

THE ECOLOGY AND BIOLOGY OF WOBBERGONG SHARKS
(GENUS *ORECTOLOBUS*) IN RELATION TO THE
COMMERCIAL FISHERY IN NEW SOUTH WALES,
AUSTRALIA



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Table of Contents

Table of Contents.....	3
List of Figures	9
List of Tables	13
Summary	17
Declaration.....	21
Acknowledgements.....	23
Chapter acknowledgments.....	27
Dedication.....	29
CHAPTER 1 : General Introduction.....	31
1.1 Shark fisheries and life history characteristics	32
1.2 Wobbegongs (family: Orectolobidae)	35
CHAPTER 2 : Redescription of Two Species of Wobbegongs (Chondrichthyes: Orectolobidae) with Elevation of <i>Orectolobus halei</i> Whitley 1940 to Species Level.....	39
2.1 Abstract.....	40
2.2 Introduction.....	40
2.3 Materials and methods	43
2.4 Results.....	46
<i>Orectolobus halei</i> Whitley, 1940.....	46
<i>Orectolobus ornatus</i> De Vis, 1883	60
2.5 Discussion.....	68
2.6 Key to <i>Orectolobus</i> species in New South Wales	70

CHAPTER 3 : Using Recreational Scuba-divers to Survey the Relative Abundance and Distribution of Wobbegong Sharks (Family: Orectolobidae) in New South Wales, Australia

.....	71
3.1 Abstract.....	72
3.2 Introduction.....	72
3.3 Materials and methods	74
3.3.1 Survey description	74
3.3.2 Analysis and statistical methods	76
3.4 Results.....	77
3.4 Discussion.....	86
3.4.1 Wobbegong relative abundance and distribution.....	86
3.4.2 The use of recreational scuba-divers as volunteers	89

CHAPTER 4 : Observations of Localised Movements and Residence Time of Wobbegong Sharks (*Orectolobus halei*) at Fish Rock, New South Wales, Australia

.....	93
4.1 Abstract.....	94
4.2 Introduction.....	94
4.3 Methods	97
4.3.1 Study site.....	97
4.3.2 Tags, receivers and tagging	99
4.3.3 Analysis	100
4.4 Results.....	101
4.5 Discussion.....	111

CHAPTER 5 : Length-frequency Distribution, Length–Length, Mass–Mass and Mass–Length Relationships of Wobbegong Sharks (Genus <i>Orectolobus</i>) Commercially Fished in New South Wales, Australia.....	117
5.1 Abstract.....	118
5.2 Introduction.....	118
5.3 Materials and methods	119
5.4 Results.....	122
5.5 Discussion.....	126
CHAPTER 6 : Quantitative Diet Assessment of Wobbegong Sharks (Genus <i>Orectolobus</i>) in New South Wales, Australia.....	131
6.1 Abstract.....	132
6.2 Introduction.....	132
6.3 Materials and methods	134
6.3.1 Collection of specimens and stomach processing.....	134
6.3.2 Analysis	135
6.4 Results.....	137
6.4.1 Cumulative diversity.....	138
6.4.2 Quantitative description of wobbegong diets	142
6.4.2.1 <i>Orectolobus ornatus</i> (Table 6.2, Fig. 6.3a).....	142
6.4.2.2 <i>Orectolobus maculatus</i> (Table 6.3, Fig. 6.3b)	144
6.4.2.3 <i>Orectolobus halei</i> (Table 6.4, Fig. 6.3c).....	147
6.4.3 Species, sex and size comparison	152
6.4.4 Trophic level of wobbegongs	153
6.5 Discussion.....	153

CHAPTER 7 : Reproductive Synchrony of Three Sympatric Species of Wobbegong Shark (Genus <i>Orectolobus</i>) in New South Wales, Australia	161
7.1 Abstract.....	162
7.2 Introduction.....	162
7.3 Materials and methods	164
7.3.1 Collection of specimens and biological sampling	164
7.3.2 Male reproduction.....	170
7.3.2.1 Maturity ogive.....	170
7.3.2.2 Reproductive cycle of males.....	170
7.3.3 Female reproduction	171
7.3.3.1 Maturity and maternity ogives	171
7.3.3.2 Ovarian cycle	171
7.3.3.3 Period of gestation and embryonic growth	172
7.3.3.4 Sex ratio of embryos and distribution of <i>in utero</i> eggs and embryos.....	172
7.3.3.5 Litter size–maternal length relationship	172
7.4 Results.....	173
7.4.1 Male reproduction.....	175
7.4.1.1 Maturity ogives	175
7.4.1.2 Reproductive cycle of males.....	178
7.4.2 Female reproduction	180
7.4.2.1 Maturity and maternity ogives	180
7.4.2.2 Ovarian cycle	182
7.4.2.3 Period of gestation and embryonic growth	190
7.4.2.4 Sex ratio of embryos and distribution of <i>in utero</i> eggs and embryos.....	192

7.4.2.5 Litter size–maternal length relationship	193
7.5 Discussion.....	196
7.5.1 Maturity and maternity ogives.....	196
7.5.2 Mating period.....	197
7.5.3 Ovulation season.....	198
7.5.4 Ovarian cycle	199
7.5.5 Geographically-dependent reproductive behaviour.....	202
7.5.6 Embryonic development	203
7.5.7 Litter size–maternal length relationship	204
7.6 Conclusion	206
CHAPTER 8 : Age and Growth of Wobbegong Sharks (Genus <i>Orectolobus</i>) in New South Wales, Australia.....	207
8.1 Introduction.....	208
8.2 Materials and methods	210
8.2.1 Collection of samples.....	210
8.2.2 Vertebral preparation	211
8.2.3 Reading of growth bands	212
8.2.4 Precision and accuracy.....	216
8.2.5 Models	216
8.2.6 Validation and verification	222
8.2.6.1 Edge and marginal increment analyses.....	222
8.2.6.2 Growth rate of captive wobbegongs	222
8.2.6.3 Chemical marking of captive wobbegongs.....	223
8.3 Results.....	223

8.3.1 Collection of samples.....	223
8.3.2 Precision and accuracy.....	228
8.3.3 Models	230
8.3.4 Validation and verification	237
8.3.4.1 Edge and marginal increment analyses.....	237
8.3.4.2 Growth rate of captive wobbegongs	239
8.3.4.3 Chemical marking of captive wobbegongs.....	242
8.4 Discussion.....	245
CHAPTER 9 : General Discussion.....	251
9.1 Taxonomy uncertainties and redescription.....	253
9.2 Distribution and morphological relationships of wobbegongs	254
9.3 Localised movements and residence time of wobbegongs	256
9.4 Diet and feeding ecology of wobbegongs.....	257
9.5 Reproductive characteristics and growth parameters	260
9.6 Conclusion	262
Annexe	265
References.....	267
Appendix A.....	305
Appendix B	307

List of Figures

Figure 2.1 Lateral view of <i>Orectolobus ornatus</i> showing new head height measurement taken (HDHe: head height at eye level).	44
Figure 2.2 Dorsal view of <i>Orectolobus halei</i> showing new head width measurements (HDWs: head width at anterior of spiracle level; HDWpo: head width at anterior of posterior preorbital lobes level; HDWn: head width at nasal barbel level).....	44
Figure 2.3 Lateral view of caudal fin showing measurements taken (CDM: dorsal caudal fin margin; CVM: ventral caudal fin margin; CUM: upper caudal fin margin; CLM: lower caudal fin margin; CTL: terminal caudal fin margin; CST: subterminal caudal fin margin; CTR: terminal caudal fin margin).....	44
Figure 2.4 Photographs of neotype <i>Orectolobus halei</i> AMS I 43628-002, 1700 mm, mature male. A) lateral view; B) dorsal view; and C) ventral view.....	46
Figure 3.1 Map of New South Wales coast showing ‘locations’ where dives were made and number of dives undertaken in parenthesis.....	79
Figure 3.2 Diving effort throughout NSW during the survey period.	79
Figure 3.3 Comparison of the site mean number of wobbegong between north and south regions	81
Figure 3.4 Comparison of the site mean number of wobbegong between locations	82
Figure 3.5 Frequency of wobbegong sightings by species across size class; number above bar is sample size.....	85
Figure 3.6 Frequency of wobbegong sightings across size class separated by species and region; number above bar is sample size.	85
Figure 4.1 Location of study site with position of the receivers.....	98
Figure 4.2 Time series of acoustic detections for wobbegongs.....	102

Figure 4.3 Frequency plot of (a) visit, and (b) excursion duration recorded by all wobbegong around Fish Rock.	104
Figure 4.4 Fourier analysis of detection periodicity	105
Figure 4.5 Frequency of detections by time of day.	107
Figure 4.6 Number of detections for each receiver in proportion with the total number of detections for each shark.....	110
Figure 5.1 Sampling locations for collection of wobbegongs in New South Wales, Australia.	121
Figure 5.2 Lateral view of a wobbegong showing measurements taken.	121
Figure 5.3 Length-frequency distributions of wobbegongs caught during sampling period	123
Figure 6.1 Cumulative prey diversity curve by species based on the Shannon-Weiner Index (H') for (a) <i>O. ornatus</i> , (b) <i>O. maculatus</i> , and (c) <i>O. halei</i>	140
Figure 6.2 Cumulative prey diversity curves by sex based on the Shannon-Weiner Index (H') of males (left) and females (right) for (a) <i>O. ornatus</i> , (b) <i>O. maculatus</i> , and (c) <i>O. halei</i> . .	141
Figure 6.3 Three-dimensional graphical representation of diet in (a) <i>O. ornatus</i> , (b) <i>O. maculatus</i> , and (c) <i>O. halei</i> . (■) Total bony fishes; (□) bony fishes separated by family; (●) total Cephalopods; (○) Cephalopod separated by family; (▲) total Chondrichthyes; and (Δ) Chondrichthyes separated by family.....	151
Figure 7.1 Sampling locations for collection of wobbegongs in New South Wales.	166
Figure 7.2 Male size-at-maturity estimation based on clasper calcification and clasper length for wobbegongs in NSW	176
Figure 7.3 Temporal variation of male reproductive activity for wobbegongs in NSW .	179
Figure 7.4. Female maturity and maternity ogive of wobbegong sharks in NSW	181

Figure 7.5 Largest ovarian follicle diameter against Julian day for uterus conditions UI=3–5 of <i>O. ornatus</i>	184
Figure 7.6. Largest ovarian follicle diameter against Julian day for uterus conditions UI=3 and 5 of <i>O. maculatus</i>	185
Figure 7.7 Largest ovarian follicle diameter against Julian day for uterus conditions UI=3 of <i>O. halei</i>	187
Figure 7.8 Percent HSI against largest ovarian follicle diameter and embryo total length of wobbegongs in NSW	188
Figure 7.9 Embryonic development through time	191
Figure 7.10 Relationship between litter size and maternal total length.....	194
Figure 7.11 Relationship between different variables and maternal total length of <i>O. ornatus</i>	195
Figure 8.1 Example of growth bands observed on <i>O. ornatus</i> vertebrae	213
Figure 8.2 Relationship between vertebral radius and wobbegong total length.....	226
Figure 8.3 Age-bias plots of band counts for wobbegong sharks in NSW.....	229
Figure 8.4. Back-calculated lengths-at-age estimates for wobbegongs in NSW.....	231
Figure 8.5 Growth curves for wobbegongs in NSW	236
Figure 8.6 Monthly variation of vertebra edge and Marginal Increment Ratio (MIR) ...	238
Figure 8.7 Observed length-at-age from whole vertebrae (○), thin sections (Δ) and known length-at-age of captive sharks (■) for (a) <i>O. ornatus</i> , (b) <i>O. maculatus</i> , and (c) <i>O. halei</i>	241
Figure 8.8 Example of OTC mark visible using ultraviolet light on a vertebra of <i>O. halei</i> .	244

List of Tables

Table 2.1 Morphometric data for the holotype of <i>Orectolobus ornatus</i> and neotype of <i>Orectolobus halei</i> , with ranges provided for the other specimens examined. Total length is provided in mm, measurements expressed as percentage of the total length. Measurements in bold highlights are those that appeared to differ between the two species (missing data is due to morphometric measurements being unmeasurable).	56
Table 2.2 Ranges of measurement ratios that appear to differ between <i>Orectolobus ornatus</i> and <i>Orectolobus halei</i>	59
Table 3.1 Species ratio between ornate and spotted wobbegongs by location.	84
Table 4.1 Details of detected tagged sharks	102
Table 4.2 (a) ‘Presence rate’ calculated by dividing the number of hours detected by all receivers by the total number of daytime or nighttime hours for each shark and sharks combined, excluding long-term absences; and (b) ‘Detection rate’ calculated by dividing the hourly number of detection by the maximum hourly detection of each shark and sharks combined. P is the probability of statistical significance between daytime and nighttime tested with a Mann-Whitney test.....	108
Table 5.1 Number (with TL size range in mm) of wobbegong caught during June 2003–May 2006.	123
Table 5.2 Relationships between length–length and mass–mass	125
Table 5.3 Relationships between total mass (TM)–total length (TL) and carcass mass (CM)–partial length (PL).....	125
Table 6.1 Summary table of samples collected, hook position and number of prey items.	139
Table 6.2 Dietary information for <i>O. ornatus</i> caught in New South Wales	143

Table 6.3 Dietary information for <i>O. maculatus</i> caught in New South Wales.....	145
Table 6.4 Dietary information for <i>O. halei</i> caught in New South Wales	149
Table 7.1 Indices to stage reproductive condition (adapted from Walker 2005). Assumption of maturity is also listed.	169
Table 7.2. Number of wobbegongs caught during June 2003–May 2006.....	174
Table 7.3 Maturity and maternity estimates for wobbegongs in NSW	177
Table 7.4 Largest follicle growth estimates for wobbegongs in NSW	187
Table 7.5 Liver mass correlations for wobbegongs in NSW	189
Table 7.6 Fecundity relationships for wobbegongs in NSW	195
Table 8.1 Description of vertebrae readability.	215
Table 8.2 Growth models fitted to lengths-at-age data.....	218
Table 8.3 Proportion-based back-calculation details.....	220
Table 8.4 Number of wobbegongs sampled and number of vertebrae and sections used in analyses.....	225
Table 8.5 Relationship between vertebral radius and wobbegong total length	227
Table 8.6 Back-calculated length (BC) and Observed length (OL) with standard deviation (s.d.) and sample size (<i>n</i>) for <i>O. ornatus</i> , <i>O. maculatus</i> , and <i>O. halei</i>	232
Table 8.7 Growth parameters for <i>O. ornatus</i> , <i>O. maculatus</i> and <i>O. halei</i> calculated from counts using whole vertebrae, thin sections, and a combination of back-calculated and observed lengths-at-age, and using the von Bertalanffy growth model (VBGM); the two-parameter modified form of the VBGM forced through the length-at-birth (2P VBGM), the two-parameters Gompertz growth model (2P Gompertz), and the logistic model. L_{∞} is mean maximum age at infinite length; k is growth coefficient; t_0 is theoretical age at zero length; α is time at which the absolute rate of	

increase in length begins to decrease, or the inflection point of the curve; RSS is residual sum of squares; and w_i is Akaike's weight.	235
Table 8.8 Likelihood ratio test testing differences of growth curves between males and females for wobbegong sharks in NSW	235
Table 8.9 Growth rate details of captive wobbegongs.....	240

Summary

In New South Wales (NSW), Australia, wobbegong sharks (Orectolobidae) have been commercially targeted by the Ocean Trap and Line Fishery since 1991. A catch decrease of *ca.* 50% in a decade lead to concern over the sustainability of the fishery and to wobbegongs being listed as Vulnerable in NSW under the World Conservation Union (IUCN) Red List assessment. The aim of this research was to investigate wobbegong biology and ecology in relation to its fishery to provide essential data and information for sustainable management of the wobbegong fishery. Biological data was obtained from 904 wobbegongs collected from commercial fishing boats, using setlines and lobster pots and by scuba diving.

Previously, two species of wobbegongs were known to occur in NSW: the spotted wobbegong (*Orectolobus maculatus*) and the ornate wobbegong (*O. ornatus*). This study discovered a new species (*O. halei*) described as a subspecies by Whitley (1940), but which had been synonymised with *O. ornatus* due to a lack of taxonomic investigation. An identification key was developed that will allow fishers to correctly identify wobbegongs to species level and to report catch accordingly. Correct species identification allows for the implementation of species-specific management regulations, previously not possible.

A diver survey indicated that wobbegongs are more abundant in northern NSW and that size segregation might occur as the absence of neonates and small juveniles suggest that they may be elsewhere, possibly located in nursery areas.

Passive acoustic tracking of *O. halei* suggested that at least some wobbegongs have long-term residency. Diel patterns were also observed with sharks more frequently recorded during daylight hours than at night. The long-term residency pattern found in this preliminary study suggests that temporal closures or marine protected areas may be effective tools for the management and conservation of local populations.

Morphometric relationships between partial and total lengths; and carcass and total mass were developed to correct for the common commercial fishing practice of landing trunks only. The length-frequency of wobbegongs collected during this study also shows that neonates and small juveniles were absent from the catches.

Dietary examination indicated that wobbegongs fed primarily on bony fishes, but also consumed cephalopods and chondrichthyans. Wobbegongs were frequently gut-hooked (80–90% of the catch), potentially leading to high post-release mortality rates. Diet did not vary between the sexes, but interspecific differences were evident and were related to the total length of the shark. The high trophic level of wobbegongs means that their removal from the ecosystem may have impacts at lower trophic levels.

Reproductive parameters of wobbegong were investigated to provide a biological basis for the management of a commercial fishery targeting wobbegongs. L_{50} for male and female maturity was *ca.* 800 mm, 1250 mm, and 1750 mm TL for *O. ornatus*, *O. maculatus* and *O. halei*, respectively. These species of wobbegong had synchronous, triennial reproductive cycles. During the first year, follicles remained small, and then grew rapidly during the second year prior to ovulation during November. Gestation lasted *ca.* 10–11 months and parturition occurred during

October–November. Mean litter sizes were *ca.* 9 and 21 for *O. ornatus* and *O. maculatus*, respectively, and increased with female total length in *O. ornatus*. No pregnant *O. halei* were sampled. Pregnant *O. ornatus* and *O. maculatus* were frequently caught in northern NSW and no pregnant wobbegongs, or females with large, yolky follicles were captured south of Sydney. Differences in the reproductive stages of wobbegongs caught in northern and central NSW suggested geographically dependent reproductive behaviour.

Age and growth information was also investigated. Periodicity of growth band deposition could not be determined using marginal increment ratio, edge analysis, and growth rate and chemical marking of captive sharks. Counts of growth bands using whole vertebrae consistently underestimated age compared to thin sections. Growth parameters were obtained and compared using four different models, and counts from whole vertebrae and thin sections, and a combination of observed and back-calculated lengths-at-age. Growth parameters could not conclusively be determined because validation of growth bands and vertebral preparation was not possible.

Declaration

I hereby declare that this work is my own, except where otherwise acknowledged. It has not been submitted in any form for another degree or diploma at any university or other institution. All work conducted for this dissertation was conducted under the Macquarie University Animal Research Authority 2003/011 and the NSW DPI Research Permit P03/0057.

I consent to this thesis being made available for photocopying and loan under the appropriate Australian copyright laws.

CHARLIE HUVENEERS

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Dedication

To mum... for the education given and enabling me to be where I am
now.

CHAPTER 1: GENERAL INTRODUCTION



© Lyn Cleary (*Orectolobus maculatus*)

1.1 Shark fisheries and life history characteristics

Chondrichthyans (cartilaginous fishes) fisheries have expanded in size and number around the world since the mid-1940s when fisheries developed as a result of the market for vitamin A from livers (Stevens *et al.* 2000). More recently, fisheries have targeted chondrichthyans primarily in response to the rapidly increasing demand for shark fins, meat and cartilage. World chondrichthyan catches (60% of which are sharks) have increased more than threefold from 200,000 tonnes in 1947, to about 700,000 tonnes (or about 71 million animals) in 1991 (Bonfil 1994). For example, imports of shark fins into Hong Kong, the world's most important trader, processor and consumer, nearly doubled from 3795 tonnes in 1985 to 7011 tonnes in 1997 (Vannuccini 1999). Such an increase in demand has likely fuelled the decline in shark population worldwide.

During the 1940–1970 period many chondrichthyan fisheries underwent a “boom and bust” (Holden 1974; Anderson 1990; Compagno 1990) and shark populations have continued to decline on a worldwide basis (Bonfil 1994; Camhi *et al.* 1998; Lack and Sant 2006). Notable examples of shark fisheries that have collapsed include the Californian and Australian fishery for school shark (*Galeorhinus galeus*), several fisheries for basking shark (*Cetorhinus maximus*), the Scottish-Norwegian and Japanese fishery for spiny dogfish (*Squalus acanthias*) (Anderson 1990), the common skate (*Dipturus batis*) fishery (Brander 1981), and more recently the blue shark (*Prionace glauca*) fishery off Catalina Island in California (Hoff and Musick 1990).

Once a shark species is demonstrably over-fished, it is usually too late for management intervention as recovery may take several decades, especially when compared to many teleost

stocks which can recover in less than a decade (Hoff and Musick 1990). Furthermore, chondrichthyan recovery may be unattainable. The quasi-extinction of grey nurse sharks (*Carcharias taurus*) in New South Wales was modeled for worst-, most likely, and best-case scenarios from 13-16 years, 84-98 years and 289-324 years, respectively (Otway *et al.* 2004). In all scenarios modeled the grey nurse shark population in NSW will decline and become extinct under current rates of anthropogenic mortality.

Globally, predatory fish biomass, including chondrichthyans, declined to *ca.* 10% of pre-industrial levels globally (Myers and Worm 2003). In the Gulf of Mexico, oceanic whitetip (*Carcharhinus longimanus*) and silky sharks (*C. falciformis*) declined by over 99 and 90%, respectively, between the 1950s and late 1990s (Baum and Myers 2004). Similarly, populations of the scalloped hammerhead (*Sphyrna lewini*), white shark (*Carcharodon carcharias*) and thresher shark (*Alopias vulpinus* and *A. superciliosus*) in the Northwest Atlantic have been estimated to have each declined by over 75% in the past 15 years (Baum *et al.* 2003). However, the recent studies indicating extensive decline of shark abundance in the Northwest Atlantic and Gulf of Mexico have been criticised because of their highly selective use and interpretation of questionable datasets (Baum *et al.* 2006; Burgess *et al.* 2006a; 2006b). Internationally, many species of chondrichthyans are considered threatened with 20.2% of the species assessed by the Shark Specialist Group (SSG)/IUCN categorised as Threatened (SSG unpub. data).

The observed collapses and absence of recovery decades after decline has lead to international concerns about chondrichthyan conservation and resilience to fishing pressure. As a result, the Food and Agriculture Organisation of the United Nations (FAO) developed the International Plan of Action for the Conservation and Management of Sharks (IPOA-Sharks) to ensure the

preservation of sharks and their long-term sustainable use (FAO 2000). Protection of chondrichthyans is of particular importance because they occupy high trophic levels and play a major role within a number of marine ecosystems through the removal of prey species, their competitors, and through species replacement (Jennings and Kaiser 1998). As such, the removal of chondrichthyans from coastal ecosystems has the potential to cause a trophic cascade resulting in alterations to the abundance of lower trophic species (Jennings and Kaiser 1998).

The susceptibility of chondrichthyans to overfishing is primarily related to their life history characteristics. Chondrichthyans exhibit slow growth, late age-at-maturity, low fecundity and productivity (small, infrequent litters), long gestation periods, high natural survivorship for most age classes, and long life (Holden 1974; 1977). These K-selected life history characteristics, combined with a tendency to aggregate by age, sex and reproductive stage, have serious implications for the sustainability of chondrichthyan fisheries as they are particularly vulnerable to excessive fishing mortality (Holden 1973; 1974; Hoenig and Gruber 1990; Bonfil 1994). Chondrichthyans are now known to exhibit a wide range of life history characteristics (i.e., litter sizes among viviparous species range 1–300, Compagno 1990) with several species found to be sustainable when fisheries is managed adequately (Walker 1998; Simpfendorfer 1999).

The Australian Southern Shark Fishery exemplifies the importance of quantifying life history parameters to ensure the sustainability of harvesting. This fishery catches *G. galeus* and gummy shark (*Mustelus antarcticus*) and, generally, it is not possible to selectively fish for one or the other species. Despite this, the two species show very different responses to similar fishing pressure. The two species are similar in size, and stock assessments using age-structured models have indicated that catches of the *M. antarcticus* were sustainable, whereas *G. galeus* was over-

exploited (Caton *et al.* 1997; Walker 1998). This difference was attributed to *G. galeus* being less productive (longer longevity, older age-at-maturity, and less frequent parturition) than *M. antarcticus*, hence the discrepancy in their response to similar fishing pressure.

Clearly, knowledge of the life history characteristics is necessary to assess the sustainability of chondrichthyans, but in most cases, this information is not available. Basic biological information on age, growth and reproduction (all necessary for management) is only available for about 4% of shark species and less than 1% of batoids (Musick 2005), and as a result 37.5% of the species assessed by the SSG/IUCN have been categorised as Data Deficient (SSG unpub. data).

Commercial fisheries that have grown steadily since the 1920s appear to have had the greatest impact on chondrichthyan stocks (Walker 1998). However, management of chondrichthyan populations has been limited mainly by the absence of demographic data and, in part, by the low priority given to chondrichthyan fisheries. With the exception of a few countries, including Australia, Canada, New Zealand and the USA, most chondrichthyan fisheries worldwide remain virtually unmanaged (Musick 2005).

1.2 Wobbegongs (family: Orectolobidae)

Wobbegongs, or carpet sharks (order Orectolobiformes, family Orectolobidae), are dorsally flattened, bottom-dwelling sharks occurring in temperate to tropical continental waters of the western Pacific. They are most diverse in Australian and New Guinean waters, but occur northwards to Japan (Compagno 2001). The family currently contains seven described species with three recognised genera. Out of the seven, six species occur within Australian waters, with two species: the spotted wobbegong (*Orectolobus maculatus*) and the ornate wobbegong (*O.*

ornatus) found in coastal waters off New South Wales (NSW). Wobbegongs provide a good example of sharks that are commercially targeted in spite of the inadequate biological and ecological data on which to base sustainable management of the fishery. With this in mind, it is not surprising that concerns have been expressed over the conservation status of wobbegongs (Cavanagh *et al.* 2003).

In Australia, wobbegongs are exploited off the western and eastern coasts of the continent. They are a component of the by-catch of a commercial shark fishery utilising demersal gill-nets to target carcharhinid whalers and other sharks along the southern and lower west coasts of Western Australia with a total wobbegong catch in 2003/2004 of 49 tonnes (Simpfendorfer and Donohue 1998; McAuley and Gould 2006). Smaller catches of orectolobids also occur in commercial and recreational rock lobster pots throughout temperate coastal Western Australian waters (J. Chidlow pers. comm.).

In NSW, wobbegongs have been commercially targeted by a range of fisheries, with the majority caught in the Ocean Trap and Line Fishery using setlines, handline and trotlines (68%).

Wobbegongs are also caught by trawlers (30%) and as bycatch in lobster and fish traps (Pease and Scribner 1993; Pease and Scribner 1994; Pease and Grinberg 1995).

The total catch of wobbegongs in NSW decreased from *ca.* 150 tonnes in 1990/1991 to *ca.* 70 tonnes in 1999/2000 (Pease and Grinberg 1995; NSW DPI unpub. data). Recreational divers have also expressed concerns over the reduced sightings of wobbegongs during dives (Bohm 2002).

As a result, a discussion paper on wobbegong sharks in NSW was produced and sought the views of various stakeholders on the future management of commercial and recreational fishing of wobbegong sharks (NSW Fisheries 2001). NSW Fisheries, which changed its name to the NSW

Department of Primary Industries (NSW DPI) also requested commercial fishers report catches for *O. ornatus* and *O. maculatus* individually. Most recently, a review of NSW Recreational Freshwater & Saltwater Fishing Rules and the Fishery Management Strategy (FMS) for NSW Trap and Line Fishery have proposed minimum and maximum size limits for wobbegong sharks (NSW DPI, 2006). The FMS has also recommended that commercial fishers report their catches of each species separately.

Knowledge of basic biology and ecology of wobbegongs in NSW coastal waters is sparse and what is available is mainly limited to taxonomic records (e.g. Last and Stevens 1994; Compagno 2001). The absence of information on their basic biology is surprising given their coastal habitat and availability via the commercial fishery.

Consequently, the aim of this study is to document information on the basic biology and ecology of wobbegongs in order to assess their resilience to fishing pressure. This information may then be used by fisheries agencies to develop adequate regulations for the commercial fishery. This has been done by:

- (1) Redescribing two species of wobbegongs previously misidentified and previously referred to as the ornate wobbegong (Chapter 2);
- (2) Determining the distribution and relative abundance of wobbegongs in NSW using recreational divers (Chapter 3);
- (3) Determining the localised movements and residence time of wobbegongs around small-scale geographical locations using acoustic telemetry (Chapter 4);

And thereafter for the 3 wobbegong species by:

- (4) Providing length-frequency, length–length, mass–mass, and mass–length relationships for the 3 wobbegong species (Chapter 5);
- (5) Analysing the stomach contents to quantify the diets of wobbegong (Chapter 6);
- (6) Quantifying the reproductive biology of wobbegongs (Chapter 7); and,
- (7) Documenting age and growth of wobbegongs (Chapter 8).

CHAPTER 2: REDESCRIPTION OF TWO SPECIES OF WOBBERGONGS
(CHONDRICHTHYES: ORECTOLOBIDAE) WITH ELEVATION OF *ORECTOLOBUS HALEI*
WHITLEY 1940 TO SPECIES LEVEL



© Charlie Huveneers (*Orectolobus halei* - left; *Orectolobus ornatus* - right)

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2.1 Abstract

Two closely related species of the genus *Orectolobus* (Orectolobidae), *O. ornatus* (De Vis) and *O. halei* Whitley, are redescribed based on fresh material from temperate eastern Australia. Although described as a subspecies by Whitley (1940), *O. halei* was formerly synonymised with *O. ornatus* because of the lack of research material to assess their conspecificity. Due to its smaller size, *O. ornatus* was previously thought to be the juvenile form of the larger *O. halei*. *Orectolobus ornatus* occurs from Port Douglas, (Queensland) to Sydney (New South Wales) whereas *O. halei* occurs from Southport (Queensland) around the southern coast to Norwegian Bay (Western Australia). Both species are commercially targeted within the hook and line fishery off New South Wales. *Orectolobus ornatus* differs from *O. halei* in colour pattern, a smaller adult size, fewer dermal lobes at the posterior preorbital group, lower vertebral and spiral valve counts, and the absence of supraorbital knob. Morphometrically, *O. ornatus* has a longer pelvic fin to anal fin interspace, smaller pectoral fins, smaller head dimensions, and relatively smaller claspers in mature specimens.

2.2 Introduction

Wobbegong sharks (family Orectolobidae Gill 1896) are bottom-dwelling sharks found in warm temperate to tropical continental waters of the western Pacific (Compagno 2001). They can be distinguished from all other sharks (except angel sharks, family Squatinidae) by their flattened and variegated bodies, and from all other elasmobranchs by possessing dermal lobes along the sides of the head. Wobbegongs also have a short, nearly terminal mouth in front of the eyes, nasoral grooves, circumnarial grooves and flaps, symphysial grooves, large spiracles and dorsolateral eyes (Compagno 2001).

The family currently comprises seven valid species that are divided into three recognized genera: *Eucrossorhinus* consisting of the tasselled wobbegong *E. dasypogon* (Bleeker 1867); *Orectolobus* consisting of the Japanese wobbegong *O. japonicus* Regan 1906, the spotted wobbegong *O. maculatus* (Bonnaterre 1788), the ornate wobbegong *O. ornatus* (De Vis 1883), the northern wobbegong *O. wardi* Whitley 1939, and the western wobbegong *O. hutchinsi* Last *et al.* 2006; and *Sutorectus* consisting of the cobbler wobbegong *S. tentaculatus* (Peters 1864). The systematics of the family is not fully resolved and two new species of wobbegongs from Western Australia have recently been identified (P. Last and J. Chidlow pers. comm.). Furthermore, new material from Indonesia (W. White pers. comm.), Borneo (Manjaji 2002) and the Philippines (Compagno *et al.* 2005) suggests that additional species exist in the Indo-West Pacific.

Two species, *O. ornatus* and *O. maculatus*, are thought to occur off temperate eastern Australia, but it has been suggested that other closely related species-level taxa may also be present. Whitley (1940) described the subspecies *O. ornatus halei*, from southern Australia and distinguished it from *O. ornatus ornatus* from northeastern waters by “differences in its colour pattern and in the form of the tentacles around the head”. No further description was given by Whitley apart for the size of the holotype of 2883 mm. Furthermore, some specimens of *O. ornatus* are mature at 700–800 mm total length (TL) which is considerably smaller than the normal size of maturity at about 1750 mm TL (Last and Stevens 1994). This discrepancy between ‘small’ and ‘large’ morphs of *O. ornatus* was observed by Last and Stevens (1994), but they could not resolve the alpha taxonomy because of the paucity of research material. The small morph has since been observed mating (S. Hartley 2004 pers. comm.), and small pregnant females are regularly caught in the targeted wobbegong commercial fishery (Huvaneers *et al.* in review-b; Chapter 7). Apart from these reports, there has been no positive evidence to support the

existence of a third species off eastern and southern Australia. The original description of *O. ornatus halei* was inadequate and it has subsequently been considered as a synonym of *O. ornatus* (Compagno 2001).

Wobbegongs have been targeted off the eastern Australian state of New South Wales (NSW) by commercial fishers for at least 15 years. However, catches have declined leading to public concern about the potential impact of the fishery on wobbegong populations (NSW Fisheries 2001). There are minimal management strategies specifically regulating wobbegong fisheries in NSW. Those currently in place directly applying to wobbegongs are a recreational bag limit of two wobbegongs per day, gear limit of no more than ten lines each with a maximum of six hooks when setlining within three nautical miles of the coast, and *de facto* protection given by shared critical habitats with grey nurse shark (*Carcharias taurus*). The lack of specific strategies directed at wobbegong commercial fishing and the decline in catches, has resulted in *O. ornatus* and *O. maculatus* being listed as ‘Vulnerable’ in NSW and as ‘Near Threatened’ globally under the World Conservation Union (IUCN) Red List assessment (Cavanagh *et al.* 2003). NSW Department of Primary Industries (NSW DPI) has expressed the need for appropriate management to ensure the viability of wobbegong populations in NSW (NSW Fisheries 2001). Suitable regulations require knowledge of all wobbegongs species marketed in NSW, especially if the sizes at maturity and reproductive biology differ between those species. Consequently, the subspecies needed to be investigated to help distinguish them and assess their conspecificity. These taxa are shown to be non-conspecific and both taxa are fully described below. A taxonomic key to *Orectolobus* species in NSW is also provided.

