	29.97	16.67
Perciformes	Scombridae	*Scomber* sp.		0.29	1.10	0.27
Perciformes	Gempylidae	*Thyrsites atun*		0.18	0.63	2.07
Scorpaeniformes	Scorpaenidae	*Helicolenus percoides*		0.20	0.63	0.07
Tetradontiformes	Monacanthidae	*Meuschenia scaber*		1.28	2.52	0.74
Tetradontiformes	Monacanthidae	*Nelusetta ayraud*		0.19	0.47	0.20
Tetradontiformes	Monacanthidae			0.58	3.63	0.20
Tetradontiformes	Ostraciidae			0.01	0.16	0.00
Tetradontiformes	Diodontidae	*Allomycterus pilatus*		0.02	0.32	0.02
Unidentified				19.36	55.21	10.24
Crustacea						
Isopoda	Cirolanidae	*Cirolana* sp.		0.03	0.47	0.01
Isopoda				0.02	0.47	0.01
Tenaidacea				0.01	0.16	0.00
Amphipoda	Phronimidae			0.02	0.47	0.00
Amphipoda				0.27	1.10	0.01
Euphausiacea				3.32	0.79	0.00
Decapoda	Penaeidae			0.45	1.26	0.10
Decapoda	Scyllaridae			0.07	0.79	0.04
Decapoda	Scyllaridae			0.49	0.63	0.02
Decapoda			Brachyura	0.20	2.05	0.07
Decapoda			Brachyura, megalops	0.75	0.63	0.01
Decapoda				0.07	0.63	0.01
Stomatopoda			Pseudozoea	0.80	2.21	0.18
Unidentified				0.01	0.16	0.00

Table 2 continued

Class order	Family	Species	Other	%N	%O	%V
Cephalopoda						
Teuthida				0.58	6.31	2.12
Octopoda				0.02	0.32	0.01
Unidentified				0.06	0.79	0.00
Gastropoda						
Mesogastropoda				0.01	0.16	0.01
Total				12,196	636	9,637

Totals denote total number of prey, total number of not-empty *Thunnus maccoii* stomachs, and total volume of prey, respectively

Table 3 Frequency of occurrence (*%O*) of main prey species in stomach contents of *Thunnus maccoyii* by survey year

Survey	Pilchard (%)	Anchovy (%)	Blue mackerel (%)	Jack mackerel[a] (%)	Other (%)	Total SBT sample size
1997	23	0	26	23	86	43
1998	7	13	26	58	72	76
1999	1	0	60	43	90	177
2000	2	10	40	5	81	42
2001	46	37	15	4	85	142
2002	0	0	20	0	100	10
2003	4	0	24	40	91	45
2007	8	0	0	73	89	37
2008	58	0	0	25	42	12
2009	30	0	0	10	70	10
2010	29	2	14	45	79	42

[a] Jack mackerel in 2007–2009 includes *Pseudocaranx* sp.

Discussion

Previous studies of SBT stomach contents have indicated the diet of fish aged 3 and older to consist predominantly of cephalopods and teleosts in roughly equal measure in some areas ([8], Itoh T, unpublished data, 2009) and predominantly of amphipods in others [9], while the diet of younger fish caught in Australian coastal waters, in contrast, has been shown to comprise almost exclusively teleosts [2, 8, 10]. The present study of young (mainly age 1) SBT found in coastal waters of southern Western Australia supports these previous results.

However, Serventy [2], describing the stomach contents of an unknown number of age-1 SBT caught most probably also during summer and in the same region as the present study, reported their diet to consist "overwhelmingly" of pilchard, which is in contrast with the results presented here. Ward et al. [10], describing the diet of age 2–3 SBT caught in the Great Australian Bight in summer, also showed pilchard to be the dominant prey species and responsible for 50% of total weight. In other areas and for other age groups, such as off Australia's west coast for age 0–1 fish—as noted by Serventy [2]—and off the Tasmanian coast for age-3 fish—as described by Young et al. [8], the diet of juvenile SBT was notably more varied.

The hypothesis that pilchard is of unrivalled importance to migrating age-1 SBT off southern Western Australia, as suggested by the results of Serventy [2], could not be supported by the results obtained here. As the author did not provide information on the catch locations (or the number of samples), it cannot be ruled out that his samples may have been representative of an area where pilchard were especially abundant. Pilchard are known to form seasonal spawning aggregations in this region and tend to be more abundant in the coastal half of the continental shelf, which was loosely supported by our finding that pilchard occurred more frequently in the diet of fish caught closer to the coast [11–13]. If Serventy [2] was describing the diet of fish predominantly caught inshore, such as around some of the inshore sea mounts where SBT are known to aggregate [14] and which have been popular fishing grounds for decades, then it is likely that the importance of pilchard was overestimated (and that of jack mackerel and blue mackerel underestimated), given that the distribution of age-1 SBT in this region spans the entire continental shelf.