2.3 Materials and methods

Morphometrics followed Compagno (1984; 2001), with additional measurements taken to incorporate the different morphology of orectolobids. Dermal lobe measurements followed Last *et al.* (2006). Additionally, the distance between the nasal barbel and the anterior preorbital group (nasal-preorbital space), as well as the distance between the preorbital groups (preorbital space), were also measured. Several new head measurements were also measured to account for subtle differences in head morphology: head height at eye level (HDHe) (Fig. 2.1), head width at anterior of spiracle level (HDWs), head width at anterior of posterior preorbital lobes (HDWpo), and head width at nasal barbel level (HDWn) (Fig. 2.2). Caudal fin measurements varied from Compagno (2001) due to the difference in shape compared with carcharhinid sharks (Fig. 2.3). Counts and measurements for the holotype are given first, followed by ranges of all specimens examined. Meristics were taken from X-rays. Tooth row counts, which are difficult to obtain from radiographs, were taken directly from specimens. Spiral valve whorl counts were obtained from dissecting other specimens collected at the same locations as registered specimens.

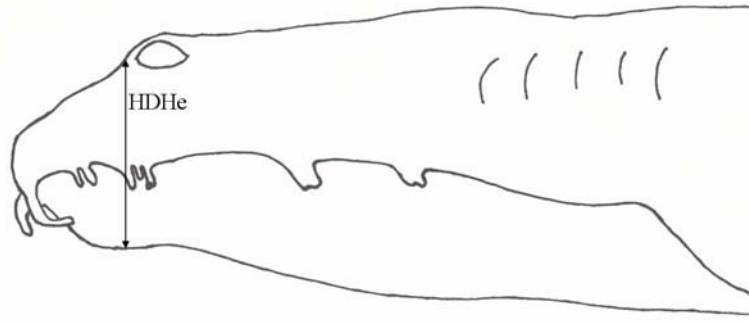


Figure 2.1 Lateral view of *Orectolobus ornatus* showing new head height measurement taken (HDHe: head height at eye level).

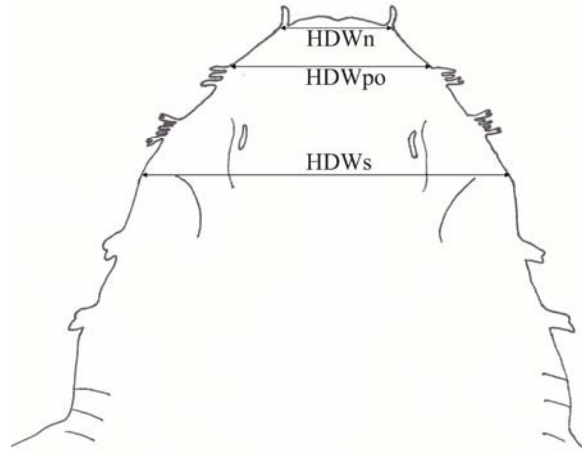


Figure 2.2 Dorsal view of *Orectolobus halei* showing new head width measurements (HDWs: head width at anterior of spiracle level; HDWpo: head width at anterior of posterior preorbital lobes level; HDWn: head width at nasal barbel level).

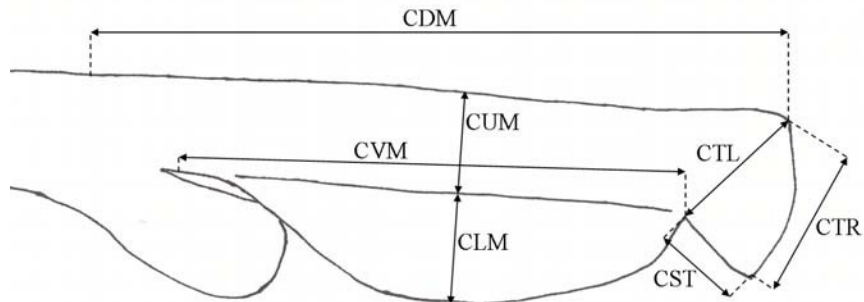


Figure 2.3 Lateral view of caudal fin showing measurements taken (CDM: dorsal caudal fin margin; CVM: ventral caudal fin margin; CUM: upper caudal fin margin; CLM: lower caudal fin margin; CTL: terminal caudal fin margin; CST: subterminal caudal fin margin; CTR: terminal caudal fin margin).

New material of the large morph were collected by NSW commercial fishers targeting wobbegongs using setlines off Sydney (34° 14'S, 151° 04'E). Specimens of the small morph were caught using a handnet (under NSW Fisheries permit number P03/0057) using SCUBA off Tomaree Head, Port Stephens (32° 43'S, 152° 11'E). The holotype of *O. ornatus* is held at the Queensland Museum (QM) and the newly designated neotype of *O. halei* was deposited at the Australian Museum (AMS). Other new material was dispersed between the AMS and the Australian National Fish Collection (CSIRO). Additional specimens were examined at the AMS, CSIRO and QM. Other institutional abbreviations follow Leviton *et al.* (1985).

2.4 Results

Orectolobus halei Whitley, 1940

(Fig. 2.4, Tables 2.1–2.2)

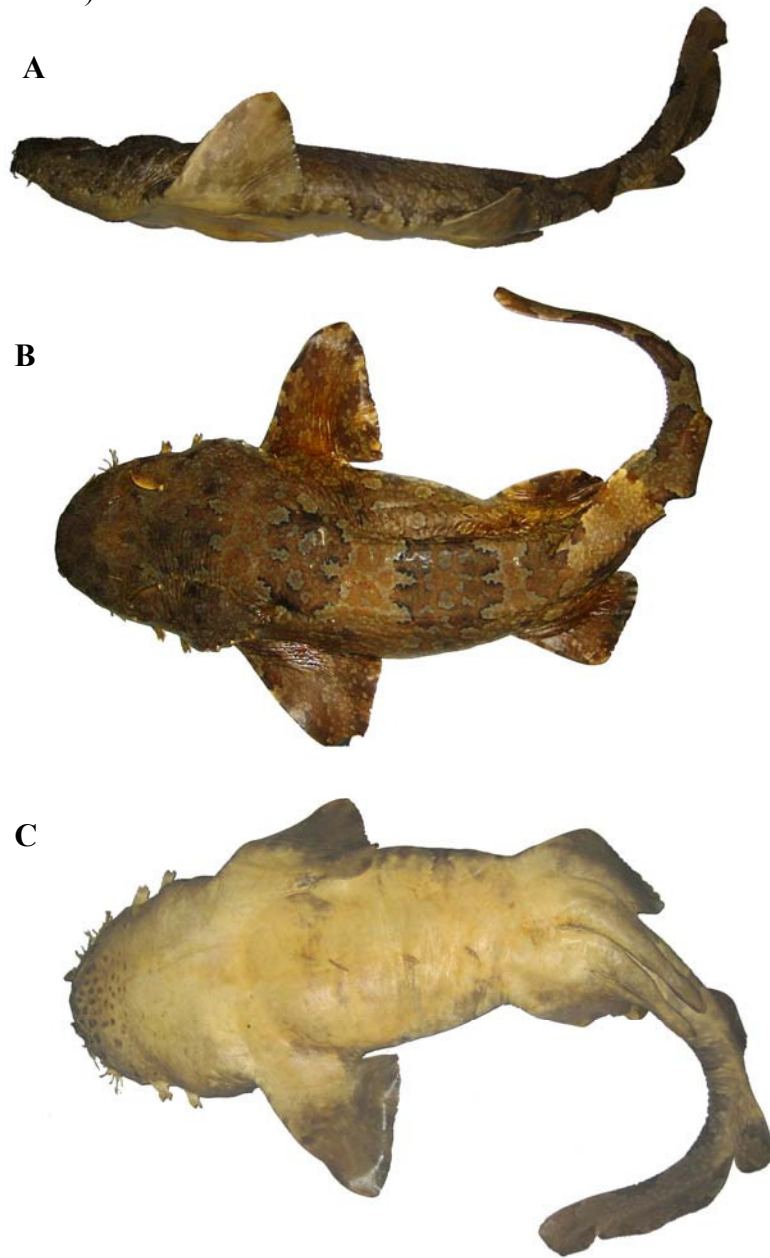


Figure 2.4 Photographs of neotype *Orectolobus halei* AMS I 43628-002, 1700 mm, mature male. A) lateral view; B) dorsal view; and C) ventral view..

Material examined

Holotype. SAMA 2883 mm TL female (cast), type locality: St. Vincent Gulf, South Australia.

Lost according to Eschmeyer (CD-Rom, 1998).

Neotype (designated herein). AMS I 43628-002, 1700 mm TL, mature male, longline, type locality: the Hump, 3.3 nautical miles offshore between Garie Beach and Wollongong, 34° 14'S, 151° 04'E, 20–35 m, 9th June 2005, collector Charlie Huvneers and Jason Moyce.

Other specimens examined. AMS I43628-001, 1285 mm TL, female; CSIRO H 6278-01, 1775 mm TL, female; CSIRO H6278-02, 1869 mm TL, mature male; AMS I43628-003, 1520 mm TL, immature male. All four specimens collected using logline at the Hump, 3.3 nautical miles offshore between Garry Beach and Wollongong, 34° 14'S, 151° 04'E, 20–35 m, 9th June 2005, by Charlie Huvneers and Jason Moyce. AMS I43629-001, 1140 mm TL, immature male, setline, Merimbula 50–100m from shore, 36° 54'S, 149° 57'E, 10–20 m, 24 April 2005, collector Charlie Huvneers, Shannon Corrigan and Shannon Fantham.

Diagnosis

A large species of *Orectolobus* with the following combination of characters: no warty tubercles on head or body; four groups of dermal lobes below and in front of eyes on each side of head; no dermal lobes on chin; nasal barbel closest to mouth branched; five to six lobes in second preorbital group (rarely four) with lobes at extremities usually longer and branched; broad branched postspiracular groups; two supraorbital knobs; base of anterior postspiracular lobe 3.28–3.69 in its distance from postorbital group, 1.36–2.36 in its distance from posterior postspiracular lobe; pelvic-fin insertion at first dorsal-fin midpoint; prepelvic length 2.40–3.13 times pelvic-anal space; pelvic-caudal space 1.04–1.25 times trunk width; teeth in upper jaw 25–28, those in medial row at symphysis rudimentary; spiral valve turns 29–32; precaudal vertebrae

count 108–112. Light and dark brown colouration with nine darker brown, blotch-shaped saddles located dorsally; each saddle has conspicuous black edges.

Description

Body depressed anteriorly from snout to pelvic-fin origin, slightly firm dorsal musculature with relatively flaccid flanks; trunk depressed, broadest over midtrunk; body shape changing from depressed to compressed and tapering from pelvic-fin origin; dorsal musculature slightly elevated from flank musculature forming a small ridge from the fifth gill slit to pelvic-fin insertion, decreasing anteriorly to first dorsal-fin origin. Head broad, strongly depressed, somewhat oval in cross-section with truncate anterior when viewed from above, length 21.4 (21.0–21.8) % TL, 2.08 (2.08–2.76) times second dorsal-fin origin to anal-fin origin, height at gill level 8.5 (7.3–9.1) % TL, 1.74 (1.33–1.74) in pelvic-fin midpoint to first dorsal-fin insertion; trunk width 21.7 (20.4–23.0) % TL; abdomen elongate, width 5.94 (5.26–6.34) % TL. Pectoral-pelvic space 19.3 (16.8–21.9) % TL, 0.90 (0.73–1.00) times head length; pelvic-anal space 2.10 (1.93–2.50) times anal-fin base; snout-vent length 0.99 (0.99–1.04) times vent-caudal length. Caudal peduncle absent, lower origin of caudal fin almost connected to anal-fin insertion, strongly compressed, oval in cross section at anal-caudal junction, caudal peduncle width 1.59 (1.33–1.64) in height.

Snout short, narrowly rounded in lateral view, truncate in dorsoventral view, slightly rounded angles; preoral length 0.8 (0.8–1.2) % TL, 12.50 (8.33–12.50) in mouth width; prenarial length negligible. Eyes dorsal on head, small, slit-like, length 1.7 (1.5–1.8) % TL, 12.35 (12.35–12.99) in head length; supraorbital crest elevated over and behind eye; two knobs on supraorbital crest, posterior knob longer; weak supraorbital ridge extending above spiracle; subocular pocket 2.26–2.70 times eye length; interorbit weakly concave. Spiracles slit-like, oblique to horizontal axis,

longer than eye, 1.99 (1.91–2.29) times eye length; anterior margin convex well elevated above weakly convex posterior margin; small eye spiracle space 0.4 (0.3–0.6) % TL; fold above spiracle anterior margin. Gill slits lateral on head, first three of similar length (2.2–3.0 % TL), fourth gill slit smaller, 0.94 (0.82–1.01) times third gill slit, last gill slit longest 1.17 (1.00–1.27) times first; last gill slit anterior to pectoral-fin midbase; pectoral-fin origin between second and third gill slit. Mouth subterminal, large 3.1 (2.9–3.3) % TL, horizontally expanded, broadly arched, width 10.7 (9.6–10.7) % TL, 3.47 (2.96–3.47) times its length, 4.76 (4.76–5.26) in vent to caudal length; 0.96 (0.83–1.09) times dorsal-fin midpoint to pelvic-fin origin; upper labial furrows 4.3 (4.1–4.9) % TL, originating at ventral margin of nostrils; lower labial furrows longer 5.4 (4.6–5.5) % TL, almost connected near symphysis of lower jaw. Nostrils small, widely separated, internarial space 5.4 (4.5–5.4) % TL, adjacent upper lip of mouth. Nasal barbel terminal on head, medial to nostrils, proboscis-like, rounded basally, tapering distally, length less than upper labial furrows; short flattened branched lobe at basal third of posterior margin; lateral nasal lobe broad, well elevated, subcircular, most expanded posteriorly.

Fang-like teeth relatively large, long and pointed, not exposed when mouth closed. Upper jaw with rudimentary symphyseal tooth recessible into upper lip and flanked distally by one larger symphyseal on either side. Lower jaw with three rows of enlarged symphyseals, their cusps subequal in length to each other and to those at symphysis in upper jaw; tooth cusps distal to symphysis decreasing sequentially in size; tooth shape varies distally from symphysis, first two to three teeth lack cusplets, one to two cusplets from the third or fourth parasymphyseal on either side of the cusp on about four to seven teeth, distal cusplets more pronounced than medial ones, three to five most distal teeth generally lack cusplets on either side of cusp; teeth formula ($n =$

14): upper jaw (11–12) + 1 + 1 + 1 + (11–12) = (25–27); lower jaw (8–11) + 3 + (8–10) = (19–24).

Dermal lobes well developed; anterior preorbital group with three to four simple lobes, posterior lobe longest; posterior preorbital group with five to six lobes, longest lobes at extremities, anterior and second most posterior lobe longer and branched; combined distance across preorbital groups 8.3 (7.0–9.8) % TL; anterior and posterior postspiracular group with short, broader, branched single lobe, base width of anterior postspiracular lobe 1.6 (0.9–1.7) % TL, base width of posterior postspiracular lobe 1.7 (0.8–1.7) % TL; distance between preorbital group and anterior postspiracular lobe 3.5 (3.2–4) % TL, between postspiracular lobes 1.9 (1.9–2.5) % TL.

Dermal denticles small, non-imbricated, crown shield-like, weakly tricuspidate at anterior end, weak ridge on all cusps at anterior end, rounded posterior end. Clasper elongate, extending well beyond tip of pelvic fins, inner length 17.8 (16.0–17.8) % TL, 6.40 (6.40–6.55) times width at base, tip bluntly pointed; four terminal cartilages: ventral terminal, accessory terminal cartilage (or spur), dorsal terminal 2 and dorsal terminal, approximate one-to-one ratio with all terminal cartilages, end-style of axial cartilage slightly calcified and fused with dorsal terminal. When terminal cartilages of clasper are open, spear-like extension near lateral side of axial 21.1 (18.5–24.7) % clasper shaft length.

Dorsal fins similar in size and shape, triangular; anterior margins oblique; apices broadly rounded, first dorsal-fin apex slightly more rounded than second dorsal-fin apex; posterior margins vertical, very slightly convex to straight; inner margin parallel originating at level of pelvic-fin rear tip; second dorsal-fin height 8.4 (7.6–9.3) % TL, 0.99 (0.69–0.99) times pelvic-fin

midpoint to second dorsal-fin origin; pre-first dorsal-fin length 48.9 (48.1–50.1) % TL, pre-second dorsal-fin length 61.2 (61.2–64.7) % TL; first dorsal-fin origin forward of pelvic-fin insertion (3.5 % TL); second dorsal-fin insertion anterior to anal-fin origin (0.7–0.8 % TL).

Pectoral fin large, length 15.7 (13.4–15.7) % TL, 2.81 (2.81–3.01) times pelvic-fin inner margin length; base fleshy, anterior margin slightly convex; apex broadly rounded; posterior margin slightly convex; inner margin straight, free rear tip very broadly rounded; prepectoral length 16.2 (16.2–19.5) % TL; pectoral-pelvic space 19.3 (16.8–21.9) % TL.

Pelvic fins moderately large, length 14.9 (12.0–14.9) % TL; anterior margin straight; apex very broadly rounded; posterior margin convex; inner margin straight, free rear tip broadly rounded; origin slightly anterior to first dorsal-fin origin, insertion first dorsal-fin midpoint; prepelvic length 44.1 (44.1–46.4) % TL, 2.51 (2.40–2.68) times pelvic-anal space; pelvic-anal space 17.6 (17.1–18.7) % TL, pelvic-caudal space 22.8 (21.9–26.57) % TL, 1.05 (1.03–1.26) times trunk width.

Anal fin elongate, lobe-like, well developed, base 8.5 (7.5–8.9) % TL, 2.09 (1.55–2.20) times interdorsal space; anterior and inner margins almost parallel, anterior margin first slightly concave then slightly convex; apex very broadly rounded; posterior margin straight, much smaller than anterior margin; inner margin straight, free rear tip slightly rounded; origin slightly posterior to second dorsal-fin insertion, insertion slightly posterior to caudal-fin origin; anal-fin height 1.61 (1.45–1.85) in base length; second dorsal-fin origin to anal-fin origin 10.3 (8.2–10.3) % TL, second dorsal-fin insertion to anal-fin insertion 1.36 (1.11–1.48) times terminal caudal margin.

Caudal fin long, strongly compressed; dorsal caudal margin length 21.0 (19.1–21.6) % TL, its origin slightly anterior to anal-fin insertion; upper lobe originating as a very low ridge, slightly distinguishable; anterior margin with a deep inflexion near its origin; outer rim straight and oblique; rounded apices; terminal caudal lobe fan-like; terminal caudal margin 6.2 (5.5–6.2) % TL.

Vertebral counts ($n = 7$): pre-first dorsal count 54–55; pre-second dorsal count 78–80; precaudal count 108–112. Spiral valve whorl count: 29–32 ($n = 32$, based on discarded specimens).

Colouration

Body light and dark brown colouration with nine darker brown blotch-shaped saddles located dorsally; each saddle has conspicuous black edges followed by greyish colouration, light brown and grey freckle-like blotches between saddles; first saddle weakly visible, posterior to spiracle, anterior to second gill slit; second saddle at pectoral-fin base level, broader than long; posterior end of third saddle at pelvic-fin origin level, length similar to width, lighter brown saddle extending laterally; fourth saddle small, anterior to first dorsal-fin origin, overlapping with inflexion of first dorsal fin; fifth saddle from first dorsal-fin midbase to slightly anterior to second dorsal-fin origin, extending laterally and ventrally below mid body, nearly connecting at ventral midline; sixth saddle from second dorsal-fin midbase to slightly anterior to caudal-fin origin, extending laterally and ventrally below mid body, nearly connecting at ventral midline; seventh saddle at origin of caudal fin, anterior to anal-fin insertion, longer than broad, extending laterally, not extending on lower lobe of caudal fin; eighth saddle on upper caudal lobe, longer than broad, extending laterally, not extending on lower lobe of caudal fin; ninth saddle slightly anterior to

caudal-fin tip, extending laterally, not extending on lower lobe of caudal fin. Grey bluish blotches sometimes with black edges on saddles decreasing in number and size from fourth saddle. V-shaped pattern anterior to interorbit; white spot on posterior tip of spiracle.

Underneath of head, trunk, abdomen and snout uniformly pale yellow, mouth and labial furrows with dark brown spots extending between posterior dermal lobe preorbital groups. Tail with three darker brown stripes on the flanks.

Pectoral fins green brown with blotches, underneath yellow at base, increasing brown colour towards posterior margins, slight light brown blotches and white freckles; pelvic fins brown grey with blotches, underneath yellow at base, increasing brown colour towards posterior margins, slight light brown blotches and white freckles; anal fin green brown, similar to tail colouration; dorsal fins brown, darker brown where saddles occur, green grey blotches/spots; caudal fin green brown, darker brown where saddles occur.

Remarks

Orectolobus halei was previously synonymised with *O. ornatus* due to the similarity in morphology and colour pattern. Whitley (1940) first mentioned this species as a subspecies of *O. ornatus* and only described it as differing from *O. ornatus* “in colour pattern and the form of the tentacles around the head”. The holotype, lodged at the South Australian Museum, Adelaide (SAMA), has been missing since at least 1997. The designation of a neotype is required due to the following. First, the previous description was so incomplete as to make it impossible to reliably distinguish *O. ornatus* from *O. halei*. Secondly, there currently is a significant problem of misidentification between those two species within the targeted fishery for wobbegong sharks.

Lastly, declining catches of wobbegong sharks strongly argue for a reliable means of identifying the target species.

Orectolobus halei can be distinguished from *O. ornatus* by several measurements (Table 2.1) and the two species also differ in 11 specific ratios (Table 2.2). *Orectolobus halei*, which is regionally sympatric with *S. tentaculatus*, *O. maculatus*, *O. wardi*, *O. hutchinsi*, and two undescribed species of *Orectolobus* off WA, can be distinguished from these species by the combination of the number of dermal lobes, colour pattern and the absence of tubercles. *Orectolobus hutchinsi* has slender unbranched postspiracular lobes (broad and branched in *O. halei* and *O. maculatus*) and a distinctive yellowish brown upper body colouration with well-defined, darker brown saddles containing paler markings that lacks whitish rings and blotches (unlike *O. ornatus* and *O. maculatus*) (Last *et al.* 2006). *Sutorectus tentaculatus* has large rounded tubercles on both the head and body, not present in the adults of other members of the family Orectolobidae. *Orectolobus maculatus* has six to ten dermal lobes, *O. wardi* has unbranched nasal barbels, whereas *O. halei* has five dermal lobes and branched nasal barbels. *Orectolobus wardi* has a simple colour pattern with fewer dark spots, whereas *O. maculatus* and *O. halei* have a more elaborate pattern of variegated spots and saddles. *Orectolobus maculatus* has white O-shaped spots and white blotches that are absent in *O. halei*.

Size

To at least 2060 mm TL; males mature at 1684–1819 mm TL, females mature at 1605–1871 mm TL (C. Huveneers unpub. data).

Distribution

Temperate Australia, from Southport (27° 06'S, 153° 26'E), Qld, to Norwegian Bay (22° 54'S, 113° 59'E), WA. Southern records to Flinders Island (40° 19'S, 147° 48'E), Bass Strait.

Table 2.1 Morphometric data for the holotype of *Orectolobus ornatus* and neotype of *Orectolobus halei*, with ranges provided for the other specimens examined. Total length is provided in mm, measurements expressed as percentage of the total length. Measurements in bold highlights are those that appeared to differ between the two species (missing data is due to morphometric measurements being unmeasurable).

	<i>O. ornatus</i>				<i>O. halei</i>			
	Holotype	other specimens (n = 5)			Neotype	other specimens (n = 5)		
	QM I 164	Min	Max	Mean	AMS I 43628–002	Min	Max	Mean
Total length	560	876	925		1700	1140	1869	
Fork length	95.5	95.5	96.4	96.0	95.3	94.5	95.5	95.2
Partial length	60.4	60.0	62.8	61.3	60.2	59.3	62.0	60.4
Precaudal length	80.2	78.1	80.2	79.3	80.2	78.8	81.9	80.0
Prenarial length	2.5	2.4	2.8	2.5	2.9	2.6	2.9	2.8
Preoral length	1.5	0.9	1.5	1.1	0.8	0.8	1.2	0.9
Preorbital length	4.6	3.9	5.2	4.8	5.3	5.2	6.0	5.7
Prespiracular length	6.8	6.8	7.4	7.0	7.2	6.8	7.6	7.2
Prebranchial length	14.7	14.4	16.1	15.1	14.7	14.7	17.9	16.0
Head length	20.8	19.3	20.8	20.3	21.4	21.0	21.8	21.4
Prepectoral length	17.3	15.3	19.1	17.5	16.2	16.2	19.5	18.0
Prepelvic length	42.5	39.6	43.5	41.7	44.1	44.1	46.4	45.1
Snout–vent length		45.8	48.5	47.2	50.4	50.2	52.5	51.2
Preanal fin length	74.3	71.8	77.4	74.4	72.6	71.9	74.7	73.1
Pre-first dorsal length	50.0	48.7	50.3	49.5	48.9	48.1	50.1	49.2
Pre-second dorsal length	64.5	61.6	64.5	63.1	61.2	61.2	64.7	63.1
Interdorsal space	5.2	3.6	5.2	4.3	4.1	4.1	4.9	4.4
Dorsal-caudal space	6.0	6.0	7.9	7.1	7.8	6.9	8.4	7.6
Pectoral-pelvic space	17.9	15.4	18.2	17.2	19.3	16.8	21.9	18.9
Pelvic-anal space	23.0	19.6	23.0	21.5	17.6	17.1	18.8	18.0
Pelvic-caudal space	30.1	28.1	31.4	29.3	22.8	21.9	26.5	24.7
Vent-caudal space		53.0	56.1	54.6	50.7	49.3	50.9	50.4
Eye length	1.7	1.6	2.0	1.8	1.6	1.5	1.8	1.6
Eye height	1.3	1.0	1.3	1.1	1.0	0.9	1.1	1.0
Interorbital space	6.7	6.2	6.8	6.5	5.4	5.4	6.8	6.4
Nostril width		0.5	0.7	0.6	0.7	0.6	0.8	0.7
Internarial space	4.4	4.4	5.1	4.8	5.4	4.5	5.4	5.0
Spiracle length	2.7	2.7	3.1	2.8	3.3	3.0	3.8	3.4
Eye-spiracle space	0.5	0.3	0.7	0.5	0.4	0.2	0.6	0.4
Mouth length	2.6	2.4	2.6	2.5	3.1	2.9	3.3	3.1
Mouth width	8.6	8.6	9.1	8.9	10.7	9.6	10.7	10.1
Upper labial furrow length	3.9	3.6	4.0	3.9	4.3	4.1	4.9	4.3
Lower labial furrow length	4.3	4.2	4.6	4.3	5.4	4.6	5.5	5.1

Intergill length	5.3	4.6	5.5	5.1	5.5	4.8	6.2	5.5
First gill-slit height	1.6	1.6	2.1	1.8	2.8	2.2	2.8	2.6
Second gill-slit height	1.8	1.6	2.1	1.9	2.8	2.6	3.0	2.7
Third gill-slit height	1.6	1.6	2.0	1.8	3.0	2.5	3.0	2.7
Fourth gill-slit length	1.6	1.5	1.8	1.7	2.8	1.9	2.8	2.4
Fifth gill-slit	2.4	2.4	2.7	2.5	3.5	2.6	3.5	3.1
Head height at third gill level	8.9	7.9	8.9	8.3	8.5	7.3	9.1	8.4
Head height at eye level	6.1	5.0	6.1	5.5	6.9	5.1	6.9	6.0
Head width at third gill level	16.8	16.8	18.5	17.7	22.0	19.5	22.0	20.6
Head width at spiracle level	14.5	14.4	16.0	15.3	17.5	16.0	17.9	16.9
Head width at posterior preorbital lobes	10.7	10.7	12.6	11.8	10.7	8.7	10.7	9.5
Head width at nasal barbel	6.0	6.0	6.7	6.3	6.5	6.0	6.7	6.3
Trunk height	9.6	7.3	9.6	8.1	8.8	7.6	9.4	8.5
Trunk width	17.4	16.9	18.7	17.8	21.6	20.4	23.0	21.7
Abdomen height	6.1	5.0	6.1	5.5	5.2	4.8	6.0	5.4
Abdomen width	5.5	5.3	5.7	5.5	5.9	5.9	6.3	6.2
Tail height	8.4	7.5	8.4	7.8	7.6	6.0	7.9	7.0
Tail width	9.0	7.5	9.0	7.9	7.7	3.3	8.1	6.2
Caudal peduncle height	2.8	2.8	3.3	3.0	3.5	3.0	3.5	3.3
Caudal peduncle width	4.0	2.1	4.0	2.5	2.2	2.1	2.5	2.2
Girth	45.6	42.0	45.6	43.2	48.4	42.1	49.9	46.9
Pectoral-fin length	12.7	12.2	13.6	13.0	15.7	14.1	15.7	14.7
Pectoral-fin anterior margin		12.7	13.6	13.1	17.9	15.1	17.9	16.5
Pectoral-fin base	7.8	6.9	8.2	7.8	9.5	8.5	10.2	9.7
Pectoral-fin height		10.0	11.8	10.8	14.8	12.0	14.8	13.8
Pectoral-fin anterior margin	5.1	4.6	5.4	5.1	5.6	4.9	5.6	5.1
Pectoral-fin posterior margin		11.1	12.9	11.6	16.1	14.5	16.1	15.2
Pelvic-fin length	11.0	11.0	14.5	13.0	14.9	12.0	14.9	13.5
Pelvic-fin anterior margin	9.5	7.9	10.2	9.1	10.5	8.2	10.9	9.9
Pelvic-fin base	8.1	8.1	11.8	10.4		9.7	12.5	10.5
Pelvic-fin height	5.4	5.4	7.5	6.3	7.1	7.1	8.7	7.9
Pelvic-fin inner margin	3.6	3.0	3.6	3.3	3.5	3.4	4.7	4.0
Pelvic-fin posterior margin	7.2	7.2	10.9	9.2	11.2	9.0	11.2	10.2
Outer clasper length (mature specimens)		8.3	8.9	8.6	10.1	9.2	10.1	9.6
Inner clasper length (mature specimens)		14.6	15.6	15.2	17.8	16.0	17.8	16.9
Clasper base (mature specimens)		3.0	3.7	3.4	2.8	2.4	2.8	2.6
First dorsal-fin length	12.8	12.6	13.9	13.3	13.6	12.4	13.9	13.1
First dorsal-fin anterior margin	11.4	11.4	12.7	12.1	13.9	11.7	13.9	12.7
First dorsal-fin base	9.3	9.3	10.7	10.2	10.4	8.9	10.9	10.0
First dorsal-fin height	6.4	6.4	8.4	7.8	9.2	7.6	9.2	8.3
First dorsal-fin inner margin	2.8	2.8	3.8	3.2	3.9	3.2	3.9	3.5
First dorsal-fin posterior margin	7.7	7.7	9.3	8.7	9.5	8.5	9.8	9.0
Second dorsal-fin length	12.2	12.0	12.9	12.5	13.1	11.8	13.1	12.2
Second dorsal-fin anterior margin	11.0	10.2	11.2	10.9	12.2	10.9	12.2	11.6

Second dorsal-fin base	10.0	9.4	10.4	9.8	10.2	8.9	10.2	9.4
Second dorsal-fin height	6.4	6.4	8.0	7.2	8.4	7.6	9.3	8.4
Second dorsal-fin inner margin	2.7	2.6	3.5	3.0	3.1	2.9	3.5	3.2
Second dorsal-fin posterior margin	7.4	7.4	8.9	8.3	8.9	8.1	9.8	9.0
Anal-fin length	8.9	8.9	11.3	10.0	10.7	9.2	10.9	10.0
Anal-fin anterior margin	8.9	8.9	10.4	9.8	11.2	8.9	11.6	10.2
Anal-fin base	7.1	7.1	8.6	7.8	8.5	7.5	8.9	8.1
Anal-fin height	3.1	3.1	4.9	4.0	5.3	4.1	5.3	4.8
Anal-fin inner margin	2.5	2.4	3.0	2.7	2.9	2.1	3.0	2.6
Anal-fin posterior margin	2.5	2.5	3.9	3.4	3.9	3.6	4.0	3.8
Dorsal caudal margin	21.1	20.3	21.9	21.3	21.0	19.1	21.6	20.5
Lower caudal margin	2.8	2.8	3.6	3.3	3.7	3.1	3.9	3.6
Ventral caudal margin	14.0	14.0	15.7	14.9	15.0	13.9	15.5	14.6
Upper caudal margin	2.6	2.6	3.4	3.1	3.4	3.1	3.7	3.4
Subterminal margin	3.5	2.9	3.8	3.2	3.0	2.6	3.4	3.0
Terminal caudal margin	4.3	4.3	5.1	4.7	6.2	5.5	6.2	5.9
Terminal caudal lobe	4.8	4.2	5.0	4.7	6.0	5.4	6.2	5.8
First dorsal midpoint-pectoral insertion	39.1	30.3	39.1	32.2	30.5	27.0	31.3	29.7
First dorsal midpoint-pelvic origin	13.5	13.4	15.4	14.0	11.2	8.9	11.8	10.3
Pelvic midpoint-first dorsal insertion	11.6	7.9	11.6	9.2	4.9	4.9	6.8	5.8
Pelvic midpoint-second dorsal origin	15.0	13.1	15.0	14.0	8.5	8.5	11.7	10.2
Second dorsal origin-anal origin	11.6	11.6	12.4	11.9	10.3	8.2	10.3	9.1
Second dorsal insertion-anal insertion	7.6	7.6	9.8	9.1	8.5	6.8	8.5	7.7
Nasal-preorbital space	0.6	0.6	0.9	0.7	1.1	1.0	1.6	1.3
Preorbital space	0.9	0.6	1.0	0.8	1.0	1.0	1.3	1.2
Preorbital-postspiracular space	3.8	3.5	4.8	4.2	3.5	3.2	4.0	3.5
Postspiracular space	2.6	1.5	2.6	2.3	1.9	1.9	2.5	2.2
Nasal barbel width	0.7	0.6	0.7	0.7	0.7	0.6	0.7	0.7
Anterior preorbital	1.3	1.3	1.6	1.5	1.9	1.4	1.9	1.5
Posterior preorbital	2.2	2.2	2.7	2.4	2.7	2.2	3.3	2.8
Anterior postspiracular	1.1	1.1	1.3	1.2	1.6	0.9	1.7	1.3
Posterior postspiracular	0.9	0.9	1.2	1.0	1.7	0.8	1.7	1.1

Table 2.2 Ranges of measurement ratios that appear to differ between *Orectolobus ornatus* and *Orectolobus halei*.

Ratios of morphometric measurements	<i>O. ornatus</i>	<i>O. halei</i>
Head length/second dorsal origin-anal origin	1.61–1.79	2.08–2.76
Prepelvic length/pelvic-anal space	1.83–2.22	2.40–2.68
Snout-vent length/vent-caudal length	0.81–0.91	0.99–1.04
Pelvic-caudal space/trunk width	1.52–1.85	1.04–1.26
Mouth width/first dorsal midpoint-pelvic origin	0.58–0.67	0.83–1.09
Head height at gill level/pelvic midpoint-first dorsal insertion	0.82–1.06	1.37–1.74
Pectoral length/pectoral inner margin	2.40–2.74	2.81–3.01
Second dorsal height/pelvic midpoint-second dorsal origin	0.43–0.59	0.69–0.99
Second dorsal insertion-anal insertion/terminal caudal fin margin	1.74–2.04	1.10–1.47
Preorbital-postspiracular space/lower labial furrow length	0.83–1.13	0.64–0.74
Spiracle length/eye length	1.43–1.76	1.91–2.29

***Orectolobus ornatus* De Vis, 1883**

(Fig. 2.5, Tables 2.1–2.2)



Figure 2.5 Photographs of holotype *Crossorhinus ornatus*, QM I 164, 560 mm TL, female: A) lateral view; B) dorsal view; and C) ventral view.

Material examined

Holotype. QM I 164, 560 mm TL, female, type locality: Moreton Bay, registered 5th of December 1911.

Other specimens examined. Five specimens: AMS I 43621-001, 890 mm TL, mature male; AMS I 43628-002, 890 mm TL, mature male; AMS I 43628-003, 876 mm TL, mature male; AMS I 43628-004, 925 mm TL, mature male; AMS I 43628-005, 905 mm TL, mature male. All specimens caught together in 5–10 m of water, 10–15 m off northern tip of Tomaree Head, Port Stephens, NSW, 32° 43'S, 152° 11'E. Collector Charlie Huveneers, Rob Harcourt and Roger Laird on the 7th and 8th of May 2005.

Diagnosis

A small *Orectolobus* species with the following combination of characters: no warty tubercles on head or body; four groups of dermal lobes below and in front of the eyes on each side of head; no dermal lobes on chin; nasal barbel closest to mouth branched; three lobes at second preorbital group (rarely four) with first and last lobes branched and longer than middle one; broad unbranched postspiracular groups; lack of supraorbital knobs; base of anterior postspiracular lobe 2.19–3.56 in its distance from postorbital group, 1.19–2.11 in its distance from posterior postspiracular lobe; pelvic-fin insertion anterior to first dorsal-fin midpoint; prepelvic length 1.78–2.22 times pelvic-anal space; pelvic-caudal space 1.52–1.95 times trunk width; teeth in upper jaw 23–27, those in medial row at symphysis rudimentary; spiral valve turns 20–23; precaudal vertebrae count 98–104. Brownish, greenish and greyish colouration with eight darker brown blotch-shaped saddles located dorsally; small light brown, freckle-like blotches between saddles.

Description

Body depressed anteriorly from snout to first dorsal fin origin, firmness of body unknown as holotype is a dry mount, but other examined specimens have slightly firm dorsal musculature with relatively flaccid flanks; trunk depressed, broadest over midtrunk; body shape changing from depressed to compressed and tapering from pelvic-fin mid-point; dorsal musculature slightly elevated from flank musculature forming a small ridge from the fifth gill slit to pelvic-fin insertion, decreasing anteriorly to first dorsal-fin origin. Head broad, strongly depressed, somewhat oval in cross-section with truncate anterior when viewed from above, length 20.8 (19.3–20.8) % TL, 1.79 (1.61–1.79) times second dorsal-fin origin to anal-fin origin, height at gill level 8.9 (7.9–8.9) % TL, 0.77 (0.77–1.06) in pelvic-fin midpoint to first dorsal-fin insertion; trunk width 17.4 (16.9–18.7) % TL; abdomen elongate, width 5.5 (5.3–5.7) % TL. Pectoral-pelvic space 18.0 (15.4–18.2) % TL, 0.86 (0.74–0.92) times head length; pelvic-anal space 3.24 (2.58–3.24) times anal-fin base; snout-vent length (0.81–0.91) times vent-caudal length. Caudal peduncle absent, lower origin of caudal fin almost connected to anal-fin insertion, strongly compressed, oval in cross section at anal-caudal junction, caudal peduncle width 0.71 (0.71–1.56) times height.

Snout short, narrowly rounded in lateral view, truncate in a semi-hexagonal shape in dorsoventral view; preoral length 1.5 (1.0–1.5) % TL, 5.88 (5.88–10.00) in mouth width; prenarial length negligible. Eyes dorsal on head, small, slit-like, length 1.7 (1.6–2.0) % TL, 12.5 (10.00–12.50) in head length; supraorbital crest elevated over and behind eye; no supraorbital knob; ridge extending supraorbital crest above spiracle terminating slightly behind spiracle, terminating above spiracle in other specimens examined; supraocular crest absent in holotype, moderate in size in other specimens examined; interorbit flat to weakly convex, 3.89 (3.07–4.04) times eye

length. Spiracles slit-like, oblique to horizontal axis, longer than eye, 1.56 (1.43–1.76) times eye length; anterior margin convex well elevated above concave posterior margin; small eye spiracle space 0.5 (0.3–0.7) % TL; fold above spiracle absent. Gill slits lateral on head, first three of similar length (1.6–2.1 % TL), fourth gill slit smaller, 0.91 (0.82–0.92) times second gill slit, last gill slit longest, 1.38 (1.18–1.46) times second, last gill slit anterior to pectoral-fin midbase; pectoral-fin origin between second and third gill slit. Mouth subterminal, large 2.2 (2.2–2.6) % TL, horizontally expanded, broadly arched, width 8.1 (8.1–9.1) % TL, 3.35 (3.35–3.81) times its length, 1.59 (1.49–1.59) in dorsal-fin midpoint to pelvic-fin origin; upper labial furrows 3.9 (3.6–4.0) % TL originating at ventral margin of nostrils; lower labial furrows longer 4.8 (4.2–4.6) % TL, 1.09 (1.07–1.17) times upper labial furrows, almost connected to symphysis of lower jaw. Nostrils small, widely separated, internarial space 4.4 (4.4–5.1) % TL, adjacent upper lip of mouth. Nasal barbel terminal on head, medial to nostrils, proboscis-like, rounded basally, tapering distally, length subequal to upper labial furrows; short flattened unbranched lobe at basal third of posterior margin; lateral nasal lobe broad well elevated, subcircular, most expanded posteriorly.

Fang-like teeth relatively large, long and pointed, not exposed when mouth closed. Upper jaw with rudimentary symphyseal tooth recessible into upper lip and flanked distally by one larger symphyseal on either side. Lower jaw with three rows of enlarged symphyseals, their cusps subequal in length to each other and to those at symphysis in upper jaw; tooth cusps distal to symphysis decreasing sequentially in size; tooth shape varies distally from symphysis, first two to three teeth lack cusplets, one to two cusplets from the third or fourth parasymphyseal on either side of the cusp on about four to seven teeth, distal cusplets more pronounced than medial ones,

three to five most distal teeth generally lack cusplets on either side of cusp; teeth formula ($n = 12$): upper jaw $(10-12) + 1 + 1 + 1 + (10-12) = (23-27)$; lower jaw $(7-9) + 3 + (7-9) = (18-21)$.

Dermal lobes well developed; anterior preorbital group with two to three simple lobes, posterior lobe longest; posterior preorbital group with three lobes, anterior and posterior lobe longer and branched; combined distance across preorbital groups 6.7 (6.1–7.9) % TL; anterior and posterior postspiracular group with short, broader, unbranched single lobe, base width of anterior postspiracular lobe 1.1 (1.1–1.3) % TL, base width of posterior postspiracular lobe 0.9 (0.9–1.2) % TL; distance between preorbital group and anterior postspiracular lobe 3.8 (3.5–4.8) % TL, between postspiracular lobes 2.6 (1.5–2.6) % TL.

Dermal denticles small, non-imbricated, crown shield-like, weakly tricuspidate at anterior end, weak ridge on all cusps at anterior end, rounded posterior end. Clasper elongate, extending well beyond tip of pelvic fins, inner length of mature male 14.6–15.6 % TL, (3.91–5.06) times width at base, tip bluntly pointed; four terminal cartilages: ventral terminal, accessory terminal cartilage (or spur), dorsal terminal 2 and dorsal terminal, approximate one-to-one ratio with all terminal cartilages, end-style of axial cartilage slightly calcified and fused with dorsal terminal. When terminal cartilage of clasper is open, spear-like extension near lateral side of axial 16.9 (14.5–19.5) % clasper shaft length.

Dorsal fins similar in size and shape, triangular; anterior margins oblique; apices broadly rounded; posterior margins vertical, very slightly convex to straight; inner margin parallel originating behind pelvic-fin rear tip; second dorsal-fin height 6.3 (6.3–8.0) % TL, 0.43 (0.43–0.59) times pelvic-fin midpoint to second dorsal-fin origin; pre-first dorsal fin 50.0 (48.7–50.3) %

TL, pre-second dorsal fin 64.5 (61.6–64.5) % TL; first dorsal-fin origin slightly forward to pelvic-fin insertion (1.6 % TL); second dorsal-fin insertion slightly anterior to anal-fin origin 1.9 (1.8–3.0) % TL.

Pectoral fin large, length 12.7 (12.2–13.6) % TL, 2.48 (2.40–2.74) times pelvic-fin inner margin length; unknown fleshiness of base due to preservation, but fleshy base in other specimens examined; anterior margin slightly convex; apex broadly rounded; posterior margin slightly convex; inner margin straight, free rear tip very broadly rounded; prepectoral length 17.3 (15.3–19.1) % TL; pectoral-pelvic space 17.9 (15.4–18.2) % TL.

Pelvic fins moderately large, length 11.0 (11.0–14.5) % TL; anterior margin straight; apex very broadly rounded; posterior margin convex; inner margin straight, free rear tip broadly rounded; origin anterior to first dorsal-fin origin, insertion anterior to first dorsal-fin midpoint; prepelvic length 42.5 (39.6–43.5) % TL, 1.85 (1.83–2.22) times pelvic-anal space; pelvic-anal space 23.8 (19.6–23.8) % TL, pelvic-caudal space 30.1 (28.1–31.4) % TL, 1.73 (1.52–1.85) times trunk width.

Anal fin elongate, lobe-like, well developed, base 7.1 (7.2–8.6) % TL, 1.37 (1.37–2.15) times interdorsal space; anterior and inner margins almost parallel, anterior margin first slightly concave then slightly convex; apex very broadly rounded; posterior margin straight, much smaller than anterior margin; inner margin straight, free rear tip slightly rounded; origin slightly posterior to second dorsal-fin insertion; anal-fin height 2.27 (1.49–2.44) times base length; second dorsal-fin origin to anal-fin origin 11.1 (11.6–12.4) % TL; second dorsal-fin insertion to anal-fin insertion 1.74 (1.74–2.04) times terminal caudal margin.

Caudal fin long, strongly compressed; dorsal caudal margin length 21.2 (20.3–21.9) % TL. its origin slightly anterior to anal-fin insertion; upper lobe originating as a very low ridge, slightly distinguishable, anterior margin with a deep inflexion near its origin; outer rim straight and oblique; rounded apices; terminal caudal lobe fan-like; terminal caudal margin 4.1 (4.1–5.1) % TL.

Vertebral counts ($n = 10$): pre-first dorsal count 46–51; pre-second dorsal count 69–74; precaudal count 98–104. Spiral valve whorl count: 20–23 ($n = 22$, based on discarded specimens).

Colouration

Body brownish, greenish, and greyish with eight darker brown, blotch-shaped saddles located dorsally; light brown freckle-like blotches between saddles; first saddle broader than long, posterior to spiracle, anterior to first gill slit, symmetrical from dorsal midline; second saddle at pectoral-fin base level, broader than long; posterior end of third saddle at pelvic-fin origin level, length similar to width, lighter brown green saddle extending laterally; fourth saddle small, lighter brown, anterior to first dorsal-fin origin, overlapping with inflexion of first dorsal fin; fifth saddle from first dorsal-fin midbase to slightly anterior to second dorsal-fin origin, extending laterally and ventrally below mid body, nearly connecting at ventral midline; sixth saddle from second dorsal-fin midbase to slightly anterior to caudal-fin origin, extending laterally and ventrally, nearly connecting at ventral midline; seventh saddle at origin of caudal fin, anterior to anal-fin insertion, longer than broad, extending laterally, not extending on lower lobe of caudal fin; eighth saddle on upper caudal lobe, longer than broad, extending laterally, not extending on

lower lobe of caudal fin; green grey blotches on saddles decreasing in number and size from snout to caudal fin. V-shaped pattern anterior to interorbit; white spot on posterior tip of spiracle.

Underneath of head, trunk and abdomen uniformly yellow green. Tail with three darker brown stripes on the flanks.

Pectoral fins light and dark brown with blotches and white freckles, underneath uniform yellow with white spots; pelvic fins light and dark brown with blotches and white freckles, underneath yellow at base, increasing brown green colour towards posterior margins, slight blotches; anal fin grey brown, similar to tail colouration; dorsal fins light and dark brown with blotches and white freckles and darker brown where saddles occur; caudal fin brown green, darker brown where saddles occur.

Remarks

Orectolobus ornatus was previously considered to be juvenile *O. halei* due to its similarity in morphology and colour pattern. It can be distinguished from *O. halei* by several measurements (Table 2.1) and also differs in 11 specific ratios (Table 2.2).

Orectolobus ornatus is also sympatric with *O. maculatus* and *O. wardi* and can be easily distinguished from them by the number of supraorbital knobs and dermal lobes, and the colour pattern. *Orectolobus maculatus* and *O. wardi* have one or two supraocular knobs, whereas these knobs are absent in *O. ornatus* (Goto 2001). *Orectolobus maculatus* has six to ten dermal lobes, *O. wardi* has unbranched nasal barbels, whereas *O. ornatus* has five dermal lobes and branched nasal barbels. *Orectolobus wardi* has a simple colour pattern with few dark spots, whereas *O.*

maculatus and *O. ornatus* have more elaborate variegated spots and saddles. *Orectolobus maculatus* has white rings that are absent in *O. ornatus*.

Size

To at least 1017 mm TL; males mature between 796–830 mm TL, females mature between 795–864 mm TL (C. Huveneers unpub. data).

Distribution

Eastern Australia from Port Douglas (16° 32'S, 145° 29'E), Qld, to Sydney (151° 23'E, 33° 36'S), NSW.

2.5 Discussion

The very poor description of *O. halei* (Whitley 1940) makes it impossible to quantitatively compare diagnostic features between the neotype herein designated and the previous description. The neotype was therefore assigned from the differing characters in “the colour pattern and the form of the tentacles” as highlighted by Whitley (1940).

The aim of this paper was to define and redescribe *O. halei* and *O. ornatus* to facilitate species identification. Unfortunately, juvenile *O. halei* (smaller than 1100 mm) were not collected despite intensive searching over two years. The ranges of sizes of *O. ornatus* and *O. halei* examined did not overlap and thus differences in morphometry should be interpreted with caution due to allometric factors. Juvenile *O. halei* (smaller than 900 mm) are needed to confirm morphometric differences identified in this study.

The two species can, however, be differentiated using counts of precaudal vertebrae (greater than 105 in *O. halei* and less than 105 in *O. ornatus*) and/or spiral valves (greater than 26 in *O. halei* and less than 26 in *O. ornatus*). However, these characters are impractical for application in the field. Therefore, simpler, but equally robust methods are needed to differentiate species under field conditions.

Total length is the simplest field character for differentiating NSW species. Any wobbegong exceeding 110 cm is either *O. halei* or *O. maculatus* (but not *O. ornatus*) and these two can be easily differentiated using colour pattern and dermal lobes. Wobbegongs smaller than 110 cm are harder to identify. In the case of small males, if the claspers are calcified, the species is *O. ornatus*. For immature males or females, other traits have to be used. Colour pattern may help identification with *O. ornatus*, which is freckled and green/grey (brownier in *O. halei*), and lacks black edges along its saddle markings (otherwise present). However, colouration is highly variable in these species and *O. ornatus* specimens have been observed with an *halei*-like colour pattern. Care must therefore be taken when using colouration alone to identify *Orectolobus* species. Three further key features to differentiate between the two species are the number of dermal lobes at the posterior preorbital group, the position of the pelvic fins, and the supraorbital knobs. *Orectolobus ornatus* usually has only three lobes at the posterior preorbital group, consisting of two branched lobes at the extremities and a shorter unbranched lobe in the middle (more lobes are present in *O. halei*). However, both *O. ornatus* and *O. halei* have been observed with four lobes. Pelvic fins are located further back on *O. halei* with the pelvic-fin insertion at the level of the first dorsal midpoint (*O. ornatus* has the pelvic-fin insertion anterior to the first dorsal midpoint). Lastly, *O. halei* has two small knobs on the supraorbit (absent in *O. ornatus*).

By preference, these features should always be used together to maximise correct identification of *Orectolobus* species in NSW. Commercial fishers using these features should be able to identify *Orectolobus* species and report them accordingly. In the past, all species have been combined together as ‘carpet shark’. Commencing in 2005, NSW DPI has required fishers to report *O. maculatus* separately. Using the characteristics described above, fishers should now be able to report catches of *O. maculatus*, *O. ornatus* and *O. halei* separately. Catch rate statistics could then be used to assess each species independently to investigate potential population decline.

2.6 Key to *Orectolobus* species in New South Wales

1. About 6 to 10 dermal lobes at the posterior preorbital group; white O-shaped spots and white blotches.....*Orectolobus maculatus*

About 3 to 6 dermal lobes at the posterior preorbital group; back with dark colour variegated with blotches and prominent saddle markings.....**2.**

2. Spiral valve whorl count 20–23; precaudal vertebrae count 98–104; size-at-maturity about 800 mm; about 3 to 4 dermal lobes at the posterior preorbital group; no supraocular knobs; pelvic-fin insertion slightly anterior to the first dorsal midpoint

.....*Orectolobus ornatus*

Spiral valve whorl count 29–32; precaudal vertebrae count 106–112; size-at-maturity about 1750 mm; about 4 to 6 dermal lobes at the posterior preorbital group; two distinct supraocular knobs; pelvic-fin insertion at about the level of the first dorsal midpoint

.....*Orectolobus halei*

CHAPTER 3: USING RECREATIONAL SCUBA-DIVERS TO SURVEY THE RELATIVE
ABUNDANCE AND DISTRIBUTION OF WOBBERGONG SHARKS (FAMILY:
ORECTOLOBIDAE) IN NEW SOUTH WALES, AUSTRALIA



© Robert Harcourt (*Orectolobus maculatus* and diver)

This chapter is currently under peer-review with the journal *Conservation Biology*. I am primary author with Dr. Nick Otway (NSW DPI), Dr. Kehui Luo (Macquarie University) and Ass. Prof. Rob Harcourt (Macquarie University) as co-authors. I was responsible for sampling, data analysis and interpretation, and writing the manuscript. Rob Harcourt and Nick Otway contributed by supervising the development of the project and providing comments on earlier versions of the manuscript, whereas Kehui Luo helped with statistical analyses.

Huveneers, C., Luo, K., Otway, N.M. and Harcourt, R.G. (in review) Using recreational scuba-divers to survey the relative abundance and distribution of wobbegong sharks (family: Orectolobidae) in New South Wales, Australia. *Conservation Biology*

3.1 Abstract

Recreational scuba-divers were used to complete a statewide survey of the distribution and relative abundance of wobbegong sharks in New South Wales, Australia during July 2003–January 2005. A total of 316 dives was undertaken by divers reporting 419 wobbegong sightings. A larger number of wobbegongs was sighted north of Newcastle than south of Newcastle. Spotted and ornate wobbegongs were sighted in similar numbers in NSW, but species composition was highly variable across locations. Only a few juvenile and newborn spotted wobbegong (*Orectolobus maculatus*) were sighted throughout the survey whereas small ornate wobbegong were mostly sighted North of Newcastle. These were possibly dwarf ornate wobbegong (*Orectolobus ornatus*). The paucity of small wobbegong sightings suggests that juveniles and newborns are found in areas not surveyed by divers. Imputed potential species segregation as well as nursery areas suggests that conservation measures such as closing areas to fishing might help wobbegong to sustain current fishing pressure. Scuba-diver volunteers were essential to the completion of this large scale survey, but a considerable effort was needed to ensure correct collection of data and continuation of the survey. A full-time facilitator is recommended to ensure temporal and spatial homogeneity of diving effort in future similar studies.

3.2 Introduction

Amateurs and volunteers have helped collect and gather data for scientific purposes for centuries (Mims 1999; Fore *et al.* 2001). This use of volunteers has rapidly increased in the past decade (USEPA 1998). Volunteers have been used worldwide in many conservation orientated projects to conduct baseline surveys and to monitor marine (Halusky *et al.* 1994; Evans *et al.* 2000; Barrett *et al.* 2002), terrestrial (Johnson 2001; Brandon *et al.* 2003), and aerial animals (Blakers

et al. 1984; Brown *et al.* 2001). Recreational scuba-divers are a specialised type of volunteers that can be used to assess species abundance and composition in the marine environment. Recreational divers have previously been used to investigate species distribution and relative abundance of marine species (e.g. Parker and Bucher 2000; Otway *et al.* 2003; Goffredo *et al.* 2005), and to assess the effects of Marine Protected Areas (MPA) (Barrett *et al.* 2002).

Large-scale projects using volunteers require organised and well-coordinated events to collect data. These often need supervision by staff of the project as well as availability on specific dates for large numbers of volunteers. The logistics of organising the appropriate number of volunteers to run an event; in combination with having appropriate weather on the day can be difficult. Events may have to be cancelled due to bad weather and this is complicated by the need to contact and notify all participants (Barrett *et al.* 2002). An alternative is to acquire information from volunteers during their normal recreational activities. In this study, recreational divers were asked to collect data for assessing the distribution and relative abundance of wobbegong sharks in New South Wales (NSW), Australia during regular recreational dives without the constraints imposed by the need to organise large events.

Wobbegong sharks (family Orectolobidae) are bottom-dwelling sharks found in temperate to tropical continental waters of the western Pacific (Compagno 2001). Although there are many taxonomic uncertainties within the Orectolobidae family, eight species are currently known to occur worldwide with three inhabiting NSW waters: the spotted wobbegong (*Orectolobus maculatus*), the dwarf ornate wobbegong (*O. ornatus*), and the large ornate wobbegong (*O. halei*) (Last and Stevens 1994; Chapter 2; Compagno 2001; Huveneers 2006). Wobbegongs have been commercially targeted in NSW within the Ocean Trap and Line Fishery since 1991 for sale as

boneless fillet or “flake”. Their catch has declined from *ca.* 150 tonnes in 1990/01 to *ca.* 70 tonnes in 1999/00 showing a decrease of more than 50% in a decade (Pease and Grinberg 1995; NSW DPI unpub. data). This reduction has lead to wobbegongs being listed as ‘Vulnerable’ in NSW under the World Conservation Union (IUCN) Red List assessment (Cavanagh *et al.* 2003).

Despite their commercial importance, little is known of the population status of any of these species of wobbegongs. Given the dramatic change in landed catch, there is a clear need to ensure that basic ecological data such as distribution and abundance are available for management use. Such ecological parameters are important to better understand the effects of natural and anthropogenic changes such as extensive targeted fishing.

The aim of this paper is to discuss the efficacy of using scuba-divers to carry out surveys during recreational dives using wobbegong sharks as a case study. Distribution and relative abundance of wobbegongs found in NSW as well as species composition and size frequency was investigated using surveys filled out by volunteers.

3.3 Materials and methods

3.3.1 Survey description

Recreational divers were recruited to our survey by advertising the project and the requirements of the survey through scuba-diving and spear-fishing magazines, e-mails to dive clubs and shops and on scuba-diving websites and forums. Presentations about the project’s aims and proposed survey methods were also given at several diving clubs and shops with the aim to train volunteers to accurately record data underwater and to correctly identify wobbegong species. Volunteers

also provided photos distinguishing ornate from spotted wobbegongs showing their ability to discern differences between these two species.

Information requested on the survey form included the lead diver's name and address, dive site details (site, date, habitat and dive duration) and details on each wobbegong sighting (species, sex and estimated size).

At the time the study was organised, only two species of wobbegongs were known to occur in NSW, the spotted wobbegong (*O. maculatus*) and the ornate wobbegong (*O. ornatus*). A third species, *O. halei* formerly synonymised with *O. ornatus*, has since been found to differ from *O. ornatus* (Huveneers 2006; Chapter 2). As the differences between the two species of ornate wobbegongs were unknown at the time the survey commenced, distribution and relative abundance of the dwarf and large ornate wobbegong are combined in this study as ornate wobbegong. Hereafter, ornate wobbegong will be used for all information collected from dwarf and large ornate wobbegong combined, unless stated otherwise. We provided an identification sheet with a picture of ornate wobbegong and spotted wobbegong on the back of the survey form to help divers distinguish between them as well as an instruction sheet to ensure correct filling of the survey form.

A pilot study was undertaken to assess the willingness and ability of divers to undertake multiple surveys and to test their aptitude to record the required biological data. From this pilot study, minor changes were made to the survey form and instruction sheets. Divers were retained in the study if they were able to undertake regular surveys and if they recorded all the required information ('good' surveyors). Some areas of the NSW coast are very popular dive spots.

Therefore an attempt was made to exclude some respondents from the most heavily dived areas by only retaining records from ‘good’ surveyors and to encourage reporting from less popular areas to balance diving effort throughout the NSW coast.

3.3.2 Analysis and statistical methods

Recreational divers may dive at many different sites within a small geographical area, or ‘location’. For example, in Byron Bay, there are at least 19 different dive sites. Therefore, we combined adjacent dive site into ‘location’ using geographic proximity. We divided the study area (NSW) into two regions ‘North’ and ‘South’ based on a previous study on wobbegong distribution (NSW DPI unpub. data). ‘North’ covered from the Queensland (Qld)/NSW border (28° S, 153° E) to Newcastle (32° S, 151° E), whereas the South region covered from Newcastle to the NSW/Victoria border (37° S, 150° E).

Although we selected divers according to their location to try and balance effort, some areas were still overly represented compared to others. Some sites were surveyed only once (e.g. ‘Anemone Bank’, Coffs Harbour and ‘Circus’, Port Stephens), whereas others were surveyed several times (e.g. 23 dives at Shelly Beach, Sydney). The resighting of wobbegongs over successive dives at the same site combined with this lack of consistent effort at different locations can potentially lead to biases in the estimation of wobbegong relative abundance. Different dives at the same dive site are likely to be correlated and thus violating the independent assumption of most standard statistical methods.

To account for this, the mean number of wobbegongs per dive was calculated for each dive site and used as a measure of wobbegong relative abundance, thereafter referred to as ‘site mean

number of wobbegong'. It is reasonable to believe that the site means are independent across dives.

The difference in wobbegong relative abundance between regions was also tested using only locations where more than 15 dives were undertaken to remove locations where a small number of dives were undertaken and which might have not been representative of the area. The locations kept for analysis are Byron Bay, Coffs Harbour and Port Stephens in the North region, and Sydney, Jervis Bay and Batemans Bay in the South region. The number of dives undertaken was also found to be inconsistent temporally. Due to a lack of diving effort during certain months, the variation of wobbegong abundance through time could not be tested across different locations. Sydney was the only location with sufficient number of dives undertaken regularly throughout the year to test for temporal variation.

3.4 Results

We conducted the survey using recreational divers at dive sites along the NSW coast from Byron Bay to Eden covering about 1,275 km over about one year and a half from July 2003 to January 2005. The pilot study lasted from July to November 2003 and was used to ensure correct data recording by recreational divers. Sixty-one divers participated to the survey and completed 316 survey forms. The number of wobbegongs seen in a dive varied from none in 170 dives to 14 in a single dive at South West Rock, with a total of 454 wobbegongs recorded over the entire survey. Out of 316 dives reported, nine were missing dive site and were therefore excluded from further analysis. The remaining 307 dives were undertaken at 142 different dive sites along the NSW coast. At least one wobbegong was seen in 140 out of 307 dives, with a total of 419 wobbegongs recorded during surveys with dive site information.

The diving effort was neither homogenous spatially (Fig. 3.1) nor temporally (Fig. 3.2). There was a strong spatial bias with the largest proportion of dives undertaken in Sydney (56%). Consequently, 76.5% of the dives were undertaken within the South region. Similarly, dives were undertaken in much larger proportion during summer months with nearly 70% of the dives undertaken in the five months during November to March. After the pilot study, the number of dives per month reached a peak of about 70 dives in November 2003 after which it progressively decreased down to about five dives in January 2005 (Fig. 3.2).

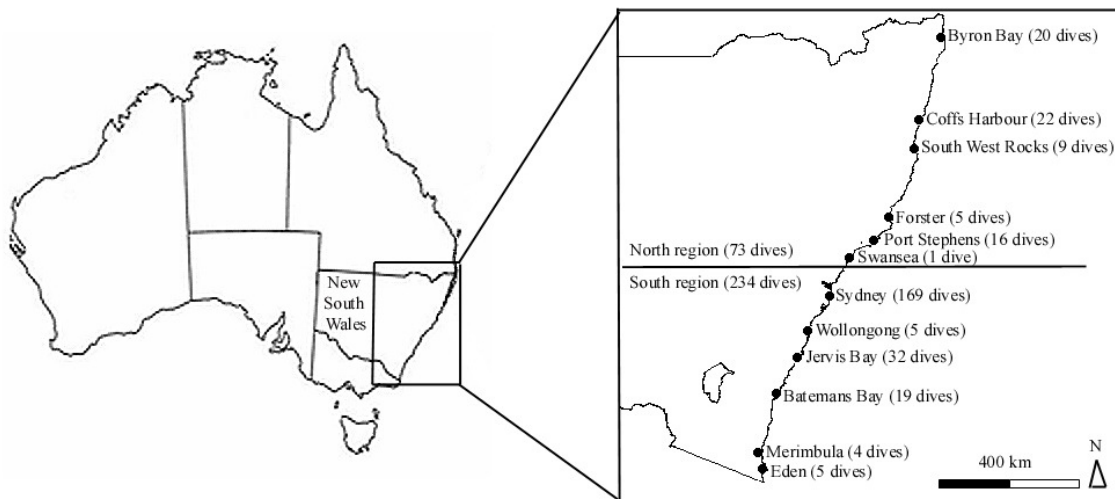


Figure 3.1 Map of New South Wales coast showing ‘locations’ where dives were made and number of dives undertaken in parenthesis.

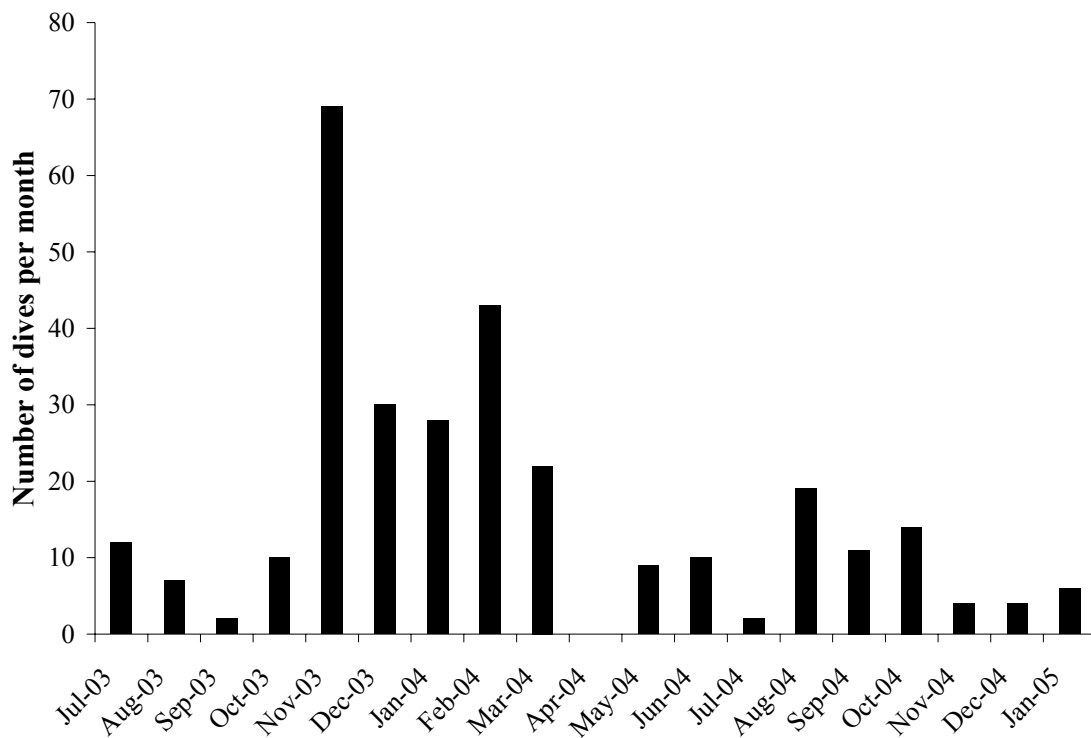


Figure 3.2 Diving effort throughout NSW during the survey period.

As surveys were undertaken during recreational dives, dive duration varied and ranged 30–120 minutes. Accordingly, abundance as a function of dive time would be expected to be a more adequate measure of the wobbegong relative abundance. However, there was no correlation between the number of wobbegongs recorded and dive duration (Spearman's rank correlation: $r^2 = 0.025$, $P > 0.05$). Therefore, the actual numbers of wobbegong sighted was used for all analyses rather than a time-adjusted measure.

There was no statistically significant seasonal variation (based on water temperatures) in the number of wobbegong sighted in Sydney (Mann-Whitney: $P > 0.05$). Because of this and also due to the limitation of dive data across seasons, seasonal effects were not accounted for in further analysis.