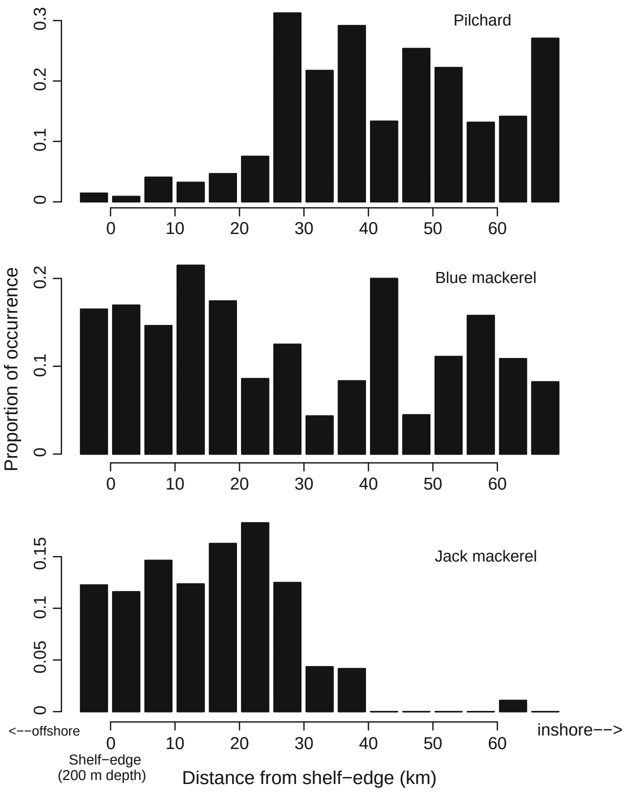
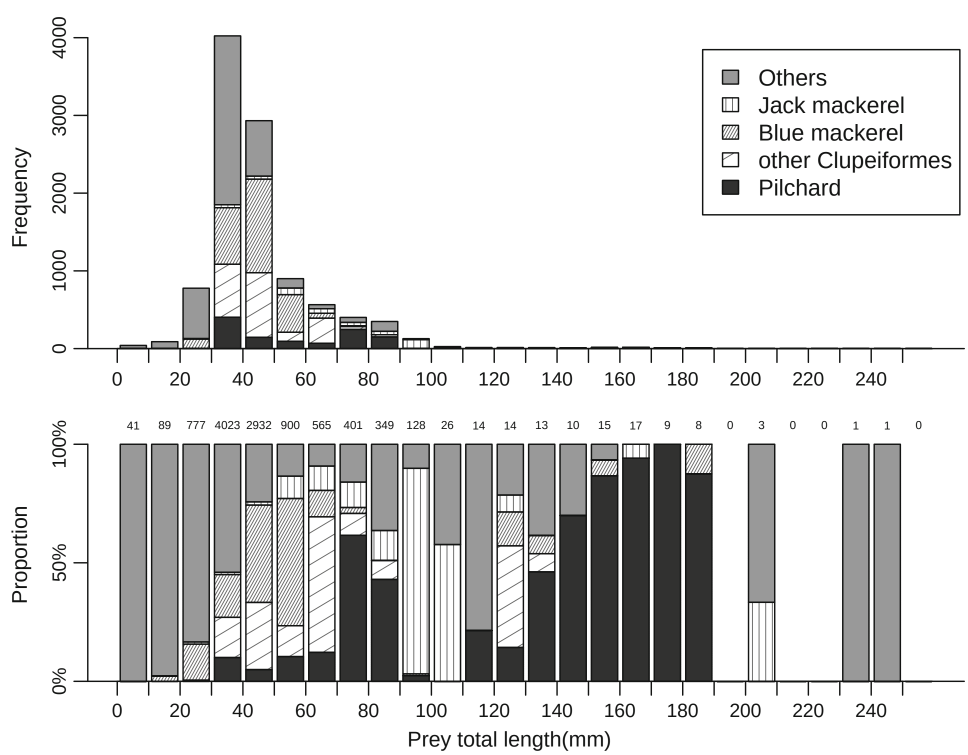


Fig. 3 Proportion of *Thunnus maccoyii* with pilchard *Sardinops sagax* (*top panel*), blue mackerel *Scomber australasicus* (*middle panel*), and jack mackerel *Trachurus declivis* (*bottom panel*) found in the stomach, by distance from shelf-edge (every 5 km, toward coast is positive value)