The site mean number of wobbegong in the Northern region of NSW (2.85) appeared to be much higher than in the South (0.54) (Mann-Whitney: $P < 0.001$) (Fig. 3.3). Similarly, the site mean number of wobbegong was also higher in the North region when only locations with more than 15 dives undertaken were selected (one-way ANOVA: $P < 0.001$).

The site mean number of wobbegong was also different between locations across the whole NSW coast (Fig. 3.4) (Kruskal-Wallis: $P < 0.05$). The highest site mean number of wobbegong was recorded in South West Rocks and in Byron Bay with a mean of 11 and 5.7 wobbegongs sighted respectively.

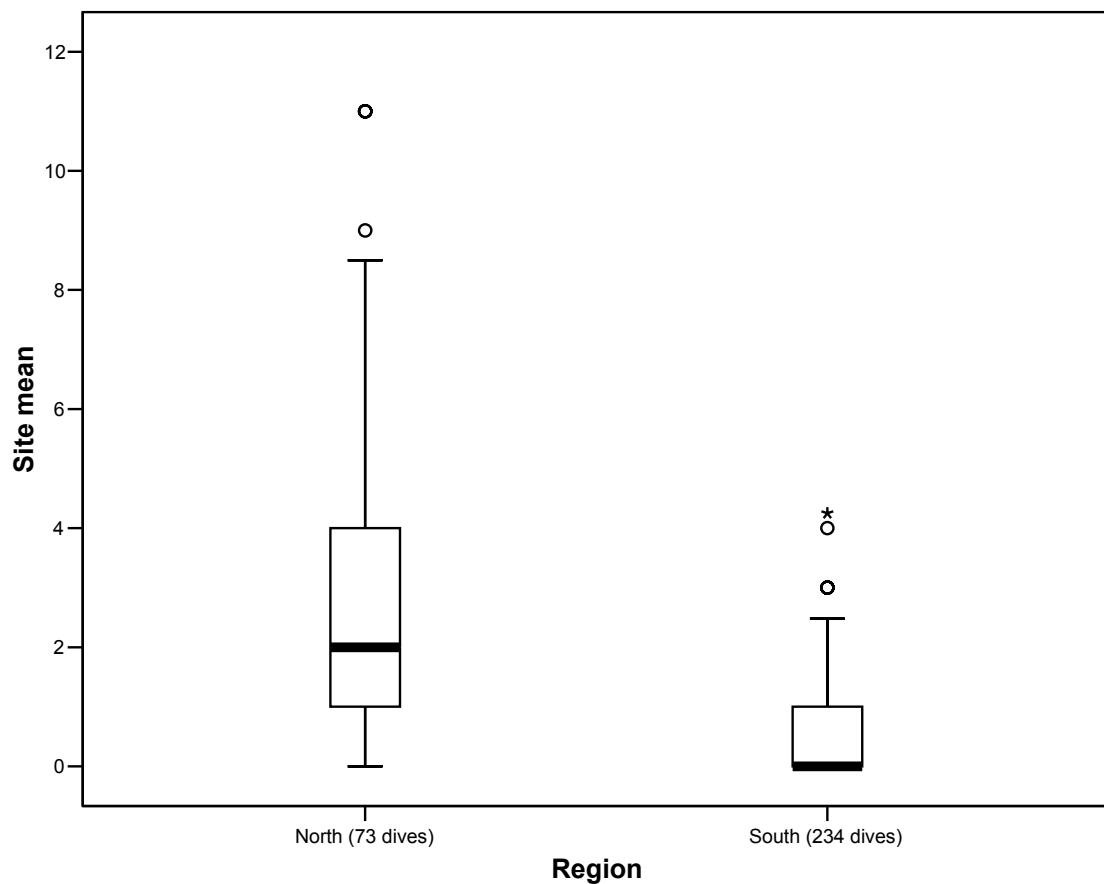


Figure 3.3 Comparison of the site mean number of wobbegong between north and south regions

Median values are indicated by the bold horizontal bar; the length of the box is the interquartile range; whiskers represent quartiles; ○ are extreme values; and * are potential outliers.

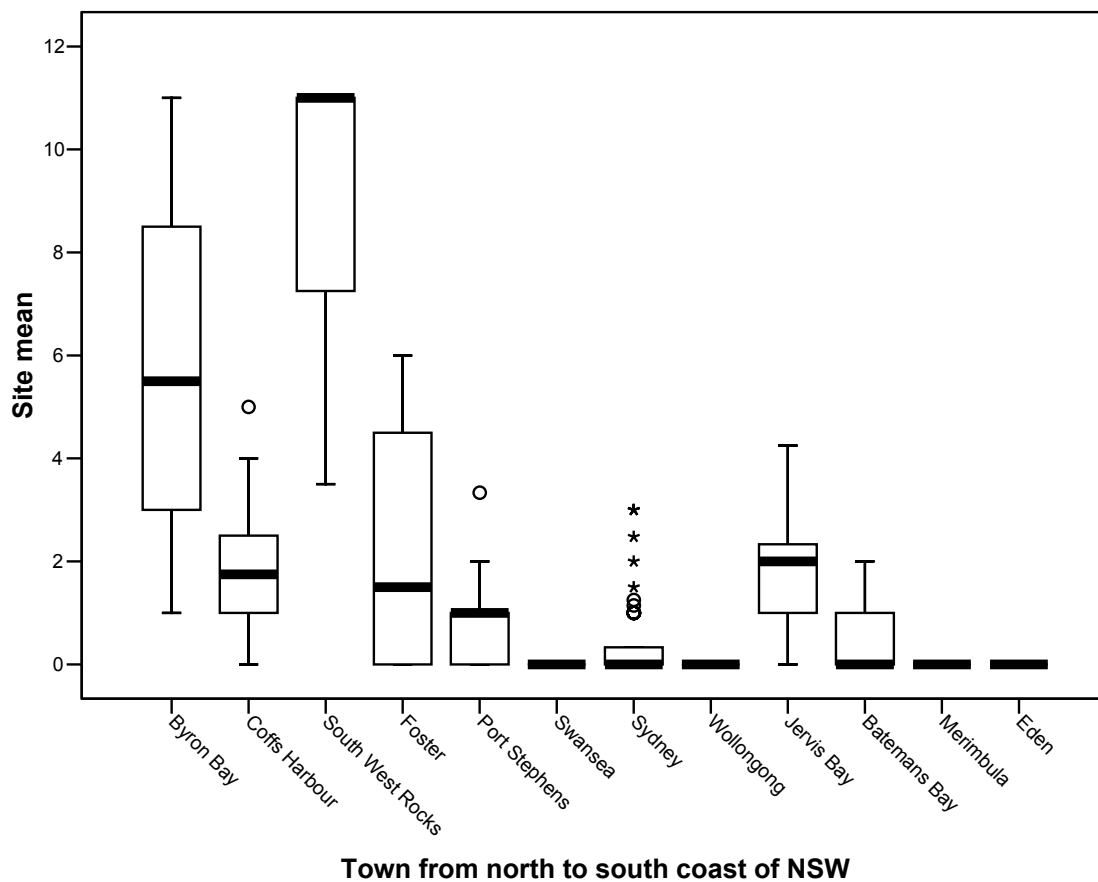


Figure 3.4 Comparison of the site mean number of wobbegong between locations
 Median values are indicated by the bold horizontal bar; the length of the box is the interquartile range; whiskers represent quartiles; o are extreme values; and * are potential outliers.

Although the number of ornate wobbegong was similar to the number of spotted wobbegong across the whole NSW coast, species composition was different between locations (Table 3.1). For example, Coffs Harbour showed approximately equal frequencies of spotted and ornate wobbegongs (48.8 and 51.2% respectively), whereas ornate wobbegongs were far more frequently sighted at South West Rocks (76.7% of sightings), located only 40 minutes South of Coffs Harbour. Similarly, 86.4% of the sharks sighted were ornate wobbegongs in Port Stephens (200km North of Sydney), whereas the majority of sharks sighted in Sydney were spotted wobbegongs (63.1%).

Information on shark size was obtained for 425 wobbegongs. There was a difference in size frequency between species with spotted wobbegongs being sighted in higher numbers at a size of 100–150 cm and 150–200 cm (36% and 33% respectively), whereas ornate wobbegongs showed a greater breadth in size range and were sighted in similar numbers (about 25%) at a size of 50–100 cm, 100–150 cm and 150–200 cm. There were very few wobbegongs smaller than 50 cm sighted for species (3.7 and 5.5% for ornate and spotted wobbegong respectively) (Fig. 3.5).

When analysing size class separately by regions the frequency of small ornate wobbegong (<1.5 m) was much lower in the South (17%) than in the North (62%) (Fig. 3.6).

Table 3.1 Species ratio between ornate and spotted wobbegongs by location.

Location	ornate : spotted wobbegong ratio	<i>n</i>
Byron Bay	1.00 : 1.23	154
Coffs Harbour	1.00 : 1.05	43
South West Rocks	1.00 : 0.30	43
Forster	1.00 : 2.00	9
Port Stephens	1.00 : 0.16	22
Sydney	1.00 : 1.71	84
Jervis Bay	1.00 : 3.00	64
Batemans Bay	1.00 : 0.50	6

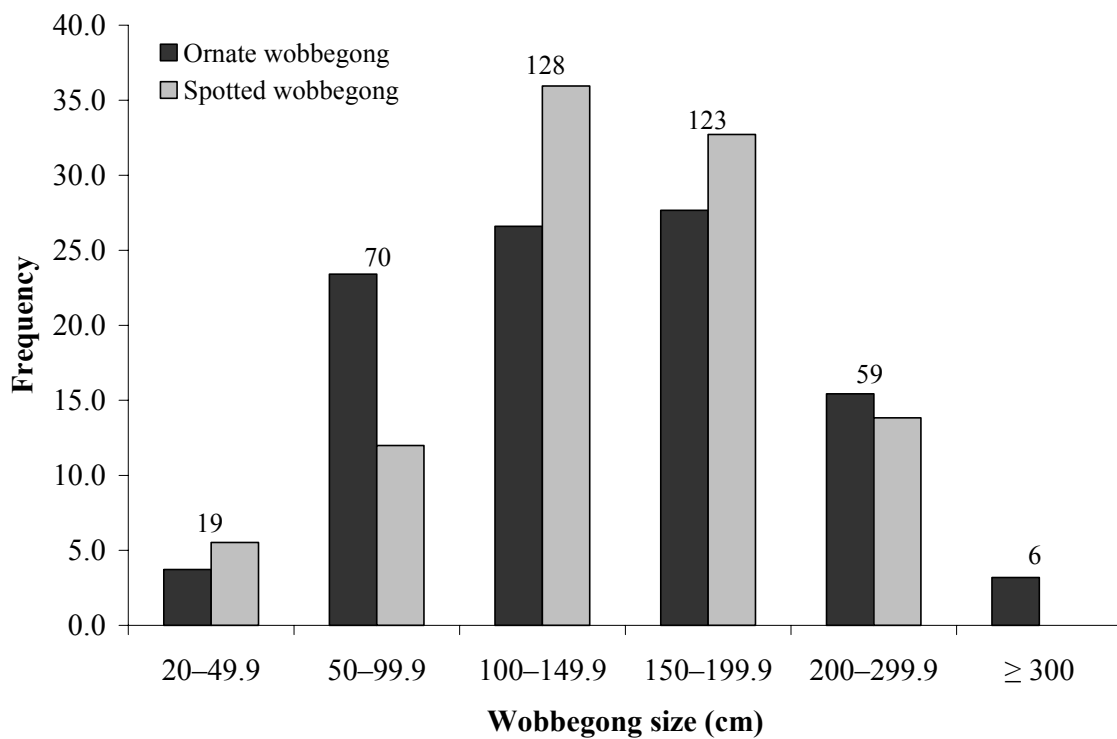


Figure 3.5 Frequency of wobbegong sightings by species across size class; number above bar is sample size.

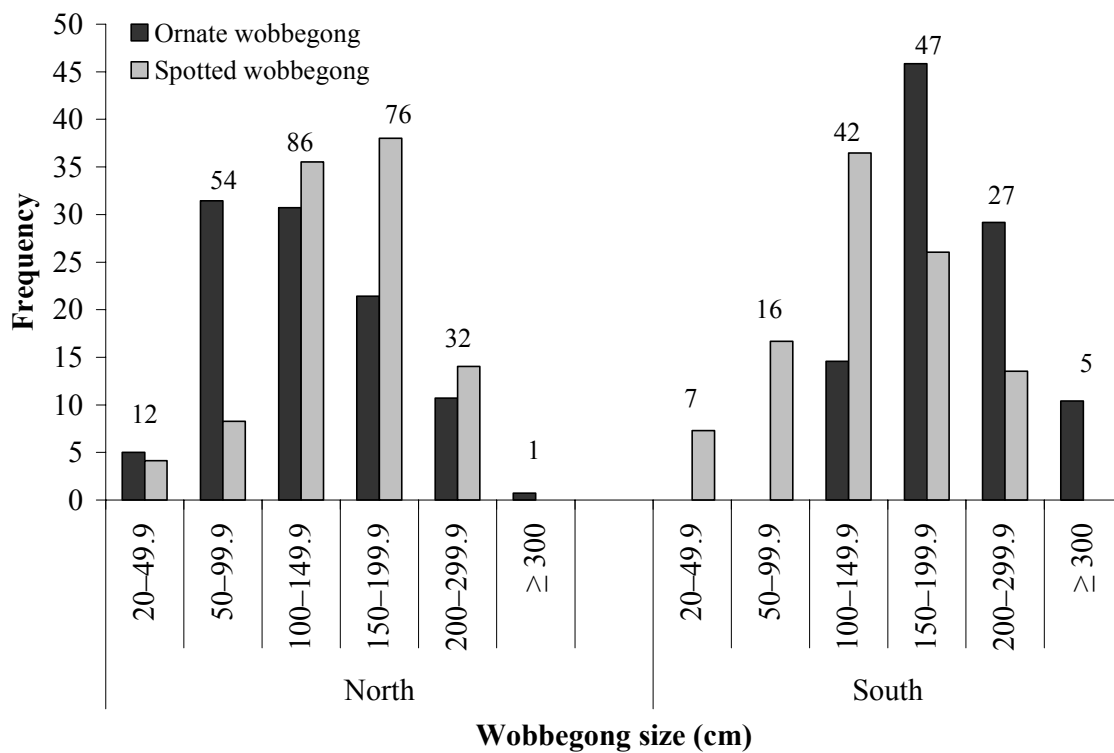


Figure 3.6 Frequency of wobbegong sightings across size class separated by species and region; number above bar is sample size.

3.4 Discussion

3.4.1 *Wobbegong relative abundance and distribution*

Wobbegongs are cryptic sharks mostly living in cracks and crevices. Sighting rate may therefore vary according to the proportion of divers' time actively spent searching for wobbegongs under rock overhangs and inside crevices. As recreational divers are primarily diving for their own needs, their motivation and therefore dive pattern may vary. Whereas some might spend most their dive observing pelagic fishes others may have devoted their dive to the survey and searched carefully for wobbegongs. Dive duration was recorded to measure effort and was not related to sighting success, but the extent to which divers actively searched for wobbegongs could not be quantified.

Although diving effort was temporally inconsistent, potentially affecting the abundance estimation at the different location, dives were mostly undertaken around the same period across NSW limiting spatial biases arising as an artifact of temporal variation. Furthermore, no seasonality in the number of wobbegong was found in Sydney suggesting that the lack of temporal homogeneity had a limited effect on the results obtained in this study. Consistent diving effort across different locations throughout the year is necessary to confirm the lack of temporal variation in abundance.

A larger number of wobbegongs were sighted by divers north of Newcastle. This accords with a preliminary study by NSW DPI (NSW DPI unpub. data). Water temperature has been found to influence chondrichthyan distribution both directly and indirectly (Klimley and Butler 1988; Klimley *et al.* 1988; Casey and Kohler 1992; Morrissey and Gruber 1993; Economakis and Lobel 1998). Within Southeastern North Carolina coastal waters, some chondrichthyan species such as

smooth dogfish (*Mustelus canis*) may favour temperature colder than 24°C, whereas others such as finetooth shark (*Carcharhinus isodon*) favour temperature warmer than 26°C (Thorpe *et al.* 2004). Water temperature variations can also be a key factor controlling chondrichthyan migrations (Compagno 1984), but could not be tested in this study due to the lack of diving undertaken throughout the year and at various locations up and down the NSW coast.

Only a few small spotted wobbegongs were sighted by volunteers. Similarly, only a few small ornate wobbegongs were sighted by volunteers south of Newcastle. However, 62% of ornate wobbegongs sighted north of Newcastle were sharks smaller than 1.5 m. Although only two species were recorded during the survey, recent research has confirmed the existence of a third wobbegong species in NSW (Huveneers 2006; Chapter 2). *Orectolobus halei* was formerly believed to be the adult specimens of *O. ornatus*, whereas what is now identified as *O. ornatus* was previously mistaken for juveniles. It is possible that many of the small ornate wobbegong were actually adult *O. ornatus*. The southern limit for *O. ornatus* is Sydney (Huveneers 2006; Chapter 2), possibly explaining the lack of small ornate wobbegongs in Southern NSW. Small *O. halei* may therefore be rare along the whole NSW coast. This is supported by data collected from commercial catches in which small juvenile and newborn wobbegongs are only sporadically caught (Huveneers *et al.* in review-a; Chapter 5).

Wobbegong sharks in NSW have a size-at-maturity of 175 cm for large ornate, 135 cm for spotted wobbegong and 80 cm for dwarf ornate (Last and Stevens 1994; Chapter 7; Compagno 2001; Huveneers *et al.* in review-b). Most sharks sighted were therefore mature sharks, whereas small juvenile and young of the year were nearly absent and were sighted in small numbers only. Size segregation in wobbegongs is believed to occur around Byron Bay with mainly ‘juvenile

ornate wobbegong' of about 60-100 cm and adult spotted wobbegong (Baker 1998). The discovery of the existence of *O. ornatus* and *O. halei* indicates that such size segregation might be inaccurate with juvenile ornate wobbegongs actually being adult *O. ornatus*. Therefore, size segregation might occur in Byron Bay, but rather than having mostly juvenile ornate wobbegong and adult spotted wobbegong, a lack of both juveniles and young of the year for all three species occurs in Byron Bay. Newborn and small juvenile wobbegongs are likely to be overlooked by divers as small wobbegongs can hide in small cracks not visible to divers. However, newborns and small juveniles might also occur in areas not surveyed. Such areas might not have been explored due to their difficult access (e.g. offshore in deeper waters where it is dangerous for divers to dive in estuaries where visibility and currents result in poor diving conditions) or in areas which are characterized by a lack of 'interesting' things to see for divers (e.g. large tracts of seaweed covering the seabed tend to be avoided by divers as limited wildlife can be seen through the thick seaweed). Many chondrichthyan species use nursery areas which have been identified as important areas for the protection of shark species (e.g. Gruber *et al.* 1988; Heupel *et al.* 2004; Thorpe *et al.* 2004). If nursery areas are important to wobbegongs to ensure that pups and juveniles grow sufficiently to reach maturity and enter the breeding population, then identification of such areas is an important conservation priority.

There was some variation in species composition within geographically close locations and sites. For example, 86.4% of the sharks sighted in Port Stephens were ornate wobbegong, whereas in Sydney most sharks were spotted wobbegongs. This variability in species composition indicates patchiness in the distribution and relative abundance of wobbegong species potentially suggesting species-specific site preference. This is further suggested when comparing the species composition observed by divers to that caught by fishers (Table 5.1, Chapter 5). The species

composition of wobbegongs caught by fishers in Sydney and Port Stephens is highly different to the composition observed by divers. In both locations, dive sites and fishing sites were geographically separated supporting species-specific site preference. The creation of aquatic reserves or marine parks in those areas where a particular species of wobbegongs is found may help protect that species. If this is the case, the identification of those species-specific preferred sites is needed.

The potential existence of nursery areas and species-specific preferred sites indicates that areas closed to fishing such as marine parks, aquatic reserves or critical habitats may be helpful towards wobbegong conservation along the NSW coast. This is further supported by the residency pattern of wobbegongs where some individuals have been recorded for over two years within a geographic location similar in size to a large dive site (Huveneers *et al.* in press; Chapter 4). The information gathered by this study should also be compared to the catch and effort data from the targeted fishery to identify locations where wobbegong numbers are high and where area closure would be the most efficient. However, effort data is currently unavailable due to catch reports to the NSW Department of Primary Industries requiring insufficient effort data from commercial fishers. Although sample size is relatively small, this study gives an indication of wobbegong relative abundance around the NSW coast and could be used as pilot study to focus future research on the ecological studies of wobbegong sharks.

3.4.2 The use of recreational scuba-divers as volunteers

Volunteer monitoring programs have the capacity to provide large amounts of cost effective and reliable data {Forster-Smith, 2003 #612} {Pattengill-Semmens, 2003 #613}. In our study, the use of non-specialist volunteers such as recreational divers was found to be a useful and cheap

method to gather a large amount of distribution and relative abundance data. Large economies can be made by the transfer of resources as most of the costs are borne by the volunteers, whereas sampling effort and geographic coverage are much larger than would otherwise be feasible. For example, more than 6000 dives by over 200 individuals were required to complete the baseline survey of seagrass beds in Tanzania (Darwell and Dulvy 1996). This study was only possible through the participation of a large number of volunteers. Similarly in the present study, 316 dives were undertaken in a total of 550 days, including about 390 working days, along 1280km of coast. In order to achieve such diving effort, a scientific dive team would have had to dive nearly every working day for a year and a half while traveling throughout the whole NSW coast which is not only realistically unachievable, but would also entail large financial costs not required when using volunteers.

An essential component of community involvement is to enhance adequate training to ensure accuracy of data recorded. Diver volunteers have been shown to collect meaningful data that closely approximates those obtained by skilled researchers with the bare minimum of training if analysed at the appropriate level (Darwell and Dulvy 1996). It was attempted to minimise species misidentification and misrecording of data by providing a clearly marked identification sheet on the back of the forms which divers could refer to *in situ* during the dive; by presentations on the methodology at dive clubs and shops; and by excluding unreliable divers after the pilot study. Furthermore, only two species were needed to be identified, whereas the other tasks were relatively simple for divers. A close relationship between volunteers and the scientific community is a way to promote and ensure data quality of volunteer recording activities.

Another major limitation of this survey was the lack of homogeneity across regions. When using a network of volunteers across a wide area, effort is likely to be greater in some areas compared with others and that it will be greater at particular seasons. This was seen in our survey with 56% of the dives undertaken around Sydney reflecting a bias introduced due to human demography. Sixty two percent of the NSW population lives in Sydney (ABS 2001 Census)¹. Furthermore, survey locations were difficult to plan as recreational divers dive for pleasure and choose dive sites that are more enjoyable. Therefore, some areas were not dived due to their lack of wildlife, cold water, exposed conditions or general inaccessibility. Effort should be made to extend coverage evenly over as wide an area as possible and to do likewise for coverage throughout the year. Although the use of organising survey events with their own limitations was avoided by using recreational dives, the need to ensure the program is organised and executed properly and ensure data quality and homogeneity of survey effort may require substantial organisational input at a professional level to facilitate such a project. This may be accomplished by using a full-time employee or facilitator. The need for such a skilled facilitator increases the cost of running a volunteer program and highlights the decisions that need to be made by the chief investigators when deciding whether or not to use volunteers.

The level of commitment from volunteers is also highly unpredictable. It is important to maintain the engagement of volunteers. The repetition of detailed studies in single areas has been found to lead to a drop in the level of interest which is likely to lead to the decrease of volunteers involved as well as a reduction in the quality of data collected (Barrett *et al.* 2002). Volunteer interest was difficult to maintain as illustrated by the decline of surveys undertaken during the present survey.

¹ Australian Bureau of Statistics Census 2001, Sydney, NSW, Australia Available from <http://www.abs.gov.au/websitedbs/d3310114.nsf/home/Previous%20Censuses:%20Census%20data> (accessed 6th June 2006)

The colder waters of winter and spring further limits the ability to keep a regular program underway throughout the year. Interest waned when water and air temperatures fall below comfortable levels, as seen in the present study with nearly 70% of the dives undertaken in summertime. Both spatial and temporal homogeneity of diving effort is a major challenge requiring much effort, and is often given too little attention further emphasising the need for a facilitator.

The use of volunteers to assess distribution and abundance of marine creatures across a large geographical area, such as the whole NSW coast is very cost effective, provided the limitations of the data collected are recognised. Volunteers represent a huge workforce able to undertake labor intensive, but technically straight-forward work, i.e. beyond the resources of most scientific studies, as they can cover a large geographic range in a short period of time. Before deciding on using volunteers to help in the gathering of data a careful assessment should be undertaken to estimate the costs and benefits of using non-specialist volunteers. This assessment should include: the type of information volunteers will be gathering; the timeframe available; and the real costs involved in organisation of the project; in particular taking in to account the potential need for a facilitator.

CHAPTER 4: OBSERVATIONS OF LOCALISED MOVEMENTS AND RESIDENCE TIME OF
WOBBEGONG SHARKS (*Orectolobus halei*) AT FISH ROCK, NEW SOUTH WALES,
AUSTRALIA



© Ulysse Bove (*Orectolobus halei* tagged with a V16 acoustic tag)

This chapter has been accepted in the journal *Cybium* as part of the proceedings of the European Elasmobranchs Association 2005 Annual meeting. I am primary author with Dr. Nick Otway (NSW DPI), and Ass. Prof. Rob Harcourt (Macquarie University) as co-authors. I was responsible for sampling, data analysis and interpretation, and writing the manuscript. Rob Harcourt and Nick Otway contributed by supervising the development of the project and providing comments on earlier versions of the manuscript. Permission from the editor of the proceedings to reproduce the manuscript was obtained by the first author.

Huveneers, C., Harcourt, R.G. and Otway, N.M. (in press) Observations of localised movements and residence time of wobbegong sharks (*Orectolobus halei*) at Fish Rock, New South Wales, Australia. *Cybium*

4.1 Abstract

Passive acoustic telemetry was used to assess the localised movements of seven wobbegong sharks (*Orectolobus halei*) for about two years at Fish Rock, NSW, Australia. Four of the seven sharks were detected for less than 40 days only. This was most likely due to tag loss, although emigration of these individuals cannot be dismissed. However, three sharks were regularly detected for periods of approximately four, 10 and 20 months suggesting longer-term residency. Wobbegongs were mostly detected around the southern side of Fish Rock by one or two receivers. Diel patterns were also observed with a greater presence of sharks during daylight hours than at night. The long-term residency pattern displayed by three of the sharks suggests that temporal closures or marine protected areas may be effective tools for the management and conservation of local populations.

4.2 Introduction

Wobbegong sharks (family *Orectolobidae*) are bottom-dwelling sharks found in temperate to tropical continental waters of the western Pacific (Compagno 2001). While there are taxonomic uncertainties, eight different species are currently found worldwide with seven in Australian waters. Previously two species of wobbegongs, the spotted wobbegong (*Orectolobus maculatus*) and the ornate wobbegong (*O. ornatus*), were known to occur in New South Wales (NSW) waters (Last and Stevens 1994; Compagno 2001). However, *O. ornatus* has recently been found to comprise two distinct species differing in their morphometric and meristic measurements as well as their biology (Huveneers 2006; Chapter 2). *Orectolobus ornatus* grows to about 110 cm Total Length (TL), whereas *O. halei* can grow to 300 cm TL.

Wobbegongs have been commercially targeted in NSW by the Ocean Trap and Line Fishery since 1991 and sold as boneless fillets or “flake”. The catch has declined from *ca.* 150 tonnes in 1990/01 to *ca.* 70 tonnes in 1999/00, a decrease of more than 50% in a decade (Pease and Grinberg 1995; NSW DPI unpub. data). Little information has been collected on this fishery and thus, the extent to which this decline may be attributed to changes in fishing effort is unclear. Furthermore, as the catch is not identified to species, it is not known whether this decline is consistent among the three species. Despite this, concerns that this overall decline may be indicative of changes in wobbegong abundance along the NSW coast led to wobbegongs being listed as ‘Vulnerable’ in NSW under the World Conservation Union (IUCN) Red List assessment (Cavanagh *et al.* 2003).

Given the decline in landed catch, there appears to be a clear need to ensure that basic ecological and biological data are available for use in management of the wobbegong fishery. Quantitative data on the ecology of marine vertebrates such as habitat utilisation, dispersal, periodicity of movements, residence times and home ranges can augment understanding of the spatial dynamics of fisheries and guide management and conservation strategies (Simpfendorfer 1992; Economakis and Lobel 1998; Ackerman *et al.* 2000; Heupel and Hueter 2002; Nakano *et al.* 2003; Sepulveda *et al.* 2004).

Passive acoustic telemetry is one effective means of determining home range size, diel activity patterns, site fidelity and habitat preferences (Holland *et al.* 1996; Zeller 1999; Meyer *et al.* 2000) and has been used to document these parameters in a variety of marine animals including teleosts (e.g. Klimley and Holloway 1999; Hartill *et al.* 2003; Humston *et al.* 2005), cephalopods (e.g. Stark *et al.* 2005), marine mammals (e.g. Wartzok *et al.* 1992; Hindell *et al.* 2002; Bradshaw *et*

al. 2006) and sharks (e.g. Heupel and Simpfendorfer 2005). Results obtained with this technology have been used to discuss the effectiveness of Marine Protected Areas (MPAs) (e.g. Lowe *et al.* 2003; Egli and Babcock 2004; Lindholm and Auster 2005), albeit not with wobbegongs. While MPAs have become an essential component of marine management plans aimed at protecting teleosts from overfishing (Bohnsack 1998), it has been argued that MPAs are not effective for large, mobile or migratory species such as sharks (e.g. Bonfil 1999b; Roberts 2000). However, marine reserves are now increasingly being considered as a possible component of management and conservation strategies for sharks (Camhi *et al.* 1998; Baum *et al.* 2003; Chapman *et al.* 2005) especially when MPAs protect animals when they are highly vulnerable or during key parts of their life-cycles such as in nursery or mating areas (Bonfil 1999b; Heupel and Simpfendorfer 2005).

One of the main considerations when designating a spatially-based management strategy, such as MPAs, is the extent of movement in and out of the area and site fidelity exhibited by the target animals (Bonfil 1999b; Kenchington 1999; Kramer and Chapman 1999; Roberts *et al.* 2001; Botsford *et al.* 2003; Meester *et al.* 2004; Chapman *et al.* 2005). Long residence times associated with limited movements outside a specific geographical area increases the chances of a local population decline if extensive fishing occurs within that area. Research efforts should, therefore, be directed towards defining the size of home ranges, migratory routes and timing and the rates of movement in and out of potential marine reserves (Bonfil 1999b). The paucity of such information for most chondrichthyans makes it difficult to design appropriate MPAs and manage chondrichthyans effectively (Chapman *et al.* 2005).

If MPAs may be used to conserve and/or manage wobbegong sharks, their degree of mobility needs to be determined; yet, little research has been undertaken on their movements and residence time. The only previous study investigating the habitat usage of individual *O. ornatus* showed that *O. ornatus* were not permanent residents within a small aquatic reserve covering 75 hectares and had variable residence times. Some individuals exhibited temporary site fidelity of up to 211 days with frequent re-sightings while others were temporary visitors, being re-sighted only once after initial identification (Carraro and Gladstone 2006). However, the study was undertaken using scuba diving surveys combined with photographic and tagging techniques, therefore limiting the continuous recording of shark presence. Some wobbegongs might also have been present, but were not sighted during the underwater surveys.

The aim of the present study was to use automated acoustic telemetry techniques to assess the localised movements and residence times of wobbegongs at Fish Rock.

4.3 Methods

4.3.1 Study site

Fish Rock (30° 56.4' S, 153° 06.1' E) is located 1.2 nm offshore from Smoky Cape lighthouse (Fig. 4.1). Fish Rock is a small, granitic pinnacle approximately 120 m in width surrounded by fringing rocky reef extending laterally for about 100 m. Thereafter, the habitat comprises extensive undulating sediments in 30–40 m of water. Fish Rock itself has a subtidal cave that passes through the rock with its western entrance in 12–15 m of water and its eastern entrance in about 23 m. Grey nurse sharks (*Carcharias taurus*), wobbegongs and many species of teleost fishes have been observed swimming in and out of the cave.



Figure 4.1 Location of study site with position of the receivers.

4.3.2 Tags, receivers and tagging

The movement patterns of tagged sharks were monitored and recorded using acoustic receivers deployed to document the localised usage of Fish Rock by *C. taurus* (see Bruce *et al.* 2005 for details). Wobbegong sharks were tagged with V16 R-coded transmitters (Vemco Ltd, Shad Bay, Nova Scotia, Canada). Transmitters were coded with a unique pulse string so that each shark could be individually identified. The pulse transmitted an ID code at 69.0 kHz at randomly spaced intervals between 20 and 69 seconds. Theoretical maximum detection rate was between 180 detections/hour for a 20s interval and 52 detections/hour for a 69s interval.

R-coded tags were inserted into small positively buoyant floats (80 mm x 35 mm) to avoid the tags rubbing against the shark's skin potentially causing skin lesions and tethered to a metallic dart (32 mm x 8 mm) with 5 to 10 cm of 90 kg monofilament nylon line. The tag/float combination was coated with antifouling paint to reduce fouling by algae and/or barnacles that could potentially limit tag transmissions and/or cause skin lesions. Each dart was inserted into the dorsal musculature of the wobbegong at the base of the first dorsal fin and allowed to float next to the fin. Tags were applied by scuba divers using a modified hand spear. One shark (shark 175) was tagged in a pilot study ten months prior to the remaining six to test tag retention and feasibility of the study.

The presence of tagged wobbegongs was recorded by six VR2 acoustic receivers (Vemco Ltd, Shad Bay, Nova Scotia, Canada) deployed individually at Fish Rock for up to 22 months (Fig. 4.1). The acoustic receivers were retrieved and replaced at 6–8 month intervals to ensure no data were lost due to battery failure or overloading of a receiver's memory.

4.3.3 Analysis

To determine residence times of wobbegongs around Fish Rock, the amount of time over which a wobbegong was continuously detected by any receiver without an absence longer than 24 hours was calculated and defined as a 'visit'. If a shark was detected on at least one receiver during a 60 min period it was assumed to be present for that hour. Excursions were defined as the duration in which a wobbegong was not detected, for a period longer than 24 hours, by any receiver. As the distributions of visits and excursions were highly skewed and could not be normalised by transformation, the median was used instead of the mean.

The time series of the daily patterns of mean hourly detections for shark with detections longer than four weeks was analysed using a Fourier analysis to detect periodicity. Fourier analysis, a type of harmonic mean analysis, is a decomposition of a time series into the sum of its sinusoidal components. Fourier transforms can only be performed on data series whose lengths are a power of two and thus some truncation of the data series was necessary. As a result of this truncation, 85.3 days of data (i.e. 2048 one hour periods) were available for three sharks.

Detection rates (hourly number of detections standardised by the mean hourly detection) and presence rate (number of hours detected) were used to assess daily behavioural pattern. Diel differences were examined by calculating detection rates and presence rates for day and night separately. They were compared using the non-parametric Mann-Whitney test as data were not normally distributed and remained so after transformation. Statistical tests were undertaken on sharks that had been detected for more than 30 days (sharks 175, 104, 102).

When the receivers were first recovered, SWR 3 was missing and SWR 6 had been flooded. All remaining receivers detected tags reliably. During the second deployment of the receivers, SWR 3 was abandoned and moved to a different location (Green Island) about 2.4 nm to the north of Fish Rock to determine whether movements between Fish Rock and Green Island occurred. After the second recovery of the receivers, it became apparent that SWR 1 and SWR 6 had been unable to detect tags due to technical problems. All remaining receivers detected tags reliably. Technical problems with several receivers and the inability to calibrate receivers' range due to time and weather constraints limited analysis of preferred location around Fish Rock. A conservative estimate of 400 m detection radii has been assumed in other studies where receiver calibration was not possible (Stark *et al.* 2005). Although, no data from receiver positioned on SWR6 was recoverable, sharks located in that area would have most likely been detected by either SWR1 or SWR5 as their ranges overlapped as shown by a shark detected by those receivers simultaneously. However, the range of receivers adjacent to SWR3 did not overlap resulting in a 'blind spot' around SWR3.

4.4 Results

The single *O. halei* (shark 175) tagged for the pilot study was monitored for 669 days. Six other *O. halei* (sharks 99 to 104) were tagged on the 12th of October 2004 and monitored for 362 days. All sharks were about 150–200 cm TL and were tagged in close proximity to receiver SWR 5 (Fig. 4.1). Four of the seven tagged *Orectolobus halei* were detected for less than 37 days. The three remaining sharks were detected for 122, 297 and 603 days and were considered “Residents” (Fig. 4.2).

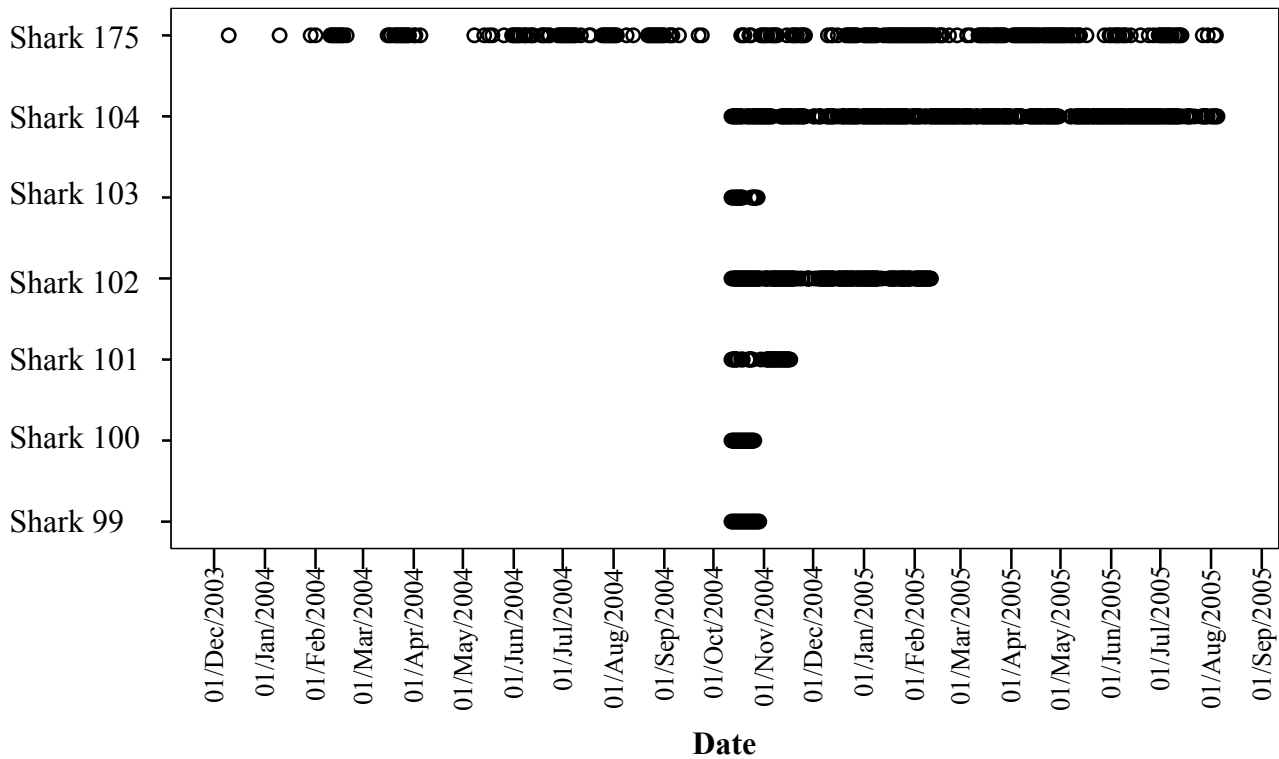


Figure 4.2 Time series of acoustic detections for wobbegongs.

Table 4.1 Details of detected tagged sharks

‘Dates tracked’ is the date of tagging and last detection for each shark; ‘Period detected’ is the number of days from tagging to last detection; ‘Number of days detected’ is the number of actual days on which each shark was detected; ‘Visit’ is the duration for which a wobbegong was continuously detected by any receiver without an absence longer than 24 hours; ‘Excursion’ is the duration in days in which a wobbegong was not detected by any receiver for a period longer than 24 hours. For ‘Visit’ and ‘Excursion’, minimum and maximum is given with median in brackets.

Tag	Dates tracked	Period detected	No of days detected	Visit (day)	Excursion (day)
99	12/10/2004 - 29/10/2004	17	17	17.04	-
100	12/10/2004 - 26/10/2004	14	14	0.51–11.7 (6.11)	1.44
101	12/10/2004 - 17/11/2004	36	27	0–14.87 (1.97)	1.06–4.82 (2.39)
102	12/10/2004 - 11/02/2005	122	108	0.01–13.64 (2.42)	1.1–3.68 (1.47)
103	12/10/2004 - 28/10/2004	16	12	3.9–7.01 (5.46)	5.18
104	12/10/2004 - 05/08/2005	297	259	0.5–54.05 (2.48)	1.03–6.39 (1.55)
175	10/12/2003 - 04/08/2005	603	267	0.2–25.07 (0.36)	1.01–33.48 (2.51)

The durations of visits were mostly short with 75% of visits less than 4 days and the longest visit being 54 days (Fig. 4.3a). The duration of visits also varied greatly for any given shark and among individual sharks (Table 4.1). For example, the visits of shark 104 varied from less than one hour up to 54 days. In contrast, shark 175 exhibited shorter visits with a median of 0.36 days. Lastly, shark 99 was only detected for 17 days and never left Fish Rock for more than 24 hours and, by definition, had only one visit. Excursions outside the detectable range of the receivers were predominantly short in duration, but longer excursions were also evident. The vast majority (85%) of the excursions lasted less than 5 days, whereas some were as long as 33.48 days (Fig. 4.3b and Table 4.1). The median excursion duration over the entire length of the study was 1.85 days. Visual inspection of visits and excursions through time showed no periodicity with sharks showing no distinct pattern in the lengths of visit and excursion or intervals between them. However, the Fourier analysis of 2048 hours (24 weeks) of continuous observations revealed a potential 3 day periodicity (Fig. 4.4). Three smaller peaks also indicate a potential 2 day, 16 hour and 12 hour periodicity.

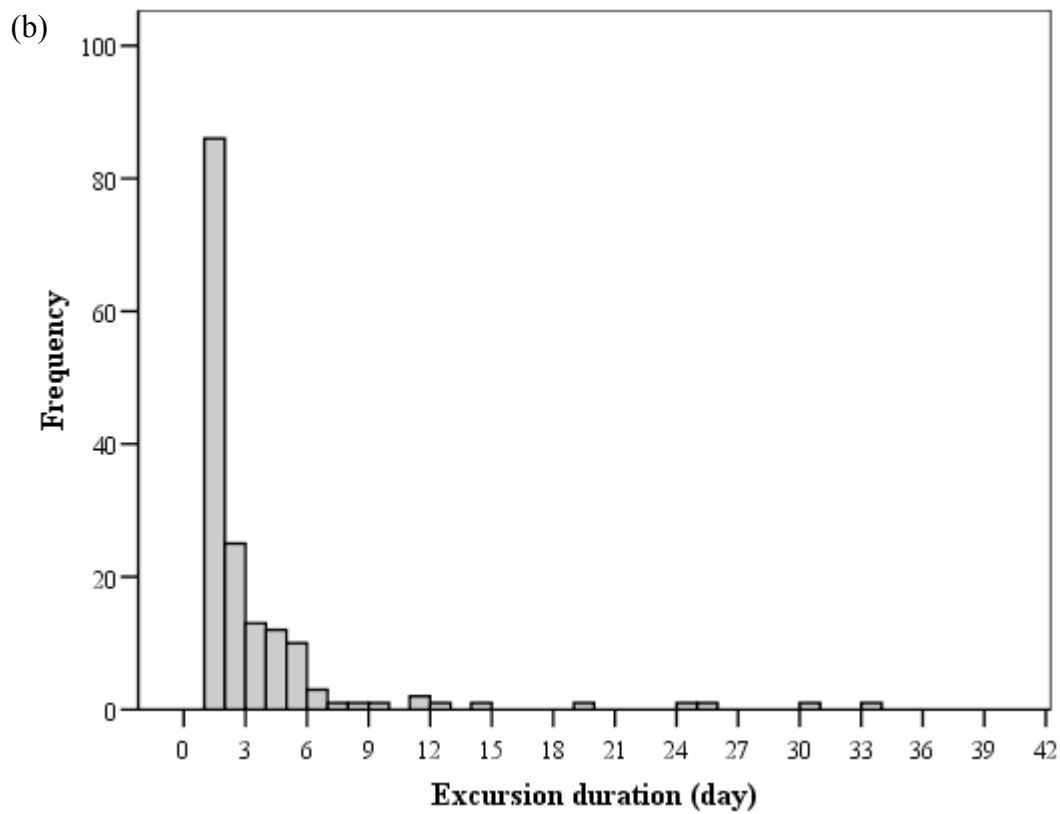
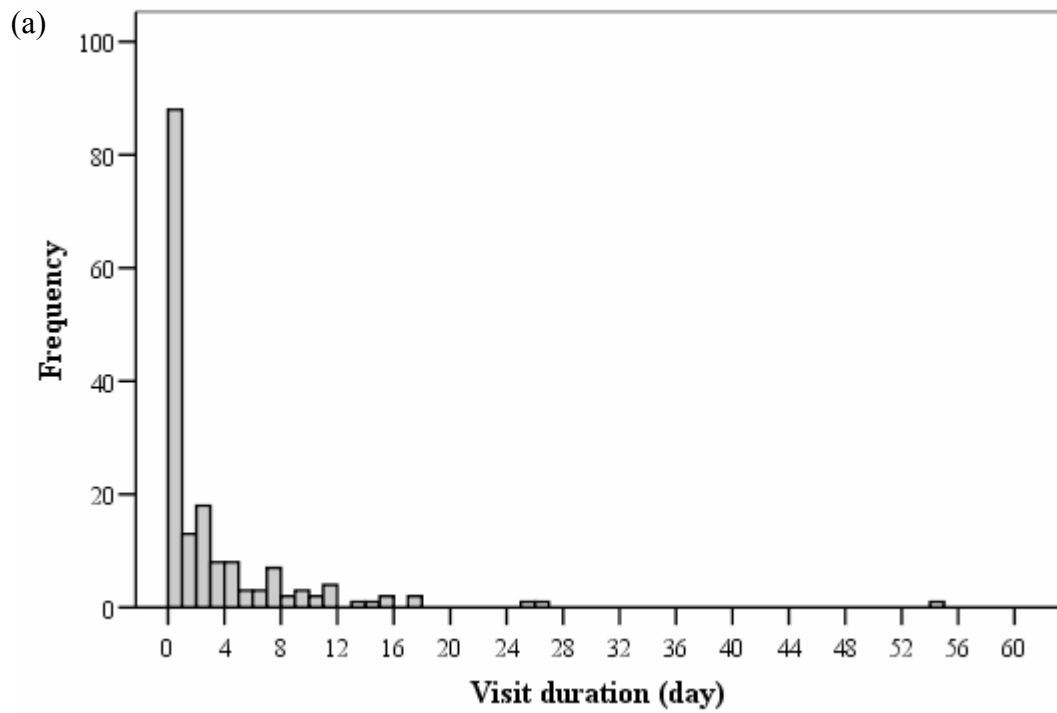


Figure 4.3 Frequency plot of (a) visit, and (b) excursion duration recorded by all wobbegong around Fish Rock.

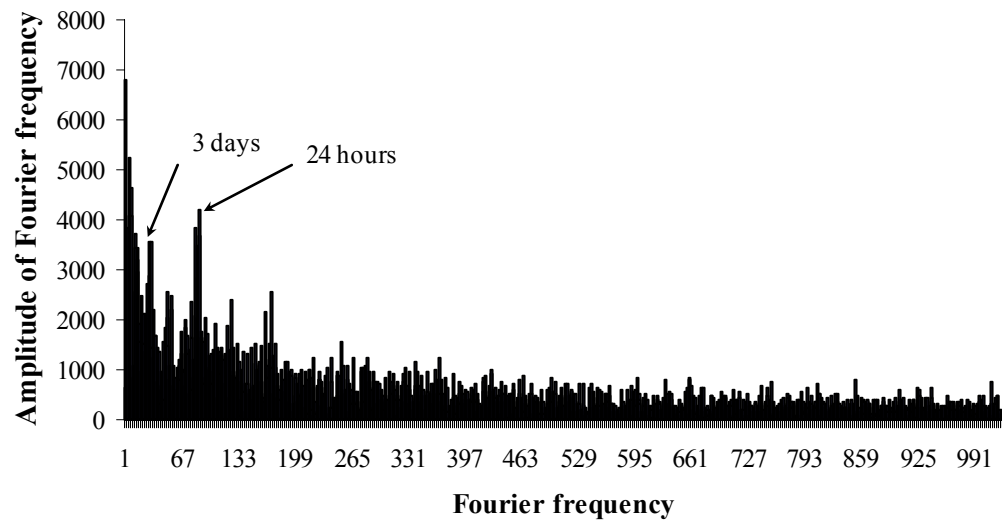


Figure 4.4 Fourier analysis of detection periodicity

A 24 hours and 3 days periodicity peaks are evident and are indicated by the arrows in a 2048 continuous hours of detections from three sharks.

Tagged wobbegongs also showed a 24-hour periodicity, as indicated by the Fourier analysis with a higher number of detections during the day than at night. Presence rate between day and night was significantly different when all sharks were combined together (Mann-Whitney: $P < 0.05$). Differences in day and night total detection were mostly observed in sharks that were detected around Fish Rock for a longer period of time. The total number of detections of sharks 104 and 175 rapidly increased around 6 am. Detection stayed relatively constant from 7 am to 4 pm before decreasing around 5 and 6 pm (Fig. 4.5a). The daily pattern of sharks detected around Fish Rock for a shorter period was less obvious. Shark 101 and 102 still showed an increase in detection during the day compared to at night although to a lesser extent than shark 174 and 104 and starting slightly earlier around 4-5am. No distinct diel pattern could be discerned for sharks 99, 100 and 103 (Fig. 4.5b). Analyses of individual sharks showed that presence rates were significantly different for sharks 175 and 104 (Mann-Whitney: $P < 0.05$), but not for sharks 102 and 101 (Mann-Whitney: $P > 0.05$), although shark 102 approached significance (Table 4.2a). Detection rates between day and night for all tagged sharks and also for sharks 175, 104, 102 and 101 were not significantly different (Mann-Whitney, $P > 0.05$) (Table 4.2b).

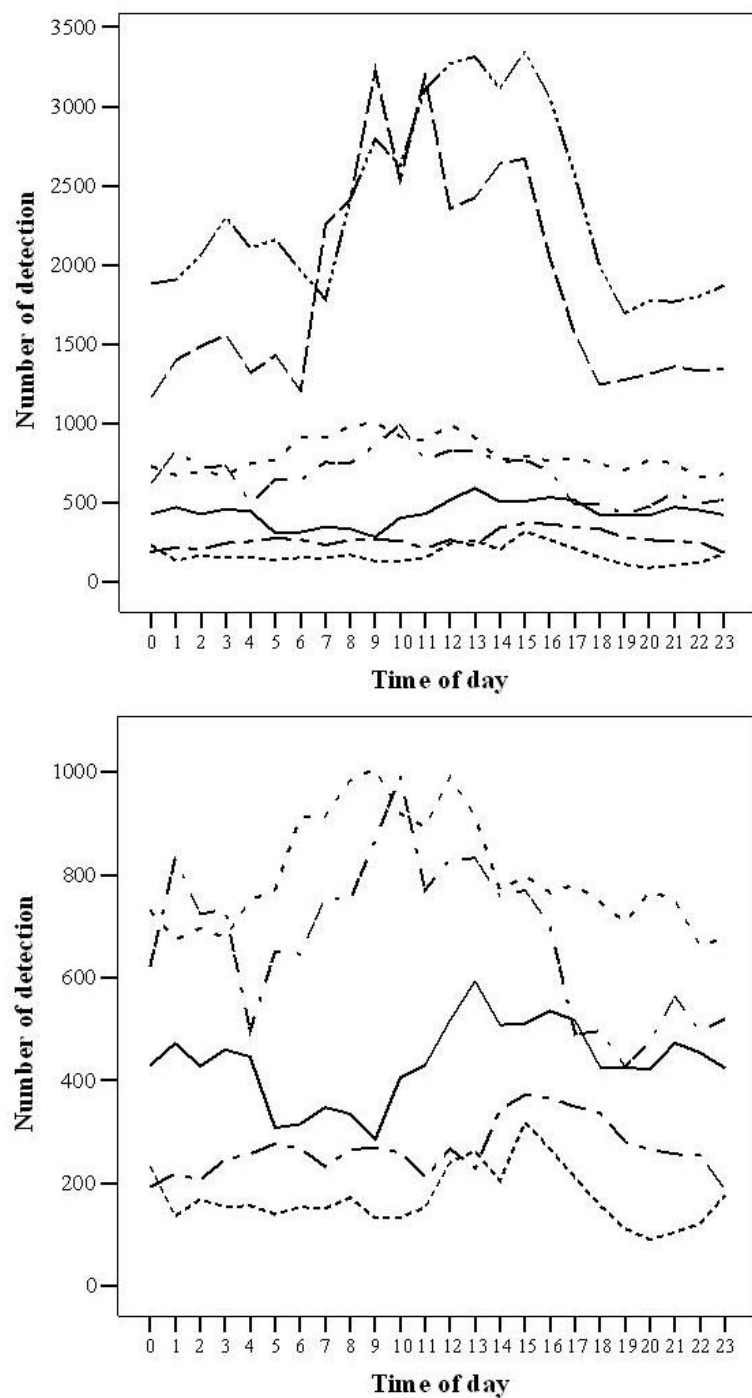


Figure 4.5 Frequency of detections by time of day.

(a) for all sharks; (b) for shark 99, 100, 101, 102 and 103. Shark 99 (—); Shark 100 (---); Shark 101 (- -); Shark 102 (— ·); Shark 103 (— -); Shark 104 (— · ·); Shark 175 (— —).

Table 4.2 (a) ‘Presence rate’ calculated by dividing the number of hours detected by all receivers by the total number of daytime or nighttime hours for each shark and sharks combined, excluding long-term absences; and (b) ‘Detection rate’ calculated by dividing the hourly number of detection by the maximum hourly detection of each shark and sharks combined. P is the probability of statistical significance between daytime and nighttime tested with a Mann-Whitney test.

(a) Presence rate			
Shark	Day	Night	P
101	0.56	0.42	>0.05
102	0.46	0.34	=0.10
104	0.49	0.36	<0.05
175	0.31	0.23	<0.05
Total	0.4	0.3	<0.05
(b) Detection rate			
Shark	Day	Night	P
101	0.63	0.68	>0.05
102	0.81	0.92	>0.05
104	0.90	0.71	>0.05
175	0.52	0.48	>0.05
Total	0.64	0.68	>0.05

Sharks were mostly detected by SWR 4 and 5, with a frequency of 41.2 and 35.9% of detections respectively compared to 12.7 and 10.2% for SWR 1 and 2 respectively. Sharks 99, 100, 101, 102 and 103 were all detected around SWR 4 and 5 for at least 95% of all detections. Sharks 104 and 175 were mostly detected by SWR 1 and SWR 2 (60% and 96% of all detections, respectively). While some sharks were only (or mostly) detected by one receiver (e.g. shark 99 detected by SWR 5 only and shark 101 detected by SWR 4 only), others were detected by several receivers (e.g. shark 104 detected by SWR 1, 2, 4 and 5 at 18%, 42%, 35% and 5%, respectively) (Fig. 4.6).

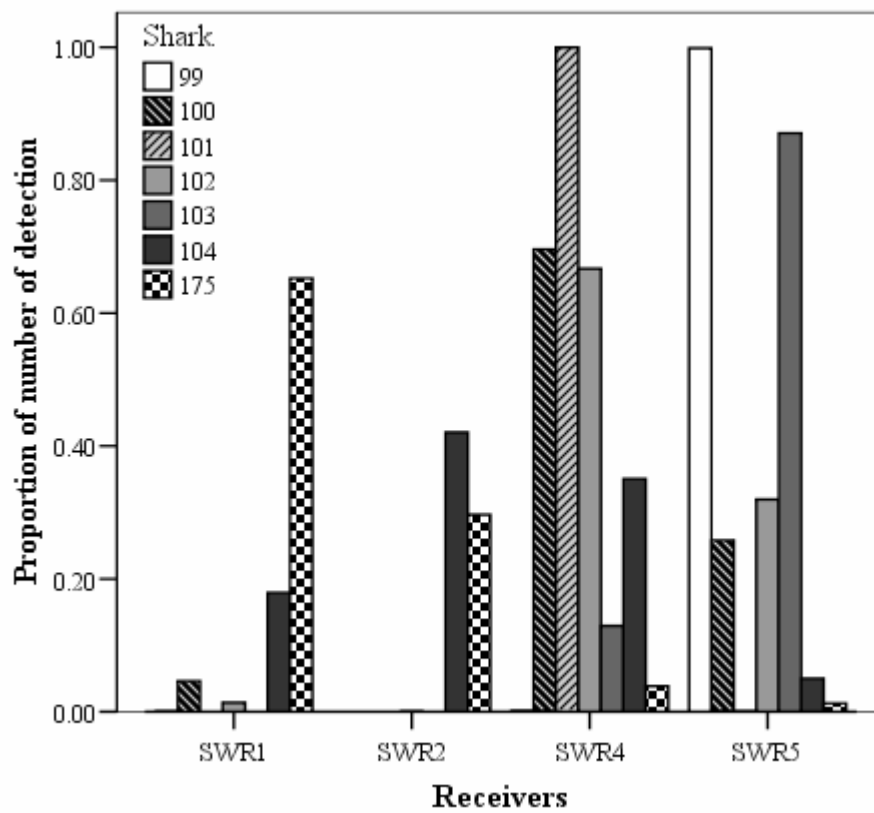


Figure 4.6 Number of detections for each receiver in proportion with the total number of detections for each shark.

4.5 Discussion

Site fidelity was identified for three of the tagged sharks. These were regularly detected at Fish Rock with the longest resident detected nearly two years after tagging. Long term residency at Fish Rock is consistent, albeit of considerably greater duration, with other wobbegong species. For instance, a sympatric species of *Orectolobus* has also been re-sighted within a 75 hectares area for a period of up to 211 days (Carraro and Gladstone 2006). Excursions away from Fish Rock were usually short around 1.8 days with the longest excursion lasting 33 days. Although longer excursions up to 88 days have previously been reported (Carraro and Gladstone 2006). In that study a sporadic sampling method was used and excursions may have consisted of multiple shorter units.

The remaining four tagged sharks of this study were detected for less than 40 days after tagging. The reduced period of detection was most likely due to tag loss or emigration of the wobbegongs, although tag failure, and/or the capture of the wobbegongs by fishers cannot be ruled out.

Tag failure occurring in more than 50% of the tags within two weeks to a month of deployment is unlikely. Similar tags have been deployed in multiple long-term studies with nil or minimal tag failure (e.g. Klimley and Holloway 1999; Egli and Babcock 2004; Humston *et al.* 2005).

Fish Rock has been declared a critical habitat for the critically endangered *C. taurus* and thus, setlines used by fishers to target sharks, especially wobbegongs, are prohibited within 200 m from the rock. It is unlikely that the wobbegongs would have been caught by fishers. However, wobbegongs may have ventured beyond the 200 m protection zone and been caught during these excursions away from Fish Rock. Recreational fishers rarely catch wobbegongs and often release

them. Commercial fishers targeting wobbegongs are known to operate in that area, but while plausible, it is unlikely that over 50% of the tagged wobbegongs were caught by fishers within one month of the study, especially given the long-term residency of other sharks.

While tag shedding rates have been calculated for a few species (Davies and Joubert 1967; Xiao *et al.* 1999), these rates vary among (Pepperell 1990) and within species (Holden and Horrod 1979; Hurst *et al.* 1999). The rate of tag loss with wobbegongs is unknown, but is likely to be high due to their occupation of cracks and crevices (Carraro and Gladstone 2006; C. Huveneers pers. obs.) in which tags might easily get caught. Furthermore, tagged wobbegongs may have tried to detach their tags by rubbing their dorsal surface on rocks as witnessed for one individual following tagging (C. Huveneers pers. obs.). Similar observations have been made with whale sharks (*Rhincodon typus*) (M. Meekan pers. comm.). Divers at Fish Rock have also seen wobbegongs with broken dart tags (presumably from a previous study using dart ID tags). However, a recent study in Port Stephens (Carraro and Gladstone 2006), using photographic and tagging identification techniques, showed that about 35% of identified wobbegongs were never re-sighted or re-sighted once only after initial identification. In that study, sharks with lost or broken tags would have still been identifiable using photo-ID. The nil re-sights for 35% of their tagged sharks suggest that they did indeed leave the area. During our study at Fish Rock, it was impossible to discern whether the sharks left Fish Rock or if the tags were lost.

When wobbegongs were at Fish Rock, their presence rate was significantly higher during the day than at night for two of the resident sharks. The other two sharks were detected for 27 and 108 days and presence rate was not significantly different although exhibiting a similar pattern. The diel difference was more evident for those sharks with longer data series (i.e. detected on 259 and

267 days) and was confirmed by the Fourier analysis. The reduced presence at night may have been due to sharks resting in the Fish Rock cave or to reduced detectability from wobbegongs resting in areas of high structural heterogeneity masking tag transmissions (Arendt *et al.* 2001). It was impossible to test for the former as no receivers were deployed in the cave. However, while presence rate was smaller at night, detection rate was not significantly different between daytime and nighttime. This suggests that sharks were not hiding deeper into cracks and crevices at night limiting tag transmissions and that the reduction in detections at night is most likely due to wobbegongs moving away and out of range of the receivers.

Diel movement patterns are common in chondrichthyans with some sharks increasing nocturnal swimming speed or rates of movement (Nelson and Johnson 1970; Standora and Nelson 1977; Nelson and Johnson 1980; Holland *et al.* 1993; Morrissey and Gruber 1993; Ackerman *et al.* 2000; Cartamil *et al.* 2003), others venturing further away from their home range during the night (Klimley and Nelson 1984; Klimley *et al.* 1988; Holland *et al.* 1993), whereas some species completely change their behaviour from motionless during the day to active at night (Standora and Nelson 1977; Nelson and Johnson 1980). This is likely to be the case of wobbegong changing their behaviour and foraging method from ambush predation during the day to active predation at night. Many species showing different diel patterns with greater nocturnal activity are known to forage at night (e.g. scalloped hammerhead (*Sphyrna lewini*) (Holland *et al.* 1993); horn shark (*Heterodontus francisci*) and swell shark (*Cephaloscyllium ventriosum*) (Nelson and Johnson 1970); angel shark (*Squatina californica*) (Standora and Nelson 1977); white tip reef shark (*Triaenodon obesus*) (Nelson and Johnson 1980); Pacific electric ray (*Torpedo californica*) (Bray and Hixon 1978)).

Wobbegongs were most frequently detected by receivers located on the southern side of Fish Rock and these receivers were also closest to the site of tagging. Only two of the seven tagged wobbegongs had noteworthy detections on the northern side of Fish Rock. Previous observations on *O. ornatus* using scuba-diving showed that most sharks were re-sighted within a fine-scale geographical area with some sharks re-sighted within 10 m of where they were tagged (Carraro and Gladstone 2006). During their study, 77% of re-sighted *O. ornatus* were observed within 20 m of the site of their previous sighting, whereas one *O. ornatus* returned to the same resting position 95 days after first sighting (Carraro and Gladstone 2006). *Orectolobus halei* at Fish Rock exhibited similar behaviour with most sharks detected within the range of one or two receivers. Moreover, divers observed the same sharks under specific rocks over many dives (P. Hutchins pers. obs.). These limited observations suggest a possible high degree of philopatry by wobbegongs.

While the data obtained and subsequent analysis was hampered by equipment malfunction and the reduced detection from some of the tagged sharks, automated acoustic telemetry advanced our understanding of the residency and localised movement patterns of several wobbegongs at Fish Rock. This study showed that although excursions occur about every 3 days, wobbegongs can be found within a small area for periods as long as two years. This sedentary behaviour suggest that wobbegong sharks will have a low resilience to fishing effort if intensive fishing occurs within those locations as repopulation will be slow. Carraro and Gladstone (2006) suggest that marine reserves in the absence of other constraints on fishing may not be an effective management strategy due to the lack of long-term site fidelity. However this study showed that some wobbegongs remained within a specific site with small excursions of only about 1.8 days. Anecdotal information from divers around Sydney and the south coast of NSW suggests that

fishers have previously depleted dive sites and the surrounding area. The creation of marine parks in sensitive areas might help increase wobbegong numbers in a depleted population or protect an existing population from extensive fishing pressure. Marine parks, aquatic reserves and/or temporal fishing closures could assist with the management and conservation of wobbegongs. These approaches would also need to incorporate diel behavioural differences and consider when fishing pressure is greatest (Heupel and Simpfendorfer 2005). Marine Protected Areas must be designed to account for both day and night ranges when mobile species with diel patterns are the targeted species for conservation.

CHAPTER 5: LENGTH-FREQUENCY DISTRIBUTION, LENGTH–LENGTH, MASS–MASS
AND MASS–LENGTH RELATIONSHIPS OF WOBBERGONG SHARKS (GENUS
ORECTOLOBUS) COMMERCIALY FISHED IN NEW SOUTH WALES, AUSTRALIA



© Charlie Huveneers (Commercial fisher catching an *Orectolobus maculatus*)

This chapter is currently under peer-review with the journal *Fisheries Management and Ecology*. I am primary author with Dr. Nick Otway (NSW DPI) and Ass. Prof. Rob Harcourt (Macquarie University) as co-authors. I was responsible for sampling, data analysis and interpretation, and writing the manuscript. Rob Harcourt and Nick Otway contributed by supervising the development of the project and providing comments on earlier versions of the manuscript.

Huveneers, C., Otway, N.M. and Harcourt, R.G. (in review) Length-frequency Distribution, Length–Length, Mass–Mass and Mass–Length Relationships of Wobbegong Sharks (Genus *Orectolobus*) Commercially Fished in New South Wales, Australia. *Fisheries Management and Ecology*

5.1 Abstract

Wobbegongs are commercially targeted in New South Wales, Australia. Catches have declined *ca.* 50% in a decade, leading to concerns over the fishery's sustainability. However, as is common in many shark fisheries, length and mass composition of the catch is unknown as carcasses are trunked (i.e. beheaded and eviscerated) before landing. Wobbegongs have a different body morph from many other sharks, being dorsally ventrally flattened and indistinct upper and lower caudal lobes. We provide parameters for length–length, mass–mass and mass–length relationships to convert carcass length and carcass mass measurements to total lengths and total masses. This method should prove useful for fisheries assessments. Neonates and small juveniles were conspicuously absent in the length-frequency distributions of all three species, suggesting the potential existence of nursery areas not available to the commercial fishery.

5.2 Introduction

Three species of wobbegong shark: the spotted wobbegong, *Orectolobus maculatus*, the dwarf ornate wobbegong, *O. ornatus*, and the large ornate wobbegong, *O. halei* (Huveneers 2006; Chapter 2) occur in coastal waters off New South Wales (NSW), Australia, and have been commercially targeted by the Ocean Trap and Line Fishery. Wobbegongs have been sold as boneless fillets or “flake” and their catch has declined from *ca.* 150 tons in 1990/91 to *ca.* 70 tons in 1999/00, a decrease of > 50% in less than a decade (Pease & Grinberg 1995; NSW DPI unpub. data). This decline led to wobbegongs being listed as ‘Vulnerable’ in NSW and ‘Near Threatened’ globally under the World Conservation Union (IUCN) Red List assessment (Cavanagh *et al.* 2003) and to concerns over the sustainability of the fishery (NSW Fisheries 2001).

Given that many shark species, including wobbegongs, are trunked prior to landing, partial lengths and carcass masses are usually the only measurements that can be recorded (FAO 2000). Relationships between partial length and carcass mass and their respective total length and total mass are a fundamental requirement for an assessment of the catch composition for fishery stock assessment and hence the ecological sustainable management of the fishery.

Wobbegongs and other carpet sharks are dorso-ventrally flattened compared to many other shark groups. In contrast to other sharks, wobbegongs also have indistinct upper and lower caudal fin lobes. This study presents morphometric relationships for wobbegongs caught in the NSW commercial fishery. The measurements used are applicable to other fisheries that target sharks of similar body morphology to wobbegongs. Catch composition and length-frequency distributions recorded during the study are also presented.