The above notwithstanding, two noteworthy observations suggest that it may be too early to downplay the importance of pilchard to the diet of migrating age-1 SBT in this area. The result that pilchard strongly dominated the prey size range 130–190 mm indicates that this species is available to SBT at this size, whereas other major prey species such as jack mackerel, anchovy, and blue mackerel may not be, due to a difference in habitat and/or escape capacity. A second point to be considered is the fact that pilchard abundance in the region is known to have varied greatly over the past few decades. While the state of the local stock in the 1950s is unclear, the commercial catch off southern Western Australia reduced from as much as 8,000 tons in the early 1990s to less than 1,000 tons due to two epidemic mass mortalities during 1995 and 1998–1999 [12]. Since then the stock is thought to have recovered, with a recent commercial catch close to 2,000 tons [13]. While it is likely that one or more other species would have increased in biomass in response to the decreased abundance of pilchard during the years when the stock was most affected, it is unclear whether these species are as available to SBT, or as nutritious, as pilchard. Obviously, if pilchard is of major dietary importance in this area, which cannot be confirmed or ruled out by this study, it is plausible that a decrease in abundance in pilchard would affect SBT behavior and/or fitness.

The results of this study demonstrate distinct interannual variation in the diet of young SBT, probably due to a combination of factors that include small sample sizes for

Fig. 4 Frequency of prey size and composition for prey items of *Thunnus maccoyii* in number by length. The number of prey by length is shown *above the lower panel*



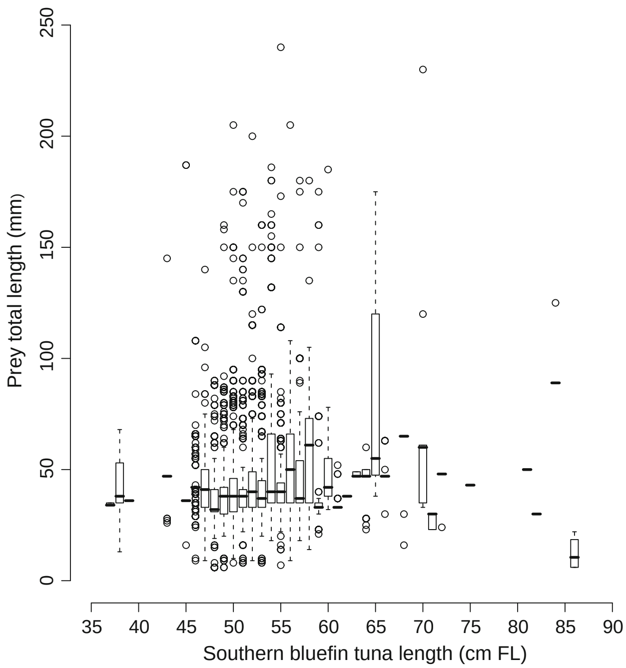


Fig. 5 Box plot of prey length found in stomach versus fork length of *Thunnus maccoyii*. The *line in the box* indicates the median value of the data. The *upper* and *lower edge* of the *box* indicate the 75th and 25th percentiles, respectively. The *whiskers* extend to 1.5 times the interquartile range. The *points* outside the ends of the whiskers are outliers

some years and changes in the distribution of SBT as well as naturally occurring fluctuations in prey species abundance and distribution caused by the strong interannual variation in oceanographic conditions and productivity in this region [6]. During the surveys of 2000, 2001, and 2002—at the same time that the pilchard populations of Albany, Bremer Bay, and Esperance were severely reduced and distribution was possibly contracting around estuaries—very few SBT were caught in the line transect survey area, which led to opportunistic sampling in coastal waters east of 121°E, where little sampling was conducted in other years. Whether this was a response of SBT to a reduction in pilchard abundance further from the coast is unclear. The interannual variation in the diet of SBT requires further work to be properly understood, which should include sampling from coastal and open shelf waters.

The results indicate that young (mainly age 1) SBT rely to varying degrees on young lifestages of a number of teleosts as well as adult pilchard. One main area of future research in relation to the feeding ecology of age-1 SBT should therefore focus on the biology and ecology of these prey species (e.g., pilchard, jack mackerel, blue mackerel, and Australian anchovy) and, in particular, on their early lifestages. Equally important will be to further investigate the link between oceanographic condition and SBT distribution as demonstrated by Fujioka et al. [6], and in particular, prey distribution and dynamics as a key factor linking environmental change and SBT distribution.

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