5.3 Materials and methods

Wobbegongs were collected from commercial fishers at six locations in NSW (Nambucca Heads, Port Stephens, Newcastle, Terrigal, Sydney and Eden) (Fig. 5.1). Wobbegongs were caught on setlines with O'Shaughnessy style hooks size 10/O or 12/O, with a 50–100 cm long wire or nylon trace attached to the bottom line by a stainless sharkclip. Hooks were baited with black fish (*Girella tricuspidata*), mullet (*Mugil cephalus*) or Australian salmon (*Arripis trutta*). Lines were set before sunset and hauled at sunrise on the following day.

The species, gender and a series of length measurements were recorded (to the nearest mm) for each shark caught. The length measurements included: total length (TL), snout to anal-fin

insertion length (SAL), and partial length from the pectoral-fin origin to the caudal-fin origin (PL) (Fig. 5.2). SAL was taken instead of fork length as upper and lower caudal fin lobes of wobbegongs are not discernible. Total mass (TM) and carcass mass (CM) were recorded using spring balances (scale: 100 ± 0.2 kg, 20 ± 0.2 kg, 5 ± 0.1 kg).

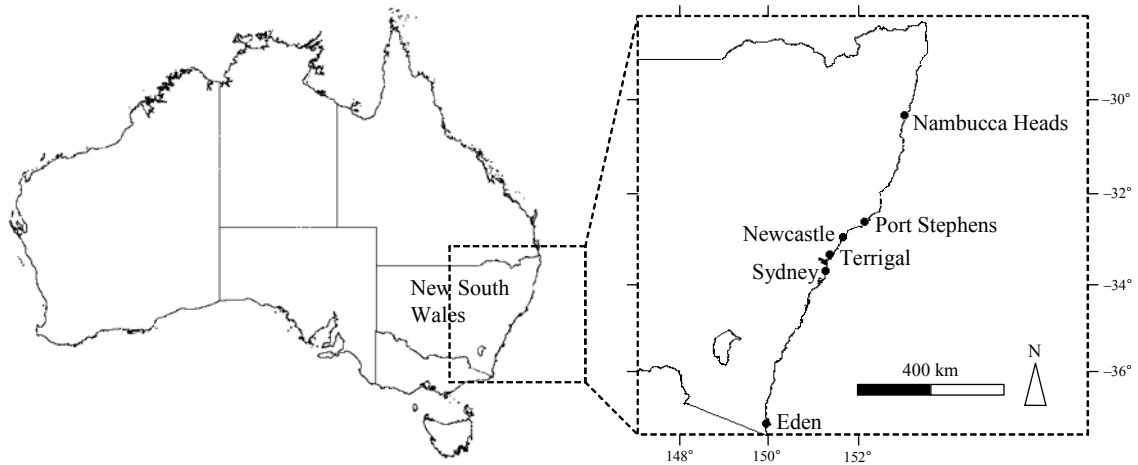


Figure 5.1 Sampling locations for collection of wobbegongs in New South Wales, Australia.

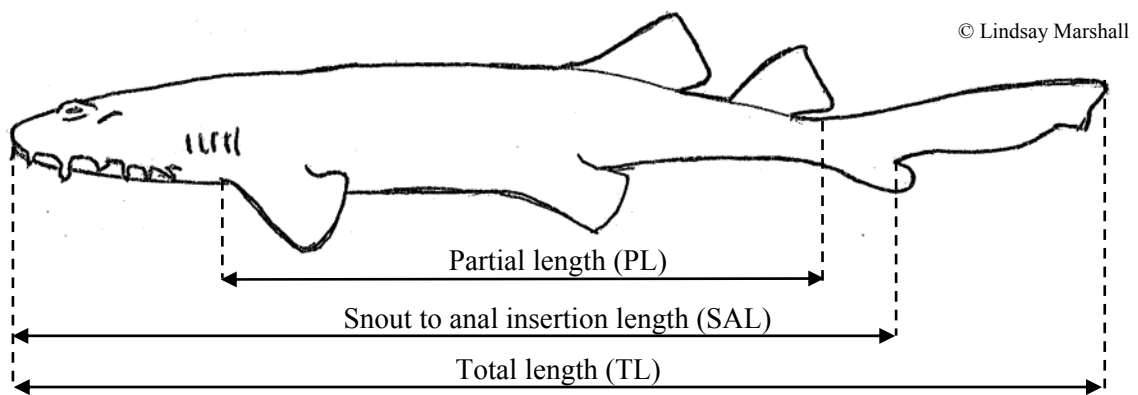


Figure 5.2 Lateral view of a wobbegong showing measurements taken.

Linear regressions of TL on SAL, TL on PL, and TM on CM were determined for each of the three species using data pooled across all sites. Log-transformed data were used for the regressions of TM on TL and CM on PL and corrected for biases caused by natural logarithmic transformation (Beauchamp and Olson 1973). Analyses of covariance (ANCOVA) were used to test for differences between sexes in all regressions. When the slopes and intercepts did not differ significantly between sexes the data were pooled and a common regression determined.

5.4 Results

A total of 904 wobbegongs (435 males and 469 females) was collected comprising: 183 male and 202 female *O. ornatus* (combined range 471–1017 mm TL), 97 male and 88 female *O. maculatus*, (combined range 870–1575 mm TL), and 155 male and 179 female *O. halei* (combined range 869–2065 mm TL). Most *O. ornatus* (86.5%) were collected off Nambucca Heads with none caught south of Port Stephens. *Orectolobus maculatus* catches were distributed among Nambucca Heads (26.5%), Port Stephens (30.8%) and Sydney (37.8%), with none caught in Eden. *Orectolobus halei* were caught at all locations, with the majority caught off Sydney (62.6%), and sporadic captures at the remaining locations (Table 5.1). Neonates (born at *ca.* 21 cm for *O. ornatus* and *O. maculatus* and *ca.* 30 cm for *O. halei*) and small juveniles were absent in the catches of all three species (Fig. 5.3).

Table 5.1 Number (with TL size range in mm) of wobbegong caught during June 2003–May 2006.

Location	<i>O. ornatus</i>	<i>O. maculatus</i>	<i>O. halei</i>	Total
Nambucca Heads	333 (471–994)	49 (1160–1485)	31 (1175–1972)	413
Port Stephens	52 (577–1017)	57 (870–1440)	10 (1280–1875)	119
Newcastle		7 (1265–1435)	3 (1444–1755)	10
Terrigal		2 (unknown)	8 (1860–1930)	10
Sydney		70 (1055–1575)	209 (869–2065)	279
Eden			73 (1190–1870)	73
Total	385 (471–1017)	185 (870–1575)	334 (869–2065)	904

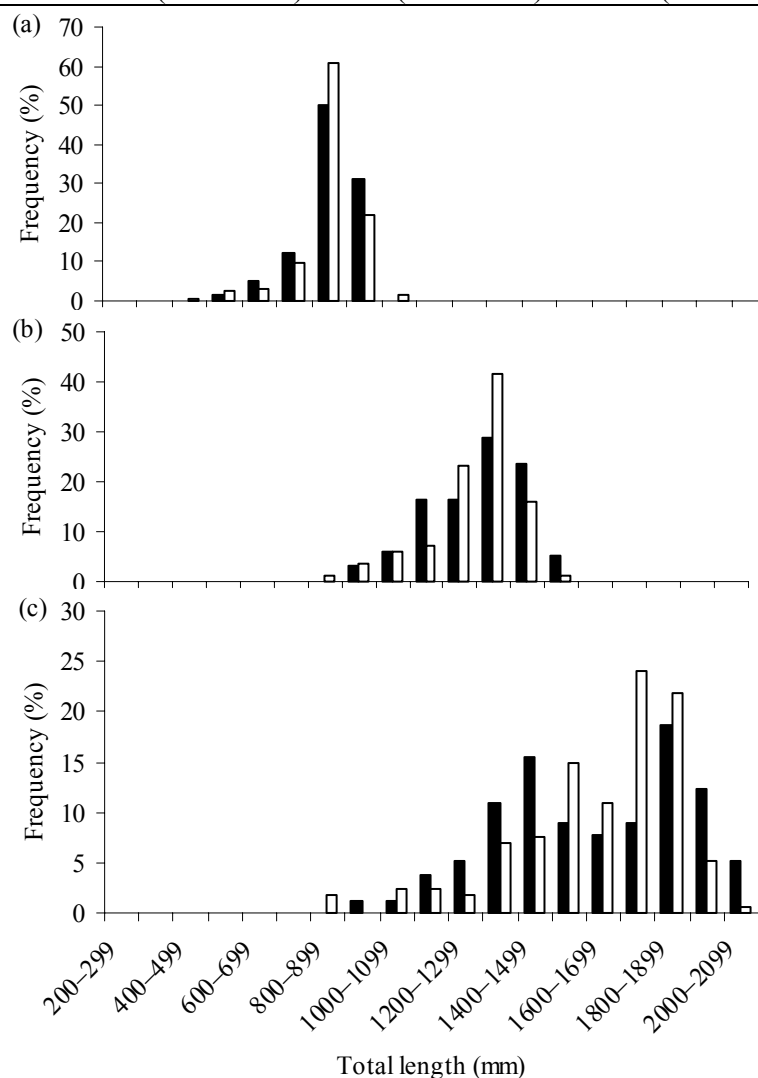


Figure 5.3 Length-frequency distributions of wobbegongs caught during sampling period. Length-frequency by 100-mm size-class for (a) *O. ornatus*, (b) *O. maculatus*, and (c) *O. halei* for males (■) and females (□).

The slopes of the regressions of TL on SAL (Table 5.2) did not differ significantly between the sexes for *O. ornatus* and *O. maculatus* (ANCOVA: $F_{\text{slopes}} = 2.17$ and 0.62 respectively, $P > 0.05$), but the intercepts differed significantly between males and females (ANCOVA: $F_{\text{intercepts}} = 5.29$ and 11.06 respectively, both $P < 0.05$). The adjusted means showed that male *O. ornatus* and *O. maculatus* had a significantly greater TL for a given SAL compared to females. Similarly, the slopes of the regressions of TL on PL (Table 5.2) did not differ significantly between the males and females of *O. ornatus* and *O. maculatus* (ANCOVA: $F_{\text{slopes}} = 3.06$ and 0.17 respectively, $P > 0.05$). Again, the intercepts of the regressions of TL on PL (Table 5.2) differed significantly between the sexes (ANCOVA: $F_{\text{intercepts}} = 9.24$ and 2.44 , $P < 0.001$ and $P < 0.05$, respectively). The adjusted means showed that the male *O. ornatus* and *O. maculatus* had a significantly greater TL for a given PL when compared to females. Neither the slopes nor intercepts of the regressions of TL on SAL and TL on PL (Table 5.2) differed significantly between the sexes for *O. halei* (ANCOVA: TL on SAL: $F_{\text{slopes}} = 2.18$ and $F_{\text{intercepts}} = 1.57$, both $P > 0.05$; TL on PL: $F_{\text{slopes}} = 0.31$ and $F_{\text{intercepts}} = 0.40$, both $P > 0.05$).

Table 5.2 Relationships between length–length and mass–mass

Estimated parameters (and standard error) from the linear regression analysis to derive the equation $Y = a + bX$; a and b are parameters; n is sample size; r^2 is square of correlation coefficient; rmse is root mean square error; and P is probability of statistical significance between sex with ns representing $P > 0.05$, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$. TL is total length; SAL is snout to anal-fin insertion length; PL is partial length; TM is total mass; CM is carcass mass.

Y–X	Species	Sex	n	a (s.e.)	b (s.e.)	r^2	rmse	P	
								slope	intercept
TL–SAL	<i>O. ornatus</i>	Male	161	44.80 (15.52)	1.16 (0.02)	0.94	19.66	ns	*
		Female	164	71.79 (15.51)	1.12 (0.02)	0.94	21.54		
	<i>O. maculatus</i>	Male	93	26.98 (24.33)	1.22 (0.02)	0.97	25.32	ns	*
		Female	77	41.52 (19.03)	1.20 (0.02)	0.98	16.52		
TL–PL	<i>O. halei</i>	Combined	236	10.34 (14.17)	1.23 (0.01)	0.98	33.38	ns	ns
	<i>O. ornatus</i>	Male	113	164.26 (26.42)	1.28 (0.05)	0.86	34.73	ns	***
		Female	124	96.00 (18.76)	1.38 (0.03)	0.93	25.60		
	<i>O. maculatus</i>	Male	63	159.61 (51.08)	1.40 (0.06)	0.90	43.40	ns	*
		Female	60	184.39 (45.98)	1.34 (0.05)	0.91	39.32		
	<i>O. halei</i>	Combined	174	103.97 (23.34)	1.49 (0.02)	0.96	54.63	ns	ns
TM–CM	<i>O. ornatus</i>	Combined	73	1.33 (00.14)	1.33 (0.06)	0.87	0.31	ns	ns
	<i>O. maculatus</i>	Combined	93	3.95 (00.75)	1.01 (0.08)	0.61	1.83	ns	ns
	<i>O. halei</i>	Combined	148	1.67 (00.77)	1.53 (0.05)	0.87	3.90	ns	ns

Table 5.3 Relationships between total mass (TM)–total length (TL) and carcass mass (CM)–partial length (PL)

Estimated parameters (and standard error) for the relationships for males and females derived from the equation $TM = acTL^b$ and $CM = acPL^b$; a and b are parameters; c is the Beauchamp and Olson (1973) correction factor; other parameters and statistical quantities are in Table 5.2.

Shark category	n	a (s.e. range) x 10 ⁻⁹	b (s.e.)	c	r ²	rmse	P	
							slope	intercept
TM–TL								
<i>O. ornatus</i>							*	***
Males	129	21.1 (10.1–44.1)	2.82 (0.11)	1.008	0.84	3.28		
Females	159	1.81 (0.95–3.46)	3.20 (0.10)	1.010	0.88	4.62		
<i>O. maculatus</i>							ns	***
Males	86	57.4 (26.3–125)	2.69 (0.11)	1.008	0.88	2.88		
Females	73	31.7 (12.8–78.3)	2.78 (0.13)	1.007	0.87	2.64		
<i>O. halei</i>							ns	*
Males	86	73.6 (39.2–138)	2.69 (0.11)	1.008	0.88	2.88		
Females	106	6.52 (3.88–11.0)	3.01 (0.070)	1.008	0.95	5.21		
CM–PL								
<i>O. ornatus</i>	26	47 (3.12–709)	2.83 (0.43)	1.008	0.9	0.16	ns	ns
<i>O. maculatus</i>	94	1090 (405–2920)	2.38 (0.15)	1.019	0.75	0.15	ns	ns
<i>O. halei</i>	149	69.9 (40.8–120)	2.80 (0.08)	1.013	0.64	0.13	ns	ns

The slopes of the regressions of TM on TL (Table 5.3) differed significantly between male and female *O. ornatus* (ANCOVA: $F_{\text{slopes}} = 6.62$, $P < 0.05$) with mass increasing at a faster rate than in females. In contrast, slopes of the regressions of TM on TL (Table 5.3) for male and female *O. maculatus* and *O. halei* did not differ significantly (ANCOVA: $F_{\text{slopes}} = 0.32$ and 0.04 respectively, both $P > 0.05$), but the intercepts were significantly different between the sexes (ANCOVA: $F_{\text{intercepts}} = 20.20$ and 5.49 , $P < 0.001$ and $P < 0.05$, respectively). The adjusted means showed that females of *O. maculatus* and *O. halei* had a significantly greater TM for a given TL when compared to males.

Neither the slopes nor intercepts of the regressions of CM on PL (Table 5.3) differed significantly between the sexes for *O. ornatus*, *O. maculatus* and *O. halei* (ANCOVA: $F_{\text{slopes}} = 1.95$, 2.15 and 1.15 ; $F_{\text{intercepts}} = 0.01$, 0.04 and 0.60 ; all $P > 0.05$ for *O. ornatus*, *O. maculatus* and *O. halei*, respectively).

5.5 Discussion

The spatial distribution of wobbegong catches provides an indication of their distribution within NSW waters. Port Stephens was the southern-most location where *O. ornatus* was caught. Although *O. ornatus* have been recorded as far south as Sydney (207 km south of Port Stephens), catch around Sydney was very low. Museum registered specimens have been collected as far north as the Whitsunday Islands (20° 20'S 148° 54'E, Australian Museum specimen IA 3831), restricting the distribution of *O. ornatus* from tropical to warm temperate waters of eastern Australia. *Orectolobus maculatus* is abundant in central NSW, around Port Stephens and Sydney. *Orectolobus maculatus* is caught in larger numbers in northern NSW than *O. halei* and has been

recorded as far north as Gladstone (Kyne, Johnson, Courtney & Bennett 2005). In contrast to *O. halei*, *O. maculatus* was rarely caught around Merimbula and Eden (S. Fantham pers. comm.), restricting its distribution in eastern Australia from tropical to temperate waters. *Orectolobus halei* catches were low in northern NSW and higher around Sydney and Eden, where it was the only species caught during this study. In NSW, *O. halei* is more abundant in temperate waters with abundance decreasing in warm temperate waters. There is apparently a similar trend for *O. halei* collected in Western Australia (WA) (J. Chidlow pers. comm.).

Neonates and small juveniles were rarely caught by commercial wobbegong fishers at any location and several reasons may account for their absence. Neonates and small juveniles might occupy crevices to avoid predation and forage on small prey living in the crevices. This may provide a physical partitioning of the habitat within a given location. Gear selectivity could decrease neonate catch because hooks and baits used in the commercial wobbegong fishery are too large. However, gear selectivity is unlikely to explain the absence of larger juveniles because *O. ornatus* of 700–1000 mm TL are commonly caught using the same gear and in the same areas where only a few *O. halei* smaller than 1300 mm TL are caught. It seems more likely that small wobbegongs are not available to the fishery and occur within different habitats. Furthermore, a similar study in WA yielded no *O. maculatus* smaller than 900 mm TL and only one *O. halei* (misidentified as *O. ornatus*) smaller than 1200 mm TL (Chidlow 2003). Size segregation might therefore occur with neonates and small juveniles living in primary and/or secondary nursery areas. Size segregation in habitat use is commonly found in chondrichthyans (e.g. Simpfendorfer 1992), with neonates living in nursery areas for the first weeks, months or years (Heupel & Hueter 2002). Nursery areas are thought to provide neonates and small sharks with increased food availability and/or protection against predators (Heupel & Hueter 2002).

The regression parameters in Tables 2 and 3 are provided for scientists and fisheries managers as an aid to determining size when TL and TM are required, but cannot be measured, but where SAL, PL or CM are available. The absence of sex differences in the CM–PL relationships suggested that somatic growth was similar between males and females (Braccini *et al.* 2006b). However, the regressions of TM on TL differed significantly between males and females with greater body mass in females. Sex-based differences in body mass are often due to discrepancies in the masses of internal organs and are common in chondrichthyans (e.g. Walker 2005). Differences occur due to the inclusion of pregnant females, and the heavier reproductive organs and liver in females (Stevens & Wiley 1986). In contrast, male *O. ornatus* and *O. maculatus* had significantly greater TL for a given SAL and PL compared to females. The reason for this sex difference is unknown.

Most life history parameters used in fisheries assessments are determined as a function of total length or mass. Wobbegongs landed in the NSW Ocean Trap and Line Fishery are, however, beheaded and eviscerated preventing the measurement of total length and total mass. The regression relationships documented in this study allow estimates of total length and total mass to be obtained from landed carcasses. This is a robust method that may correct for underestimation of catch based on tonnage, and thereby enable future assessments of the ecological sustainability of the fishery. This method should be broadly applicable to a range of species. Although many studies provide relationships between total length and total mass (e.g. Stevens & McLoughlin 1991), we concur with recommendations of the International Plan of Action for the Conservation and Management of Sharks (IPOA-Sharks) (FAO 2000) that future studies should also incorporate the measurement of partial lengths and carcass masses. Only when this is done

routinely, will it be possible to estimate, with accuracy, total length and total mass and provide much needed information on the length/mass composition of the catch of shark fisheries.

CHAPTER 6: QUANTITATIVE DIET ASSESSMENT OF WOBBERGONG SHARKS (GENUS
ORECTOLOBUS) IN NEW SOUTH WALES, AUSTRALIA



© Peter Hitchins (*Orectolobus halei* feeding upon an *O. ornatus*)

This chapter is currently under peer-review with the journal *ICES Journal of Marine Science*. I am primary author with Dr. Nick Otway (NSW DPI), Sue Gibbs and Ass. Prof. Rob Harcourt (Macquarie University) as co-authors. I was responsible for sampling, data analysis and interpretation, and writing the manuscript. Rob Harcourt and Nick Otway contributed by supervising the development of the project and providing comments on earlier versions of the manuscript, whereas Sue Gibbs helped with cephalopod and teleost identification.

Huveneers, C., Otway, N.M., Gibbs, S.E. and Harcourt, R.G. (in review) Quantitative diet assessment of wobbegong sharks (genus *Orectolobus*) in New South Wales, Australia. *ICES Journal of Marine Science*

6.1 Abstract

The diets of three species of wobbegong (*Orectolobus ornatus*, *O. maculatus* and *O. halei*) in New South Wales, Australia were investigated using stomach contents from specimens caught by commercial fishers. Eighty and sixty percent of wobbegongs caught by commercial setline and by trap/scuba-diving collection, respectively had empty stomachs and this was most likely due to regurgitation. Wobbegongs were frequently stomach-hooked (80–90% of the catch) and this potentially contributed to the higher proportion of empty stomachs compared to many other shark species examined in previous studies. The diet of all three species mainly comprised bony fishes, but some cephalopods and chondrichthyans were also consumed. Diets did not vary between the sexes, but interspecific differences were evident and were related to the total length of the shark. Octopus were more frequent in the diets of *O. ornatus* possibly due to the species smaller adult size facilitating capture of octopus in small holes/crevices. *Orectolobus halei* fed more frequently on pelagic species and chondrichthyans, possibly due to increased mobility. The high trophic level of wobbegongs means that their removal from the ecosystem may have impacts on the lower trophic levels.

6.2 Introduction

Sharks are among the top predators in the marine environment (Cortés 1999a) and have an important role in energy exchange between trophic levels (Cortés and Gruber 1990; Wetherbee *et al.* 1990). High trophic level marine animals can play major roles in communities through the removal of prey species, their competitors, and species replacement (Jennings and Kaiser 1998). As such, the removal of top predators from coastal ecosystems has the potential to cause a trophic cascades resulting in alterations to the abundance of lower trophic species (Jennings and Kaiser

1998). However, there is an absence of quantitative information on the diets of sharks in many ecosystems and this makes it difficult to assess how they contribute to marine trophic structure (Cortés 1999a).

Wobbegong sharks are abundant predators commonly found on the coastal rocky reefs off New South Wales (NSW), Australia (Last and Stevens 1994; Compagno 2001). They are targeted in NSW waters by commercial fishers with endorsements in the Ocean Trap and Line Fishery and sold as boneless fillets or “flake”. The commercial catch has declined from *ca.* 150 tonnes in 1990/01 to *ca.* 70 tonnes in 1999/00, a decrease of more than 50% in a decade (Pease and Grinberg 1995; NSW DPI unpub. data). Consequently, quantifying the diets of wobbegongs is important because the potential effects of their removal (via the commercial fishery) on the coastal marine ecosystem are unknown (Wetherbee *et al.* 1990).

Wobbegongs are often described as sluggish, demersal sharks that rest on the substratum (Whitley 1940; Stead 1963; Munro 1967; Coleman 1980; Last and Stevens 1994; Compagno 2001). However, they have been observed to ambush and actively chase their prey (Whitley 1940; Last and Stevens 1994; Compagno 2001). At present, it is unclear which method is mostly used by wobbegongs and if feeding follows a diel pattern (Huvaneers *et al.* in press; Chapter 4). Although wobbegongs feed on a variety of prey, a quantitative assessment of their diet provides a critical first step to understanding trophic interactions and possible ecosystem effects of the wobbegong fishery. No published data exist that specifically address the food and feeding habits of wobbegongs and only descriptive studies from limited samples have been undertaken (e.g. Cochrane 1992; Chidlow 2003).

The diets of the three wobbegongs species (*Orectolobus ornatus*, *O. maculatus* and *O. halei*) occurring in coastal waters off NSW were investigated using samples from commercially fished sharks. Stomach content analysis was used to examine dietary components and quantify the relative importance of each prey item. Prey diversity, dietary overlap and similarity were also investigated to assess resource partitioning within and among the 3 species.

6.3 Materials and methods

6.3.1 Collection of specimens and stomach processing

Wobbegongs were obtained from three main sources between June 2003 and May 2006.

Stomachs were collected aboard commercial vessels targeting wobbegongs in the Ocean Trap and Line Fishery at four locations in NSW (Nambucca Heads, Port Stephens, Newcastle and Sydney). Seventy-three wobbegongs were collected in Nambucca Heads as bycatch in lobster traps, whereas 42 *O. ornatus* were collected while scuba diving in Port Stephens.

Wobbegongs were identified to species, sexed and the total length (TL) and snout to anal insertion length (SAL) measured to the nearest millimetre. Palpation of the cardiac stomach *in situ* was used to determine whether any food was present. The position of the embedded hook (i.e. in the mouth, oesophagus or cardiac stomach) was recorded for each shark prior to excising the stomach. Wobbegong stomachs were removed by cutting through the pyloric sphincter, connective tissue and the anterior oesophagus. Stomachs were then placed in a labelled bag and stored at -20°C for later analysis in the laboratory. The number of empty stomachs was recorded and expressed as a percentage of the total number examined and then discarded together with stomachs containing only bait.

In the laboratory, stomach contents were thawed and washed with water. Identification was based on intact and remaining hard items including cephalopod beaks, fish otoliths, internal and external skeletal materials, combined with general shape and anatomical features of the prey. Recognisable prey items were identified to the lowest taxonomic level possible using reference collections of fish otoliths (78 Australian species) and cephalopod beaks (approximately 20 species) held at the South Australian Museum and reference guides (Smale *et al.* 1995; Lu and Ickeringill 2002). Contents identified as bait via prominent hook marks and/or knife cuts were excluded from the analysis. Prey items were assigned to a prey category (demersal, benthopelagic or pelagic) according to Stevens and Wiley (1986) using standard taxonomic literature and Kuitert (2000). The wet mass of each food item was measured on an electronic balance to the nearest 0.01 g when prey items were small and on a spring balances (600 ± 5 g or 2.5 ± 0.02 kg) for larger prey items.

6.3.2 Analysis

The contribution of different prey items to the shark's diet were determined by the numerical importance (%N - Hyslop 1980), the frequency of occurrence (%F - Hynes 1950; Hyslop 1980) and mass (Pillay 1952; %W - Hyslop 1980). Each of these parameters provided a different insight into the feeding habits of the shark (Bowen 1996; Liao *et al.* 2001). The index of relative importance (IRI -Pinkas *et al.* 1971), which incorporated the three previous indices, was also calculated and expressed as a percentage (%IRI - Cortés 1997). Importantly, the IRI mitigates the biases of its individual components and facilitates comparative studies (Bigg and Perez 1985). Graphical representation of prey items grouped by family was also used as an alternative to summary tables. Cortés (1997) developed a three-dimensional, graphical representation from

Costello (1990) where each point on the graph represents the percentage occurrence and abundance (numerically or by mass or volume) for each prey item/category.

To determine whether the sample size was sufficient to accurately describe the diet of wobbegongs, the cumulative numbers of randomly pooled stomachs were plotted against the Shannon-Weiner Index (H'). The order in which stomachs were analysed was randomised ten times (Ferry *et al.* 1997). The number of stomachs at which H' reached a stable, asymptotic value identified the minimum sample size required to adequately describe the diet (Cortés 1997).

Diets were compared among species, between males and females within each species, and between sexually mature (i.e. with total lengths ≥ 1750 mm) and immature (i.e. with total lengths < 1750 mm) individuals of *O. halei* (Huveneers *et al.* in review-b; Chapter 7). Dietary overlap between species, sexes within species and size class in *O. halei* was calculated using the Horn's (1966) index of overlap (R_0) on %IRI. Horn's index is less biased than other overlap measures when sample size and numbers of prey in the diet are not constant (Krebs 1999). A value between 0–0.29, 0.3–0.59 and > 0.6 indicates low, medium and high overlap, respectively (Langton 1982). Dietary diversity (breadth) of each species was also calculated using the combined index (CI - Cortés *et al.* 1996) calculated by taking the average of the Levin's index (B) and the Shannon-Weiner index (H') standardised on a 0–1 scale (Krebs 1999).

The similarity among species and between sexes was also tested with cluster analysis in Primer v5.2.9 (Clarke and Gorely 2001) using techniques described in Clarke and Warwick (2001). Analysis was undertaken following Platell and Potter (2001), and White *et al.* (2004). Dietary data within each species and sex were randomly allocated into groups of four or five and mean

values determined. Mean IRI values were then square-root transformed and a similarity matrix produced using the Bray-Curtis similarity coefficient. An MDS ordination plot was obtained from the resulting similarity matrix. One-way analyses of similarities (ANOSIM) were used to test for significant differences among the diets of the three species and between sexes within each species. Similarity percentages (SIMPER) were used to determine the dietary categories that typified particular groups and/or contributed most to the dissimilarities between groups. Multivariate dispersion (MVDISP) was used to determine the degree of dispersion of the dietary samples on ordination plots (Somerfield and Clarke 1997). Results obtained from the multivariate analyses were compared to the dietary overlap and breadth indices.

Finally, the trophic level of wobbegong sharks was calculated using the trophic levels of prey categories and the equation provided in Cortés (1999a).

6.4 Results

A total of 641 wobbegongs (285 *O. ornatus*, 155 *O. maculatus* and 201 *O. halei*) was examined for dietary analyses. Sharks with empty stomachs or bait only were, however, common (i.e. *ca.* 83% in *O. ornatus* caught on setlines). Wobbegongs caught in traps or while scuba diving had a consistently lower proportion of empty stomachs (i.e. *ca.* 65% in *O. ornatus*). Wobbegongs were mainly hooked in the cardiac stomach (*ca.* 75%). In a few cases ($n = 23$), not only had the hook perforated the stomach wall, but it had also damaged the liver or vertebral column. A total of 313 prey items was found in 144 stomachs and *ca.* 50% of these contained only a single prey item (Table 6.1).

6.4.1 Cumulative diversity

The cumulative diversity curves using the Shannon-Weiner Index reached asymptotes after *ca.* 30, 25 and 20 stomachs had been sampled for *O. ornatus*, *O. maculatus* and *O. halei*, respectively (Fig. 6.1). When plotted separately for each sex, the cumulative diversity curves also reached asymptotes for both sexes of *O. ornatus*, male *O. maculatus* and female *O. halei* (Fig. 6.2). The cumulative prey curve for female *O. maculatus* was close to reaching an asymptote (Fig. 6.2b), but for male *O. halei*, the standard deviation of the means at the point where the total number of stomachs sampled was reached was still large (Fig. 6.2c). Therefore, stomach samples of male *O. maculatus* and female *O. halei* may not provide a complete representation of their diet.

Table 6.1 Summary table of samples collected, hook position and number of prey items.

	Category	<i>O. ornatus</i>	<i>O. maculatus</i>	<i>O. halei</i>	Total
No of shark dissected	Total	285	155	201	641
No of stomachs with at least one prey item	Male	23	25	17	65
	Female	40	13	24	77
	Unknown sex	1	1		2
	Total	64	39	41	144
Proportion with an empty stomach or bait only (%)	Line	82.8	75.6	79.8	
	Trap/diving	64.6	49.5	66.7	
Frequency of hooking location (%)	Stomach	82.7	70.2	67.9	
	Mouth	12.2	20.2	22.6	
	Oesophagus	5.1	9.6	9.5	
No of prey items	Total	97	65	151	313

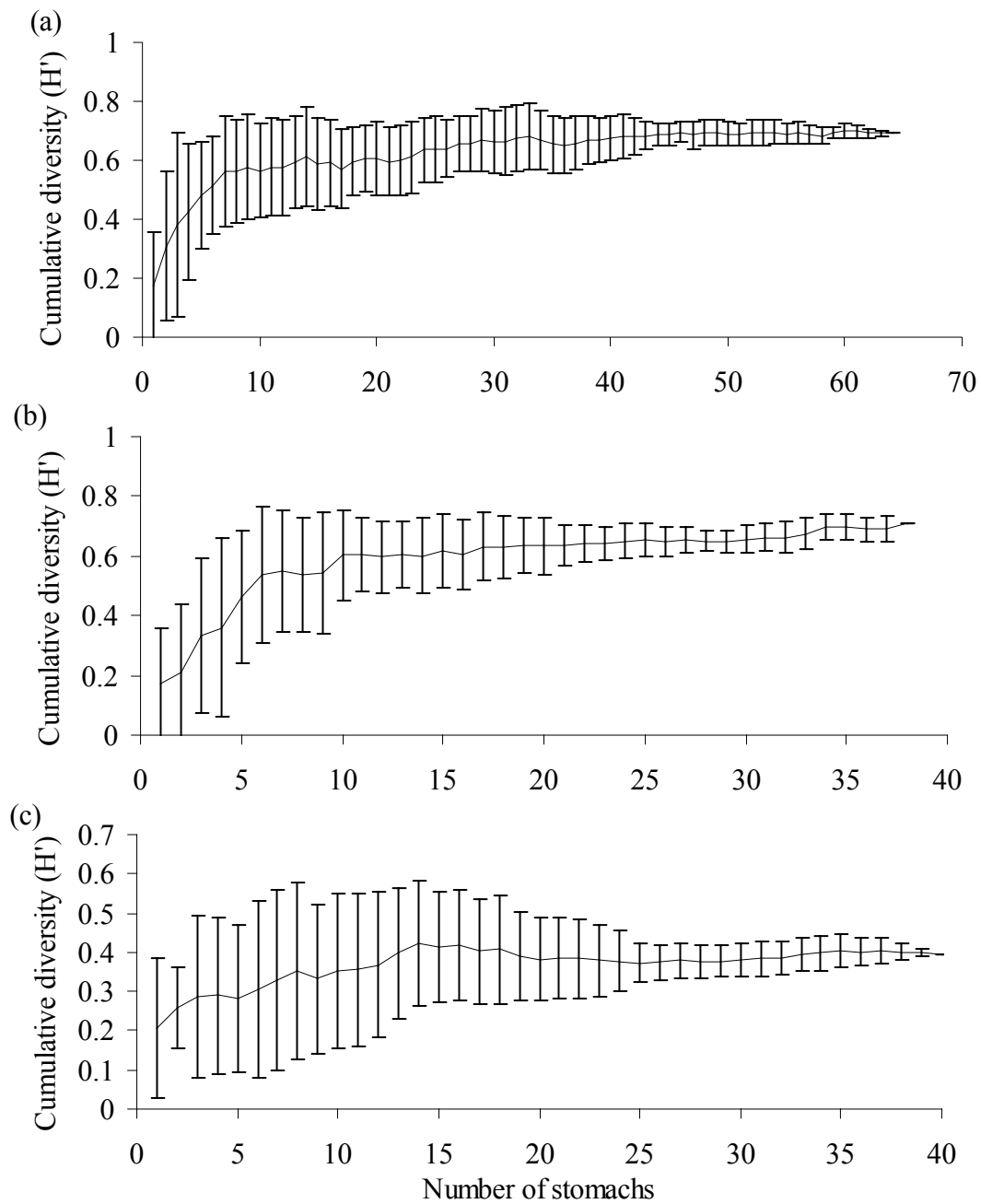


Figure 6.1 Cumulative prey diversity curve by species based on the Shannon-Weiner Index (H') for (a) *O. ornatus*, (b) *O. maculatus*, and (c) *O. halei*.

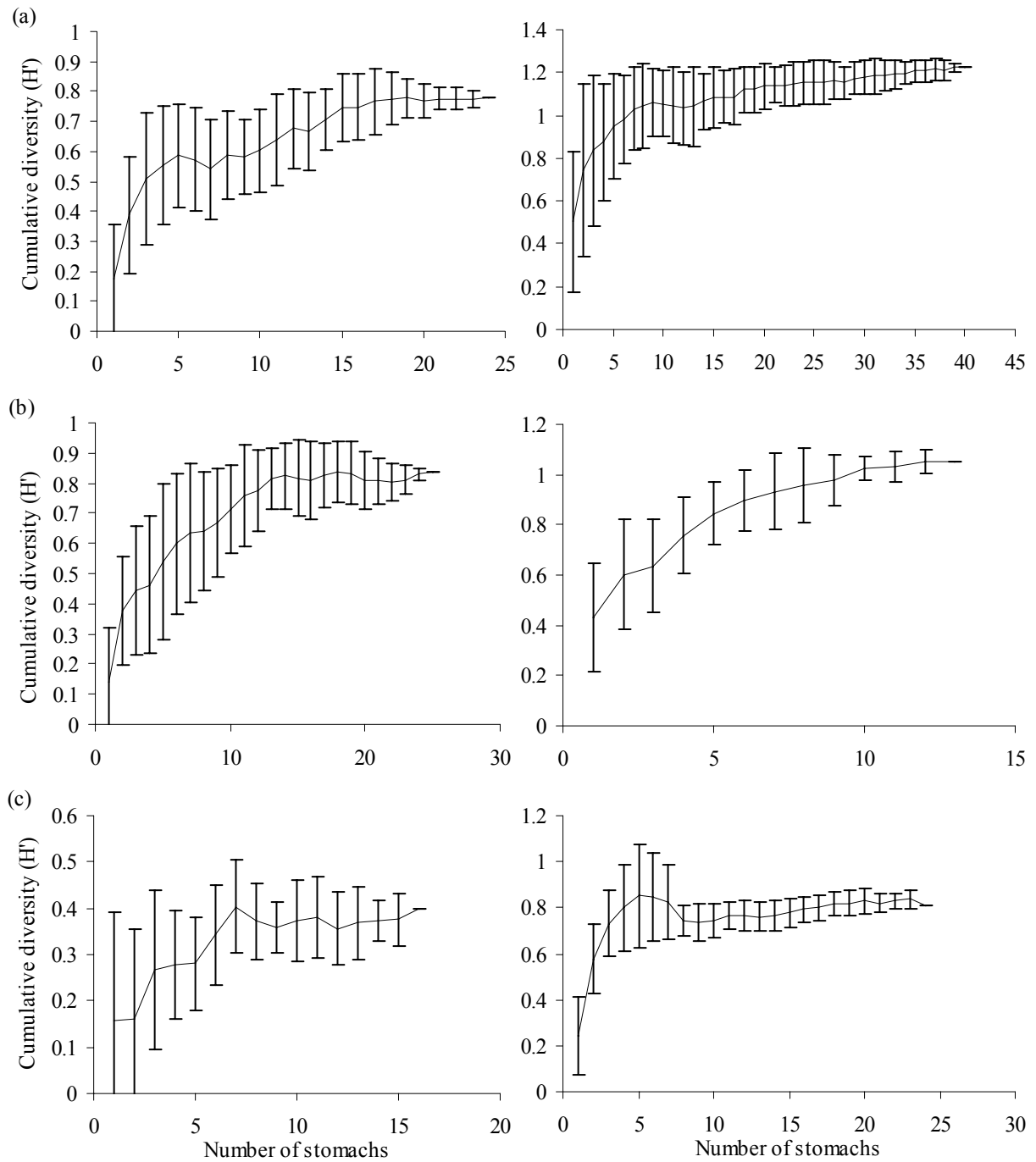


Figure 6.2 Cumulative prey diversity curves by sex based on the Shannon-Weiner Index (H') of males (left) and females (right) for (a) *O. ornatus*, (b) *O. maculatus*, and (c) *O. halei*.

6.4.2 Quantitative description of wobbegong diets

Apart from expected prey items, the stomachs of the wobbegongs also contained some extraneous items. Stones were found in single specimens of *O. maculatus* and *O. halei*, and in two *O. ornatus*. Algal fragments were found in 14 *O. ornatus*, 3 *O. maculatus* and 3 *O. halei*. Finally, molluscan shells were found in single specimens of *O. ornatus* and *O. halei*. All of these items were considered to have been accidentally consumed by the wobbegongs *per se* or by their prey and were removed from further analyses.

6.4.2.1 *Orectolobus ornatus* (Table 6.2, Fig. 6.3a)

Bony fishes (10 families) were the most dominant food category numerically (72.5%), and on the basis of wet mass (86.5%), occurrence (87.2%) and the IRI (92.2%). Cephalopods (2 families) were found in 26.6%, 13.5%, 29.7 and 7.8% on a numerical, wet mass, occurrence and IRI basis, respectively. The rankings of prey items in the bony fishes category differed with the method of quantification. Within the fish category, the IRI indicated that unidentified bony fishes were the most prominent, followed by the sparids with *Pagrus auratus* (snapper) particularly important. When quantified by mass, *Gymnothorax prasinus* (green moray) was the most prominent family of prey items followed by *P. auratus* (snapper), *Girella tricuspidata* (blackfish) and unidentified bony fishes. Within the bony fishes, a few *G. prasinus*, *P. auratus* (in 12% of stomachs) and *G. tricuspidata* contributed to a large proportion of the total mass of the stomach contents sampled, whereas unidentified items contributed more to abundance than to mass. Other bony fishes found as prey items in *O. ornatus* and ranked in accordance with the IRI included species from the families Batrachoididae, Carangidae, Platycephalidae, Monacanthidae, Mugilidae, Pempheridae and Berycidae. Within the cephalopod category, octopus were the most prominent contributing more numerically than by mass to the diet and were followed by cuttlefish.

Table 6.2 Dietary information for *O. ornatus* caught in New South Wales

Prey categories, demersal (D), predominately demersal (PD) or pelagic (P) are based on Stevens and Wiley (1986) and descriptions from Kuiter (2000); %W is the percentage mass of each prey group; %N is the percentage of the number of each prey group identified; %F is the percentage of occurrence of each prey group; %IRI is the percentage Index of Relative Importance of each prey group; general taxonomic groupings are in bold; orders are underlined.

Prey items	Prey category	%W	%N	%F	% IRI
Cephalopoda (octopuses, squids and cuttlefishes)	D	13.50	26.58	29.69	7.82
<u>Octopoda (octopods)</u>					
Octopodidae (benthic octopuses)					
<i>Octopus</i> spp	D	11.98	24.05	26.56	32.01
<u>Sepioidea (cuttlefishes)</u>					
Sepiidae	D	1.52	2.53	3.13	0.42
Osteichthyes (bony fishes)		86.50	73.42	87.5	92.18
Unidentified bony fishes		7.76	27.85	32.81	39.02
<u>Anguilliformes (eels)</u>					
Muraenidae (moray eels)					
<i>Gymnothorax prasinus</i>	D	26.24	2.53	3.13	3.03
<u>Batrachoidiformes (frogfishes)</u>					
Batrachoididae (frogfishes)	D	3.74	7.59	9.38	3.55
<u>Beryciformes (sawbellies)</u>					
Berycidae (Nannygai and red snapper)	D	0.02	1.27	1.56	0.07
<u>Scorpaeniformes (scorpionfishes and flatheads)</u>					
Platycephalidae (flatheads)	D	0.34	2.53	3.13	0.30
<u>Perciformes (perch-like)</u>					
Unidentified Perciformes		4.99	6.33	6.25	2.37
Sparidae (snapper and breams)					
Unidentified Sparidae	D	6.47	2.53	3.13	0.94
<i>Pagrus auratus</i>	D	22.85	11.39	14.06	16.17
Carangidae (jacks and trevallies)	P	1.07	2.53	3.13	0.38
Mugilidae (mullets)	PD	0.32	1.27	1.56	0.08
Kyphosidae (drummers and blackfishes)					
Unidentified Kyphosidae	D	0.68	1.27	1.56	0.10
<i>Girella sydneyanus</i>	D	1.14	1.27	1.56	0.13
<i>Girella tricuspidata</i>	D	10.27	2.53	3.13	1.35
Pempheridae (bullseyes)					
<i>Pempheris</i> spp	D	0.08	1.27	1.56	0.07
<u>Tetraodontiformes (pufferfishes and filefishes)</u>					
Monacanthidae (leatherjackets)	D	0.53	1.27	1.56	0.09

6.4.2.2 *Orectolobus maculatus* (Table 6.3, Fig. 6.3b)

Bony fishes (14 families) were the most dominant food category numerically (80.0%), and on the basis of wet mass (78.7%), occurrence (97.4%) and % IRI (95.6%). Cephalopods were the second most dominant prey group on the basis of number (13.3%), wet mass (14.5%), occurrence (20.5%) and the IRI (3.5%) with octopus comprising 23.2% IRI of the whole diet.

Chondrichthyans were also found in the stomachs of *O. maculatus* contributing 6.7% on a numerical basis, 6.7% by mass, 10.3% by frequency of occurrence and 0.8% IRI. No crustaceans or polychaetes were found in the stomach of *O. maculatus*. The rankings of prey items in the bony fishes category also differed with the method of quantification. The IRI indicated that unidentified bony fishes were the most prominent, followed by *P. auratus* (snapper) and *Scomber australasicus* (slimy mackerel). When quantified by mass, sparids were the most prominent prey items followed by unidentified bony fishes (12.3%), *Muraenesox bagio* (pike eel) and kyphosids. Unidentified items contributed more numerically than in mass to the diet, whereas *P. auratus*, *M. bagio* and *Scorpiis* species all contributed more gravimetrically than in numbers to the diet. Other bony fishes found as prey items in *O. maculatus* and ranked in accordance with the IRI included species from the families Carangidae, Sciaenidae, Berycidae, Dinolestidae, Moridae, Labridae, Serranidae, Mugilidae, Monacanthidae and Diodontidae. Within the chondrichthyan group, prey items from the order Heterodontiformes and families Rhinobatidae and Triakidae were found in the stomach contents and represented 0.3, 1.0, and 0.6% IRI, respectively.

Table 6.3 Dietary information for *O. maculatus* caught in New South Wales

Prey categories, demersal (D), predominately demersal (PD) or pelagic (P) are based on Stevens and Wiley (1986) and descriptions from Kuiter (2000); %W is the percentage mass of each prey group; %N is the percentage of the number of each prey group identified; %F is the percentage of occurrence of each prey group; %IRI is the percentage Index of Relative Importance of each prey group; general taxonomic groupings are in bold; orders are underlined.

Prey items	Prey category	%W	%N	%F	% IRI
Cephalopoda (octopuses, squids and cuttlefishes)	D	14.50	13.33	20.51	3.53
<u>Octopoda (octopods)</u>					
Octopodidae (benthic octopuses)					
<i>Octopus</i> spp	D	14.50	13.33	20.51	23.22
Chondrichthyes (cartilaginous fishes)		6.74	6.67	10.26	0.85
<u>Carcharhiniiformes (ground sharks)</u>					
Triakidae (school and gummy sharks)	D	4.05	1.67	2.56	0.60
<u>Heterodontiformes (bullhead sharks)</u>	D	1.15	1.67	2.56	0.29
<u>Rajiformes (batoids)</u>					
Rhinobatidae (shovelnose rays)	D	1.54	3.33	5.13	1.02
Osteichthyes (bony fishes)		78.76	80.00	97.44	95.62
Unidentified bony fishes		12.75	30.00	28.21	48.58
<u>Anguilliformes (eels)</u>					
Muraenesocidae (pike congers)					
<i>Muraenesox bagio</i>	D	11.05	1.67	2.56	1.33
<u>Gadiformes (cods)</u>					
Moridae (beardies)					
<i>Pseudophycis</i> spp	D	0.90	1.67	2.56	0.27
<i>Lotella rhacina</i>	D	0.74	1.67	2.56	0.25
<u>Beryciformes (sawbellies)</u>					
Berycidae (nannygai and red snapper)					
Unidentified Berycidae	D	0.15	1.67	2.56	0.19
<i>Centroberyx affinis</i>	D	1.57	1.67	2.56	0.34
<u>Perciformes (perch-likes)</u>					
Unidentified Perciformes		1.26	1.67	7.69	2.08
Labridae (wrasses)	PD	1.66	1.67	2.56	0.35
Sparidae (snapper and breams)					
Unidentified Sparidae	D	0.97	1.67	2.56	0.27
<i>Pagrus auratus</i>	D	18.60	6.67	10.26	10.54
Serranidae (rockcods and seaperches)	D	1.01	1.67	2.56	0.28
Carangidae (jacks and trevallies)					
<i>Trachurus novaezelandiae</i>	P	1.28	5.00	7.69	1.97
Scombridae (tunas, mackerels and bonitos)					
<i>Scomber australasicus</i>	P	5.50	10.00	10.26	6.47

Mugilidae (mulletts)					
<i>Mugil cephalus</i>	PD	0.83	1.67	2.56	0.26
Kyphosidae (drummers and blackfishes)					
<i>Scorpius</i> spp	D	11.05	1.67	2.56	1.33
<i>Girella tricuspidata</i>	D	0.80	3.33	5.13	0.86
Sciaenidae (jewfishes)					
<i>Argyrosomus japonicus</i>	PD	5.02	1.67	2.56	0.70
Dinolestidae (longfin pikes)					
<i>Dinolestes lewini</i>	D	3.22	1.67	2.56	0.51
<u>Tetraodontiformes (pufferfishes and filefishes)</u>					
Diodontidae (porcupinefishes)	D	0.14	1.67	2.56	0.19
Monacanthidae (leatherjackets)					
<i>Eubalichthys</i> spp	D	0.26	1.67	2.56	0.20

6.4.2.3 *Orectolobus halei* (Table 6.4, Fig. 6.3c)

Bony fishes (11 families) were the most dominant food category numerically (92.0%), and on the basis of wet mass (79.5%), occurrence (97.6%) and the IRI (97.4%), and contributed more numerically than by mass to the diet. Conversely, chondrichthyans and cephalopods, were consumed by *O. halei* in small numbers, but made up a large proportion of the total mass of stomach contents. Chondrichthyans (three families) were the second most dominant prey group in the diet of *O. halei* on the basis of number (5.3%), wet mass (12.5%), occurrence (19.5%) and the IRI (2.0%). Cephalopods were also found in the stomachs of *O. halei*, contributing 2.6% numerically, 8.0% by mass, 9.8% by frequency of occurrence and 0.6% IRI. Octopus were the only cephalopod prey items and contributed 2.8% IRI to the whole *O. halei* diet. Neither crustaceans nor polychaetes were found in the stomach of *O. halei*. Within the bony fishes category, the IRI indicated that carangids were the most important prey group in *O. halei* with *Trachurus novaezelandiae* particularly important. When quantified by mass, carangids were still the most prominent prey followed by sciaenids, labrids and kyphosids. *Trachurus novaezelandiae* and *S. australasicus* were important numerical contributors to the diet of *O. halei*, but only made up a small proportion of the total mass of prey items examined. A few *Achoerodus viridis*, *Argyrosomus japonicus* and unidentified kyphosids were found in the diet of *O. halei*, but comprised a large proportion of the stomach contents by mass. Other bony fishes found as prey of *O. halei* and ranked in accordance with the IRI included species from the families Clupeidae, Berycidae, Sparidae, Arripidae, Uranoscopidae, and Diodontidae. Within the chondrichthyan group, *Heterodontus portusjacksoni* and *O. ornatus* and species in the family Rhinobatidae were found in the stomach contents of *O. halei* and represented 0.2, 1.6, and 0.2% IRI, respectively.

Prey categories were mostly demersal with only one and two identified prey groups classified as pelagic in the diets of *O. ornatus* and *O. maculatus*, respectively. Although the preys of *O. halei* were mostly demersal and similar to the other two orectolobids, the diet had a broader diversity of pelagic prey.

Table 6.4 Dietary information for *O. halei* caught in New South Wales

Prey categories, demersal (D), predominately demersal (PD) or pelagic (P) are based on Stevens and Wiley (1986) and descriptions from Kuitert (2000); %W is the percentage mass of each prey group; %N is the percentage of the number of each prey group identified; %F is the percentage of occurrence of each prey group; %IRI is the percentage Index of Relative Importance of each prey group; general taxonomic groupings are in bold; orders are underlined.

Prey items	Prey category	%W	%N	%F	% IRI
Cephalopoda (octopuses, squids and cuttlefishes)	D	7.97	2.65	9.76	0.60
<u>Octopoda (octopods)</u>					
Octopodidae (benthic octopuses)					
<i>Octopus</i> spp	D	7.97	2.65	9.76	2.79
Chondrichthyes (cartilaginous fishes)		12.51	5.30	19.51	2.02
<u>Orectolobiformes (carpet sharks)</u>					
Orectolobidae (wobbegongs)					
<i>Orectolobus ornatus</i>	D	2.33	0.66	2.44	0.20
<u>Heterodontiformes (bullhead sharks)</u>					
Heterodontidae (Port Jackson sharks)					
<i>Heterodontus portusjacksoni</i>	D	2.76	0.66	2.44	0.22
<u>Rajiformes (batoids)</u>					
Rhinobatidae (shovelnose rays)	D	3.33	2.65	9.76	1.57
<i>Aptychotrema rostrata</i>	D	1.27	0.66	2.44	0.13
Osteichthyes (bony fishes)		79.52	92.05	97.56	97.38
Unidentified bony fishes		2.83	10.60	24.39	8.81
<u>Clupeiformes (herrings and sardines)</u>					
Clupeidae (pilchards)	P	1.05	0.66	2.44	0.11
<u>Beryciformes (sawbellies)</u>					
Berycidae (nannygai and red snapper)	D	0.55	0.66	2.44	0.08
<u>Perciformes (perch-like)</u>					
Unidentified Perciformes		4.96	5.30	12.20	3.37
Labridae (wrasses)					
<i>Achoerodus viridis</i>	PD	10.88	1.99	7.32	2.53
Sparidae (snapper and breams)	D	0.09	0.66	2.44	0.05
Arripidae (Australian salmon)					
<i>Arripis trutta</i>	P	0.61	0.66	2.44	0.08
Carangidae (jacks and trevallies)					
<i>Trachurus novaezelandiae</i>	P	27.10	52.98	31.71	68.33
Scombridae (tunas, mackerels and bonitos)					
<i>Scomber australasicus</i>	P	6.84	13.91	14.63	8.17
Uranoscopidae (stargazers)					
<i>Kathetostoma leave</i>	D	0.44	0.66	2.44	0.07
Kyphosidae (drummers and blackfishes)					

Unidentified Kyphosidae	D	10.66	1.32	4.88	1.57
<i>Girella tricuspidata</i>	D	0.05	0.66	2.44	0.05
Sciaenidae (jewfishes)					
<i>Argyrosomus japonicus</i>	PD	11.63	1.32	1.70	1.70
<u>Tetraodontiformes (pufferfishes and filefishes)</u>					
Diodontidae (porcupinefishes)					
<i>Dicotylichthys punctulatus</i>	D	1.83	0.66	2.44	0.16

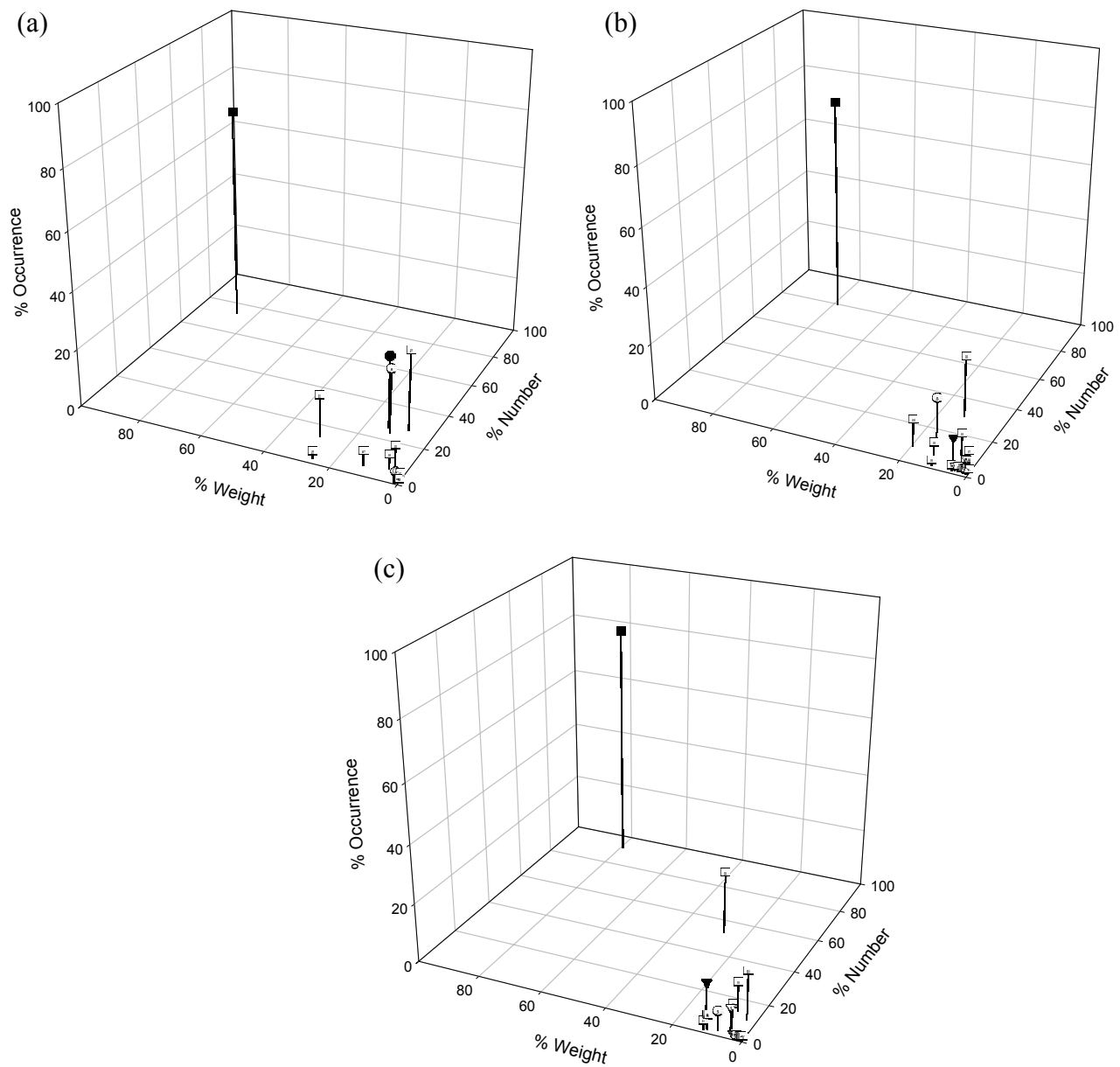


Figure 6.3 Three-dimensional graphical representation of diet in (a) *O. ornatus*, (b) *O. maculatus*, and (c) *O. halei*. (■) Total bony fishes; (□) bony fishes separated by family; (●) total Cephalopods; (○) Cephalopod separated by family; (▲) total Chondrichthyes; and (△) Chondrichthyes separated by family.

6.4.3 Species, sex and size comparison

The dispersion values for the diets were similar among species and slightly higher in males than females with 1.28 for males and 0.91 for females, 1.19 and 0.96, and 1.18 and 0.92 in *O. ornatus*, *O. maculatus* and *O. halei*, respectively. The diets did not differ significantly between the sexes in *O. ornatus*, *O. maculatus* and *O. halei* (ANOSIM: R statistics = 0.018, 0.256 and 0.077 respectively, all $P > 0.05$). This result was also supported by Horn's index which indicated a medium dietary overlap between the sexes with *O. ornatus* (0.51) and *O. maculatus* (0.54), and a strong dietary overlap between the sexes in *O. halei* (0.89). For *O. halei*, diet composition of mature animals had a high degree of overlap with immature sharks (Horn's index = 0.75).

The MDS plot had a high stress level indicating poor fit between actual distance measures and distance in the ordination. Consequently, the plot was difficult to interpret and did not show any major trends (Appendix A). Samples from all three species were largely scattered with dispersion values of 0.87, 1.07 and 1.29 for *O. ornatus*, *O. maculatus* and *O. halei*, respectively. Dietary breadth indicated that *O. maculatus* and *O. ornatus* had a similar, relatively low, diet breadth (*ca.* 0.3), whereas diet breadth of *O. halei* was slightly smaller (0.18). Overall, the diets of the three species differed significantly (ANOSIM: R statistic = 0.184, $P < 0.01$). The diets of *O. ornatus* and *O. halei* did not overlap (0.29 Horn's index) and differed significantly (ANOSIM: R statistic = 0.336, $P < 0.01$). However, neither the diets of *O. ornatus* and *O. maculatus* nor those of *O. maculatus* and *O. halei* differed significantly (ANOSIM: R statistics = 0.077 and 0.01, both $P > 0.05$, respectively). These relationships were supported by Horn's index suggesting a strong overlap of the diets of *O. ornatus* and *O. maculatus* (0.87), and a medium overlap of the diets of *O. maculatus* and *O. halei* (0.46). Octopus were most responsible for the difference between

dietary compositions of the three species of wobbegongs with carangids, sparids and chondrichthyans also contributing (SIMPER).

6.4.4 Trophic level of wobbegongs

The different prey trophic levels used to calculate wobbegong trophic levels were 3.2 for cephalopods, 3.24 for osteichthyans, and 3.65 for chondrichthyans (Cortés 1999). The trophic level of all three species of wobbegongs was calculated to be of 4.23, 4.24 and 4.25 for *O. ornatus*, *O. maculatus* and *O. ornatus*. As expected, all were tertiary consumers.

6.5 Discussion

The total combined percentage of empty stomachs was about 80% when wobbegongs were caught on setlines and 50–65% when caught in traps or while scuba diving. These values were high when compared with other shark species (Wetherbee *et al.* 1990; Simpfendorfer 1998; Joyce *et al.* 2002; Morato *et al.* 2003). Nevertheless, they were consistent with other wobbegong dietary studies (Cochrane 1992; Chidlow 2003) that found 60–70% of stomachs examined were empty. The use of setlines may explain the high percentage of empty stomachs (Cortés 1997). Bait is likely to be more attractive to hungry sharks rather than those with full stomachs because Lokkeborg *et al.* (1995) suggested that fish that feed to satiation have a reduced response to the odour of a bait. The higher percentage of stomachs with prey items present in sharks caught in traps and while scuba diving provided supporting evidence. However, Chidlow (2003) showed that 70% of wobbegongs caught in gillnets had empty stomachs. Furthermore, many sharks were captured with full stomachs and bait indicating that wobbegongs with full stomachs may still be attracted to, and feed on bait. One *O. halei* was found with 19 bony fishes in its stomach and yet still fed on the bait. Regurgitation of stomach contents is a more likely explanation for the high

proportion of empty stomachs and for the differences in the proportion of empty stomachs between sharks caught on setlines and those caught passively (Wetherbee and Cortés 2004). Regurgitation of the stomach contents was often observed when wobbegongs were brought to the surface and onto the boat and likely represented an attempt by the wobbegong to dislodge the hook (C. Huveneers pers. obs.). Therefore, regurgitation appeared to be the most plausible explanation for the high percentage of empty stomachs in wobbegongs. However, infrequent feeding or short periods of feeding followed by periods of rapid digestion cannot be discounted at this stage.

In 80–90% of the wobbegongs examined, the sharks were hooked in the cardiac stomach or anterior oesophagus. One component of their feeding behaviour can explain this very high percentage of stomach-hooked sharks. Wobbegongs are considered to be ambush predators feeding in a similar manner to angel sharks (*Squatina australis*), but with prey consumed when it is in front of the shark (Compagno 2001). The short broad mouth and large broad pharynx produces suction and prey are usually swallowed whole. This explains why hooks were embedded more frequently in the cardiac stomach than in the mouth. While most commercial fishers in NSW used J-shaped hooks to catch wobbegongs, research elsewhere (e.g. Cooke and Suski 2004) has shown that the use of circle hooks can decrease the proportion of stomach-hooked animals and, on occasions, cause a simultaneous reduction in overall catch. The Environmental Impact Statement for the NSW Ocean Trap and Line Fishery (NSW DPI 2006) has recommended a minimum legal size limit of 130 cm total length for all species of wobbegongs. Consequently, future research should examine the effects that J-shaped and circle hooks have on catches and post-release mortality of individuals under this recommended size. It is imperative that these studies be done prior to the introduction of size limits because the results

of the present study (i.e. the stomach-hooking of 80–90% of all wobbegongs) suggest that a minimum size limit will result in unquantified, fishing-related mortality. Such a management action could not be considered to be one that adheres to principles of ecological sustainable development nor would it be in line with objectives of the National Plan of Action for the Conservation and Management of Sharks in Australian waters (Shark Advisory Group and Lack 2004).

The diets of wobbegongs in NSW waters were dominated by bony fishes, with cephalopods and chondrichthyans also important. This is consistent with the early dietary reports that described wobbegongs as feeding on bottom reef fish and invertebrates such as octopus, crabs and lobsters (Whitley 1940; Stead 1963; Last and Stevens 1994; Compagno 2001). In Western Australia, bony fishes were the dominant prey in the diets of wobbegongs with occurrences of 60% and 66.7% in *O. ornatus* and *O. maculatus*, respectively (Chidlow 2003). The present study found a large proportion of bony fishes with about 95% IRI in all three species and is similar to earlier studies in northern NSW (Cochrane 1992). The majority of prey species consumed were demersal, closely associated with reef ecosystems and consistent with the habitats of wobbegongs (Whitley 1940; Stead 1963; Last and Stevens 1994; Compagno 2001). Only a few prey items were classified as pelagic. With mid-water schooling fish such as *T. novaezelandiae* and *S. australasicus*, both species have been observed to form large schools close to the seabed during periods of low water temperature. The largest proportion of *T. novaezelandiae* and *S. australasicus* were found in stomachs of *O. halei* caught off Sydney in July when water temperature is low (i.e. <16°C) and suggest that *O. halei* might have fed on *T. novaezelandiae* and *S. australasicus* when they were close to the seabed.

Previous authors have reported that the diets of wobbegongs include other sharks and suggested cannibalistic behaviour by *O. maculatus* (e.g. Coleman 1980; Compagno 2001). Cochrane (1992) did not find any evidence of chondrichthyan prey, however. Chidlow (2003) and the present study found sharks and rays in wobbegong stomachs. No evidence of cannibalism by *O. maculatus* was found in the present study. The presence of *O. ornatus* in the stomach of an *O. halei* together with several observations (R. Brislane pers. obs.; P. Hitchins pers. obs.; C. Huveneers pers. obs.) confirm that *O. ornatus* is part the diet of *O. halei*.

Cephalopods were found in the two previous studies and in the present investigation. However, the IRI for Cephalopods in NSW (i.e. 0.5–7.8%) was much lower than in Western Australia (WA) (28% - Chidlow 2003). The lower proportion of cephalopods in sharks from NSW was offset by an increased proportion of bony fishes and chondrichthyans compared to wobbegongs in WA. Octopus were clearly the most prominent cephalopod prey in NSW and WA reflecting the presence of octopus in near-shore rocky habitats and the demersal feeding behaviour of wobbegong sharks.

No crustaceans were found in the wobbegong stomachs in this study despite large sample sizes, as observed by Chidlow (2003). This contrasts with Cochrane (1992) who reported that crustaceans were found with an occurrence of 6.6% (derived from a single crustacean found in the stomach of one individual). It is possible that the crustacean reported by Cochrane (1992) may have been in the stomach of a bony fishes consumed by the shark, or may have been eaten accidentally along with other prey. This illustrates the need to apply caution when working with small sample sizes. Other authors (e.g. Whitley 1940; Stead 1963; Last and Stevens 1994; Compagno 2001) have also reported crustaceans in the diets of wobbegongs, but there is no

evidence of crustaceans in the diets of wobbegongs from the eastern and western coasts of Australia. Crustaceans may, however, feature in the diets of neonates and/or juvenile wobbegongs reflecting possible ontogenetic changes in diet. Small *O. ornatus* (< ca. 600 mm TL) and *O. maculatus* and *O. halei* (each < ca. 1100 mm TL) could not be sampled in the present study and should be the focus of future research.

Although dietary variation between sexes has previously been observed in sharks (Cortés and Gruber 1990; Simpfendorfer *et al.* 2001) and rays (Morato *et al.* 2003) it was not evident in the present study. When present, dietary differences between the sexes may be due to sexual segregation or sexual dimorphism (Klimley 1987; Wetherbee and Cortés 2004). The overlap in the diets of male and female wobbegongs may be explained by the absence of observed sexual segregation and similar maximum sizes between sexes (C. Huveneers unpub. data). There were also no differences between the diets of sexually mature and large immature *O. halei*.

Overlap indices and the analysis of similarities (ANOSIM) suggested that the diet of *O. halei* was statistically different from *O. ornatus* when based on the IRI. However, no differences occurred between *O. ornatus* and *O. maculatus*, or *O. maculatus* and *O. halei*. Interspecific differences in dentition were not evident and cannot explain the dissimilarities. The differences in the diets of *O. halei* and *O. ornatus* were mostly due to the higher number of pelagic prey items including the carangid *T. novaezelandiae*, the scombrid *S. australasicus* and chondrichthyans, and the low occurrence of octopus species in the diet of *O. halei*. The greater importance of octopus in *O. ornatus* compared to *O. maculatus* or *O. halei* may be due to the smaller adult size of *O. ornatus* permitting the capture of octopus in small holes/crevices not accessible to the larger-sized *O. maculatus* and *O. halei*. Larger size sharks may instead feed on larger prey and may be more

efficient at capturing faster prey (Wetherbee *et al.* 1990; Simpfendorfer *et al.* 2001). This may explain why pelagic prey and chondrichthyans occurred in the diet of *O. halei*. A change in diet with total length is usually reported within chondrichthyan species as ontogenetic variation (Lowe *et al.* 1996; Ebert 2002) reducing intraspecific competition.

The trophic level of wobbegong sharks calculated at *ca.* 4.24 is similar to a previous study (4.3 - Chidlow 2003) and is the highest of the Orectolobiformes (average 3.6, max 4.1 - Cortés 1999a). The trophic level estimate for Orectolobiformes from Cortés (1999a) did not include Orectolobidae. The high trophic level of wobbegong sharks indicates they are top predators. This high trophic level is in part attributable to chondrichthyans (trophic level of 3.65) in the diet of *O. maculatus* and *O. halei* and to the high proportions of cephalopods in the diet of *O. ornatus*. In Cortés (1999a), no chondrichthyans were found in the diet of any Orectolobiformes explaining their lower average trophic level of 3.6.

Given wobbegongs high trophic level (higher than seabirds and similar to marine mammals (Cortés 1999a)), removal of those top predators may potentially have top-down effects on their prey and other lower level consumers. Several authors assert that trophic cascades rarely occur in large, diverse ecosystems that are buffered by multiple trophic links and spatial heterogeneity (Strong 1992). Accordingly there are debates as to whether sharks exert significant top-down effects (Stevens *et al.* 2000; Kitchell *et al.* 2002). However, the removal of large, predatory fish, including sharks, has led to individual species declines and changes in community structure due to competitive (Fogarty and Murawski 1998) and predatory releases (Baum *et al.* 2003; Shepherd and Myers 2005; Ward and Myers 2005). Ecosystem models for southeast Australia exist (e.g. Goldsworthy *et al.* 2003), but do not include sharks, hindering an assessment of the effects of

wobbegong removal on lower trophic levels. The development of an ecosystem model that includes chondrichthyans and identifies the effects of their removal in NSW waters is clearly needed.

CHAPTER 7: REPRODUCTIVE SYNCHRONY OF THREE SYMPATRIC SPECIES OF
WOBBEGONG SHARK (GENUS *Orectolobus*) IN NEW SOUTH WALES, AUSTRALIA



© Simon Hartley (*Orectolobus ornatus* mating in Julian Rocks, NSW)

This chapter is currently under peer-review with the journal *Marine and Freshwater Research*. I am primary author with Terry Walker (PirVic), Dr. Nick Otway (NSW DPI), and Ass. Prof. Rob Harcourt (Macquarie University) as co-authors. I was responsible for sampling, data analysis and interpretation, and writing the manuscript. Rob Harcourt and Nick Otway contributed by supervising the development of the project and providing comments on earlier versions of the manuscript, whereas Terry Walker helped with data analysis and interpretation, and manuscript evaluation.

Huveneers, C., Walker, T.I., Otway, N.M., Harcourt, R.G. (in review) Reproductive synchrony of three sympatric species of wobbegong shark (genus *Orectolobus*) in New South Wales, Australia. *Marine and Freshwater Research*

7.1 Abstract

Reproductive parameters of three sympatric species of wobbegong (*Orectolobus ornatus*, *O. maculatus* and *O. halei*) off New South Wales (NSW) were investigated to provide a biological basis for the management of a commercial fishery targeting wobbegongs. Maturity based on ovary condition occurred at a smaller total length (TL) than maturity based on uterus condition for all three species. L_{50} for maturity based on uterus condition was 807 mm, 1270 mm, and 1743 mm TL for *O. ornatus*, *O. maculatus* and *O. halei*, respectively. Male length-at-maturity based on clasper calcification was similar to female maturity based on uterus condition. L_{50} for maternity was 805 mm and 1281 mm TL for *O. ornatus* and *O. maculatus*, respectively, but unknown for *O. halei*. These species of wobbegong had synchronous, triennial reproductive cycles. Follicles took two years to enlarge before ovulation. During the first year, follicles remained small, and then grew rapidly during the second year prior to ovulation during November. Gestation lasted *ca.* 10–11 months and parturition occurred during October–November. Mean litter sizes were *ca.* 9 and 21 for *O. ornatus* and *O. maculatus*, respectively, and increased with female total length in *O. ornatus*. Pregnant *O. ornatus* and *O. maculatus* were frequently caught in northern NSW and no pregnant wobbegongs, or females with large, yolky follicles were captured south of Sydney. Differences in the reproductive stages of wobbegongs caught in northern and central NSW suggested geographically dependent reproductive behaviour.

7.2 Introduction

Knowledge of the reproductive characteristics of a species is crucial to assess responses to fishing pressure and to estimate sustainable rates of harvest, and an essential component of most fisheries models. Similarly, reproductive information is essential for evaluating the conservation status of

a species (Hilton-Taylor 2000). Three reproductive components are required for the stock assessment of a fishery: sex ratio at birth, the litter size–maternal length relationship (fecundity), and the relationship between the proportion of the female population in maternal condition (contributing to the next annual recruitment) expressed as a function of female length (i.e., the maternity ogive) (Walker 2005; in review).

Wobbegongs (family *Orectolobidae*) are bottom-dwelling sharks found in tropical to temperate continental waters of the western Pacific (Compagno 2001). Although there are taxonomic uncertainties, eight different species are currently recognised worldwide with three of them inhabiting New South Wales (NSW) waters: the dwarf ornate wobbegong (*Orectolobus ornatus*), the spotted wobbegong (*O. maculatus*), and the large ornate wobbegong (*O. halei*) (Last and Stevens 1994; Chapter 2; Compagno 2001; Huveneers 2006). Wobbegongs have been commercially targeted in NSW by the Ocean Trap and Line Fishery since 1991 and sold as boneless fillets or “flake”. The catch has declined from *ca.* 150 tonnes in 1990/01 to *ca.* 70 tonnes in 1999/00, a decrease of more than 50% in a decade (Pease and Grinberg 1995; NSW DPI unpub. data). Concerns that this decline may be indicative of changes in wobbegong abundance along the NSW coast led to wobbegongs being listed as ‘Vulnerable’ in NSW under the World Conservation Union (IUCN) Red List assessment (Cavanagh *et al.* 2003). This highlighted the need to assess the productivity of wobbegongs and determine their susceptibility to fishing (Smith *et al.* 1998; Cortés 2002; Mollet and Cailliet 2002).

Despite the commercial importance of wobbegongs in New South Wales (NSW), knowledge of their reproductive characteristics is mostly anecdotal (Whitley 1940; Stead 1963; Last and Stevens 1994; Compagno 2001). A study on four species of wobbegong off Perth, Western

Australia (WA) provided reproductive information (Chidlow 2003), but the sample sizes for *O. maculatus*, *O. halei* and the cobbler wobbegong (*Sutorectus tentaculatus*) were insufficient to determine their reproductive cycles. Conversely, sample sizes for the western wobbegong (*O. hutchinsi*) were sufficient to provide a clear description of the reproductive biology of at least that species in Australia.

Specific knowledge of the reproductive strategies of wobbegongs is vital to understanding their life history and population dynamics. Furthermore, such data will help improve management practices to ensure sustainable fishing of wobbegongs. In this paper, we provide information on the reproductive biology and life history characteristics of *O. ornatus*, *O. maculatus* and *O. halei* by investigating various reproductive characteristics including: size-at-birth, size-at-maturity, size-at-maternity, gestation period, ovarian cycle, litter size, and sex ratios at or near birth.

7.3 Materials and methods

7.3.1 Collection of specimens and biological sampling

Wobbegongs were collected at sea by either hook and line fishing from commercial vessels targeting wobbegongs or by scuba-diving during June 2003–May 2006 at six main locations in NSW (Nambucca Heads, Port Stephens, Newcastle, Terrigal, Sydney and Eden) (Fig. 7.1).

Selection of these locations incorporated: seasonality in fishing effort, fishing method, the numbers of wobbegongs caught, accessibility to and the co-operation of commercial fishers.

When fishing occurred within 3 nm, specimens were collected using ten setlines each with six hooks as regulated by NSW DPI. When operating further offshore, fishers used up to 110 hooks on one line. Fishers typically used O'Shaughnessy “J” style hooks size 10/O or 12/O with a wire or nylon trace 50–100 cm long attached to a bottom line by a stainless sharkclip. Lines were set

before sunset and hauled at sunrise on the following day. On three occasions, wobbegongs were caught as bycatch in lobster traps set off Nambucca Heads.

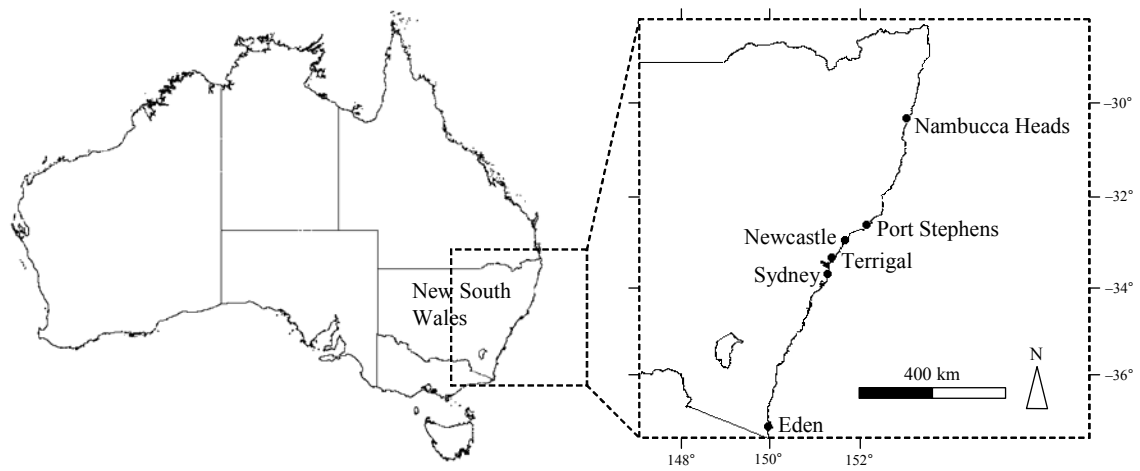


Figure 7.1 Sampling locations for collection of wobbegongs in New South Wales.

When vessel size permitted (≥ 8 m overall length), wobbegongs were measured and dissected on-board. Relevant biological material sampled from those animals was stored on ice and retained for analysis in the laboratory. If not dissected onboard fishing vessels, most sharks were dissected on the same day of capture at the nearest fishing co-operative. In addition, a further 55 specimens caught in lobster traps were frozen and dissected in the laboratory within three weeks of freezing.

Each shark was identified to species (Huveneers 2006; Chapter 2) and sex was determined by noting the presence of claspers in males. Prior to dissection, total length (TL), snout to anal insertion length (SAL), and partial length from the pectoral-fin origin to the caudal-fin origin (PL) were measured to the nearest 1 mm. Snout to anal insertion length was measured instead of fork length as the caudal fin of wobbegongs is not crescentic and without a ventral lobe. This measurement was taken in case damage to the caudal fin rendered the measurement of TL impossible. When this occurred, TL was derived from a relationship between TL and SAL (Huveneers *et al.* in review-a; Chapter 5). Total mass (TM), carcass mass (CM) and liver mass (LM) were recorded using spring balances (100 ± 0.2 kg, 20 ± 0.2 kg, 5 ± 0.1 kg, 2.5 ± 0.02 kg and 600 ± 5 g) according to the size of the specimen or liver. Male and female gonads were excised and held on ice until stored in a freezer at -20°C in the laboratory until further analysis. If females had eggs or embryos *in utero*, they were counted and taken to the laboratory for analysis.

Dissected specimens were visually inspected to assess their reproductive condition and classified using indices adapted from Walker (2005). The reproductive condition of males was based on clasper calcification (CI). The reproductive stage of females was based on two separate indices: a uterus index (UI) reflecting appearance in uterus condition, and an ovary index (OI) based on

follicular size and colour (Table 7.1). *Post partum* females were pooled with mature females without *in utero* eggs or embryos (UI = 3) because of difficulties in distinguishing between *post partum* and mature uteri in the field, and the biological similarity between these uterus conditions.

In the laboratory, testes were thawed, then excised from the surrounding epigonal organ and then each testis was weighed to the nearest 0.01 g. For females, the single ovary was thawed, then excised from the surrounding epigonal organ, and weighed to the nearest 0.01 g. Follicular colour was recorded as either pale and translucent or yellow and the total number of follicles was counted. Maximum diameter of the three largest follicles and of eggs *in utero* was measured to the nearest 0.1 mm with vernier callipers.

The TL, SAL, PL, sex, clasper length (if male), TM of each embryo in a litter (or sub-sample of a litter) together with the uterus origin (left or right) were recorded for all pregnant sharks. If present, the diameters of the external and internal yolk sacs were also measured to the nearest 0.1 mm, respectively. The diameters of the yolk sacs were measured from the longitudinal length perpendicular to the stalk. Embryos were defined as ‘near-term’ if the external yolk sac was not visible.

Table 7.1 Indices to stage reproductive condition (adapted from Walker 2005).
Assumption of maturity is also listed.

Organ	Index	Description	Maturity
Male			
Claspers	CI = 1	Small flaccid claspers with no calcification	Immature
	CI = 2	Claspers are flexible, beginning of calcification can be felt	Immature
	CI = 3	Claspers are fully calcified	Mature
Female			
Ovary	OI = 1	Largest follicle hyaline and not visible without removing epigonal organ	Immature
	OI = 2	Largest follicle white, of diameter greater or equal to 5 mm and visible without removing epigonal organ. No evidence of previous ovulation	Mature
	OI = 3	Largest follicle yellow and of diameter smaller or equal to 30 mm	Mature
	OI = 4	All follicles yellow, of similar size with small epigonal organ and of diameter greater than 30 mm	Mature
	OI = 5	Most follicles white and visible without removing epigonal organ. <i>Corpora lutea</i> or <i>corpora atretica</i> present in ovary	Mature
Uterus	UI = 1	Uniformly thin tubular structure with translucent walls. Indistinct from isthmus.	Immature
	UI = 2	Thin tubular structure partly enlarged posteriorly. Slight thickening of the walls. Distinction with isthmus start to be visible	Immature
	UI = 3	Enlarged tubular structure partly narrow anteriorly	Mature
	UI = 4	<i>In utero</i> eggs without macroscopically visible embryos	Mature
	UI = 5	Embryos macroscopically visible	Mature

7.3.2 *Male reproduction*

7.3.2.1 Maturity ogive

The degree of clasper calcification was also used to categorise maturity condition (Table 7.1).

Logistic models were used to assess the proportion of males mature at any TL. Model parameters and the ogive with the 95% confidence limits (CL) were estimated by the method of maximum likelihood of the probit procedure (Walker 2005) using the SAS statistical package (SAS Institute, Cary, North Carolina, USA). Males were defined as mature if CI = 3; otherwise they were defined as immature. In addition, the length of the left clasper measured to the nearest 1 mm from the anterior margin of the cloaca to the distal tip of the clasper was measured. The length at which isometric growth of claspers occurred was also estimated visually.

7.3.2.2 Reproductive cycle of males

Temporal variation in reproductive condition of mature males was investigated by testing for the effect of month (pooled across years) on the gonadosomatic index ($GSI = 100 \times \text{testes mass} \times (TM)^{-1}$), and the hepatosomatic index ($HSI = 100 \times LM \times (TM)^{-1}$). Testes mass was pooled across locations because small sample sizes prevented analysis of spatial variation. In some instances, where TM was not recorded, it was determined from the TM–TL relationship. The effect of month was tested by analysis of covariance (ANCOVA) with TL as a covariate. Data were log-transformed when variances were heterogeneous (Levene test - Cody and Smith 1997). When the effect of TL was significant, GSI was adjusted for the effect of TL by least square means.

7.3.3 Female reproduction

7.3.3.1 Maturity and maternity ogives

Female maturity and maternity ogives were determined the same way as the male maturity ogives using the method of maximum likelihood. Maturity ogives were calculated from ovary condition and uterus condition. Females were classed as mature if the follicles were visible without removing the epigonal organ ($OI \geq 2$), or if female uteri were enlarged ($UI \geq 3$). In calculating the maternity ogive, a female was defined as being in maternal condition at the time of capture if, had it survived, it would have contributed to recruitment during the next recruitment season (Walker 2005). For *O. ornatus* and *O. maculatus*, a female was classified in maternal condition if it had eggs *in utero* ($UI = 4$) during November–December or if it was pregnant with macroscopically visible embryos ($UI = 5$). All other females were considered to be in non-maternal condition; i.e., immature females ($UI = 1$ and 2), mature females with eggs *in utero* during January–October ($UI = 4$), and mature females without eggs or embryos *in utero* ($UI = 3$).

7.3.3.2 Ovarian cycle

The largest follicle diameter (LFD) measured was used in all statistical analysis because there was no significant difference in the size of the three largest follicles (GLM: $F_{df=2,911} = 0.54$, $P > 0.05$). The LFD for mature females was plotted against Julian day (pooled across years) for each uterus condition separately following Walker (2005). LFD was pooled across locations because of small sample sizes at some locations, which prevented analysis of spatial variation. In females where $UI = 3$, two separate reproductive stages were observed at any time of the year: non-pregnant females with small white follicles and non-pregnant females with large yolky follicles. A linear regression of LFD against Julian day was undertaken for pregnant females ($UI = 5$), for females when $UI = 3$ and follicles were pale and translucent, and for females when $UI = 3$ and

yolked follicles. The difference in LFD growth between the three reproductive stages of mature females was assessed using ANCOVA including Julian day as covariate.

7.3.3.3 Period of gestation and embryonic growth

The growth pattern of embryos was determined by plotting for each female the mean TL of embryos and the mean diameter of each of the external and internal yolk sacs against month (pooled across years). Similarly, the mean mass of embryos and mean mass of each of the external and internal yolk sacs were plotted against month. Timing of ovulation, parturition and gestation were determined by inspection of the graphs. Spatial variation in embryonic development was investigated by testing for the effect of location on the embryo TL using ANCOVA including Julian day as a covariate.

7.3.3.4 Sex ratio of embryos and distribution of *in utero* eggs and embryos

Paired t-tests were used to compare pregnant females with *in utero* eggs (UI = 4) or embryos (UI = 5) to test three null hypotheses: (1) there was no difference in the number of *in utero* eggs in the right and left uteri, (2) there was no difference in the number of embryos in the right and left uteri, and (3) there was no difference in the numbers of male and female embryos pooled across both uteri.

7.3.3.5 Litter size–maternal length relationship

The relationship between litter size and maternal length was examined using four different variables: number of embryos, TL of near-term embryos, TM of near-term embryos, and number of ovarian follicles when OI = 4. Each variable was plotted against maternal TL to determine the relationship between size of females and number of offspring using linear regression (Walker

2005). The difference between the number of follicles when $OI = 4$ and litter size was tested using ANCOVA with TL as covariate.

7.4 Results

A total of 904 wobbegongs (435 males and 469 females) was collected and dissected: 385 *O. ornatus* (183 males and 202 female, range 471–1017 mm TL), 185 *O. maculatus* (97 males and 88 females, range 870–1575 mm TL), and 334 *O. halei* (155 males and 179 females, range 869–2065 mm TL) (Table 7.2).

Table 7.2. Number of wobbegongs caught during June 2003–May 2006.

Species	Location	Number caught		
		Male	Female	Total
<i>O. ornatus</i>	Nambucca Heads	163	170	333
	Port Stephens	20	32	52
	Total	183	202	385
<i>O. maculatus</i>	Nambucca Heads	23	26	49
	Port Stephens	36	21	57
	Newcastle	5	2	7
	Terrigal		2	2
	Sydney	33	37	70
	Total	97	88	185
<i>O. halei</i>	Nambucca Heads	18	13	31
	Port Stephens	5	5	10
	Newcastle	1	2	3
	Terrigal	2	6	8
	Sydney	93	116	209
	Eden	36	37	73
	Total	155	179	334
Total		435	469	904

7.4.1 Male reproduction

7.4.1.1 Maturity ogives

Sampling yielded 183 male *O. ornatus* (579–995 mm TL), 97 male *O. maculatus* (920–1575 mm TL) and 155 male *O. halei* (955–2065 mm TL). Sizes at maturity from clasper calcification differed among species with a L_{50} (with 95% CL) of 803 (788, 814), 1282 (1261, 1299) and 1784 (1758, 1806) mm TL for *O. ornatus*, *O. maculatus* and *O. halei*, respectively (Fig. 7.2, Table 7.3). The shortest mature and longest immature shark for *O. ornatus* (790, 860 mm TL) were smaller than for *O. maculatus* (1194, 1360 mm TL), which, in turn, were smaller than for *O. halei* (1684, 1750 mm TL). Size-at-maturity estimates from isometric growth of the claspers were 800, 1200 and 1750 mm TL for *O. ornatus*, *O. maculatus* and *O. halei*, respectively. These lengths were similar to the estimates obtained using indices of clasper calcification.

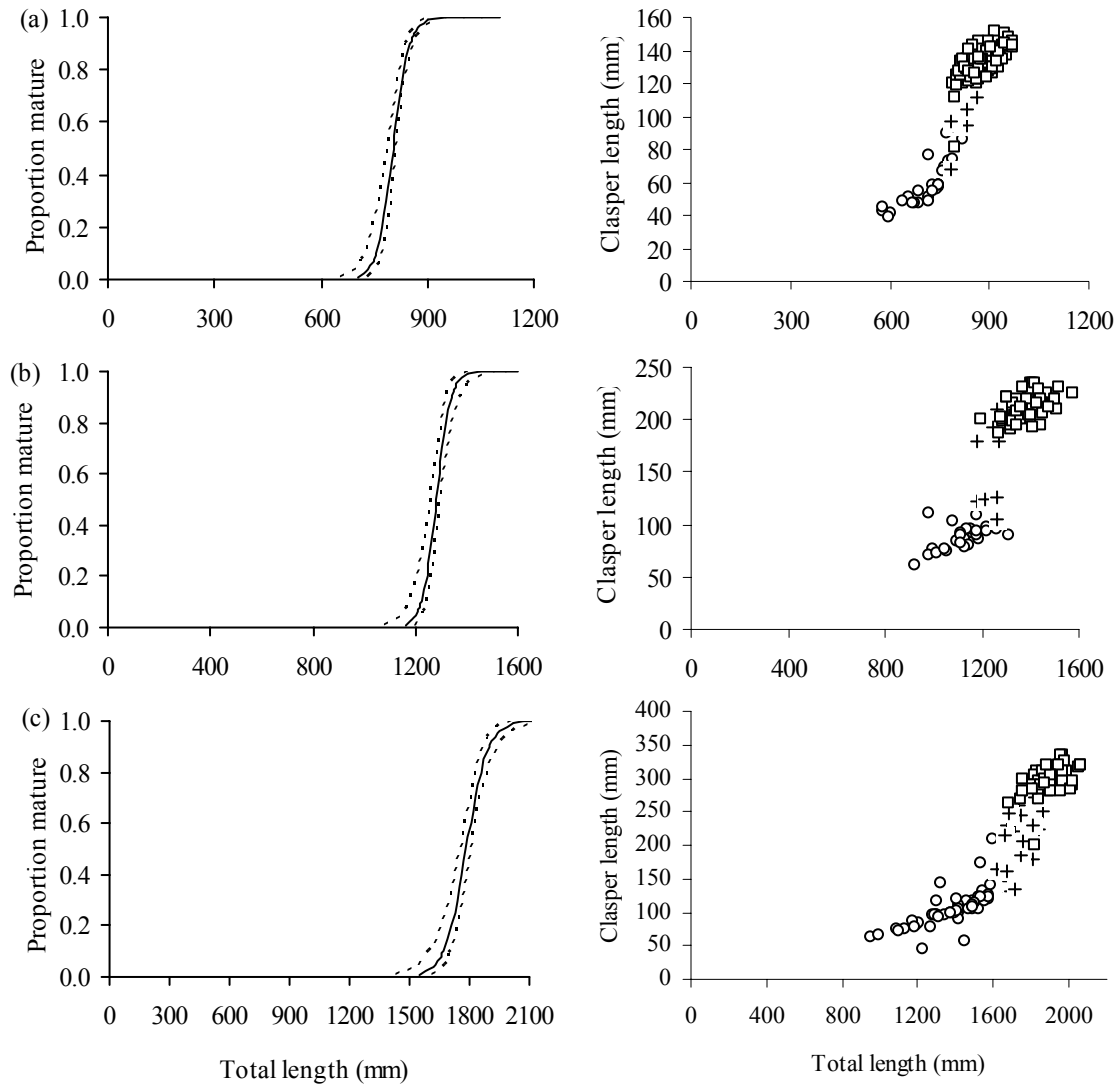


Figure 7.2 Male size-at-maturity estimation based on clasper calcification and clasper length for wobbegongs in NSW

Proportion of population mature against total length (—) with 95% confidence limits (---) (left) and clasper length against total length of immature (CI = 1, ○), maturing (CI = 2, +) and mature (CI = 3, □) (right) for male (a) *O. ornatus*, (b) *O. maculatus* and (c) *O. halei*. Values of parameters and statistical quantities are given in Table 7.3.

Table 7.3 Maturity and maternity estimates for wobbegongs in NSW

Values for parameters and statistical quantities for the equation $P_L = P_{\max} (L + e^{-\ln(19)(L-L_{50}/L_{95}-L_{50})})^{-1}$; L is total length measured in millimetres; P_L is proportion of animals at TL; L , L_{50} and L_{95} are parameters; P_{\max} is an asymptotic constant; n is the total number of animals classed as mature; N is the total number of animals examined for maturity; ML is maximum likelihood; and P is probability of the logistic regression statistical significance.

Sex and species	Ogive	<i>n</i>	N	L ₅₀ (CI)		L ₉₅ (CI)		P _{max}	ML	P
Male										
<i>O. ornatus</i>	Maturity	143	182	803	(788, 814)	867	(857, 882)	1	−82.71	<0.001
<i>O. maculatus</i>	Maturity	59	96	1282	(1261, 1299)	1360	(1336, 1405)	1	−29.10	<0.001
<i>O. halei</i>	Maturity	51	146	1784	(1758, 1806)	1938	(1902, 2000)	1	−69.79	<0.001
Female										
<i>O. ornatus</i>	Ovarian maturity	173	198	729	(683, 757)	849	(830, 872)	1	−74.54	<0.001
	Uterine maturity	143	198	807	(788, 820)	907	(892, 931)	1	−171.64	<0.001
	Maternity	50	147	805	(796, 811)	901	(893, 911)	0.33	−2454.50	<0.001
<i>O. maculatus</i>	Ovarian maturity	67	79	1117	(1016, 1170)	1297	(1246, 1380)	1	−22.61	<0.001
	Uterine maturity	47	79	1270	(1227, 1296)	1424	(1387, 1504)	1	−56.61	<0.001
	Maternity	14	65	1281	(1255, 1299)	1546	(1496, 1633)	0.33	−317.02	<0.001
<i>O. halei</i>	Ovarian maturity	68	166	1591	(1561, 1616)	1792	(1756, 1843)	1	−96.85	<0.001
	Uterine maturity	64	161	1743	(1724, 1760)	1902	(1869, 1953)	1	−119.15	<0.001

7.4.1.2 Reproductive cycle of males

The gonadosomatic and hepatosomatic indices of *O. ornatus* differed significantly among months (ANCOVA: $F_{df=9,99} = 83.25$, $P < 0.001$ and $F_{df=9,90} = 3.85$, $P < 0.001$, respectively). GSI and HSI showed opposite trends with GSI peaking during March–June, whereas HSI decreased during March–July (Fig. 7.3a).

The gonadosomatic index of *O. maculatus*, differed significantly among months (ANCOVA: $F_{df=8,41} = 4.13$, $P < 0.01$), whereas the hepatosomatic index did not differ significantly among months (ANCOVA: $F_{df=8,23} = 2.17$, $P > 0.05$). Both indices exhibited similar variation through time, and were lowest during April–July and then increased to a maximum in January (Fig. 7.3b).

The gonadosomatic index of *O. halei*, differed significantly among months irrespective of whether TL was used as a covariate (ANCOVA: $F_{df=10,30} = 10.34$, $P < 0.001$ and with TL as a covariate, ANCOVA: slope $F_{df=8} = 0.25$, $P > 0.05$, intercept $F_{df=1} = 5.44$, $P < 0.05$). The hepatosomatic index also differed significantly among months (ANCOVA: $F_{df=6,7} = 4.50$, $P < 0.05$). The gonadosomatic index of *O. halei* was similar to *O. maculatus* and peaked at about December and then declined to a minimum during March–August. The large error bars and the absence of data during some months prevent the detection of any trends in the hepatosomatic index (Fig. 7.3c).

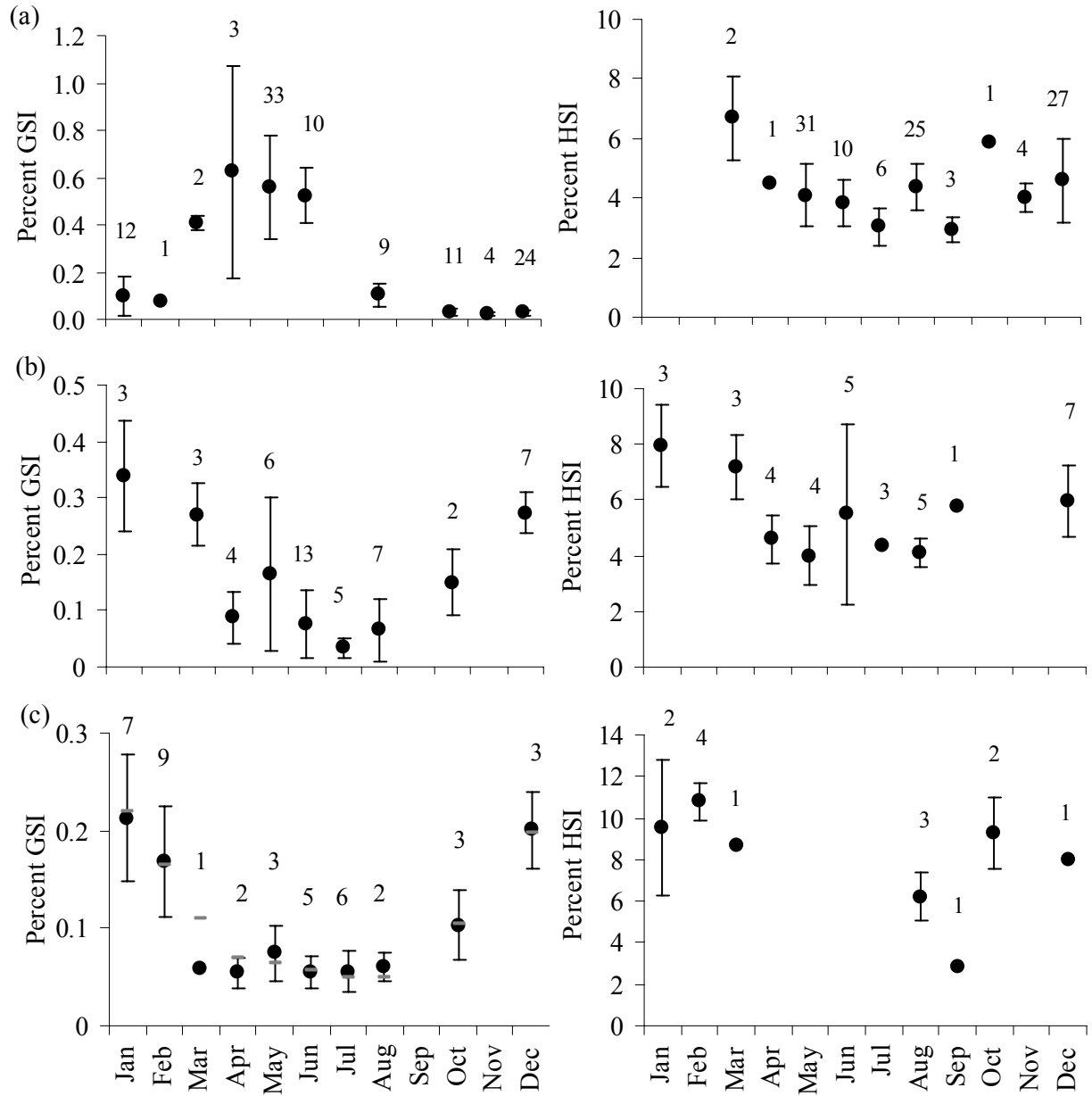


Figure 7.3 Temporal variation of male reproductive activity for wobbegongs in NSW
 Percentage gonadosomatic index (left) percentage hepatic somatic index (right) through month for (a) *O. ornatus*, (b) *O. maculatus* and (c) *O. halei*. ● mean monthly value; bars, standard error for monthly value; – mean monthly value corrected for effect of total length of shark; number above bar is monthly sample size.

7.4.2 Female reproduction

7.4.2.1 Maturity and maternity ogives

Sampling yielded 202 female *O. ornatus* (471–1017 mm TL), 88 *O. maculatus* (870–1510 mm TL) and 179 *O. halei* (869–2015 mm TL). Size-at-maturity was defined using ovary and uterus indices. Female maturity based on ovary index occurred at smaller TL than for maturity based on uterus index for all three species (Table 7.3). The L_{50} (with 95% CL) based on ovary index and uterus index occurred at 729 (683, 757) and 807 (788, 820) mm TL for *O. ornatus*, respectively; at 1117 (1016, 1170), and 1270 (1227, 1296) mm TL for *O. maculatus*, respectively; and at 1591 (1561, 1616) and 1743 (1724, 1760) mm TL for *O. halei*, respectively (Fig. 7.4 and Table 7.3).

Using uterus index to define a mature wobbegong, length of the shortest mature and the longest immature shark for *O. ornatus* (790, 924 mm TL) were smaller than for *O. maculatus* (1165, 1380 mm TL), which, in turn, were smaller than for *O. halei* (1605, 1965 mm TL).

Estimates of L_{50} (with 95% CL) for maternity ogive were 805 (796, 811) and 1281 (1255, 1299) mm TL for *O. ornatus* and *O. maculatus*, respectively. The L_{50} for the maternity ogive was larger than L_{50} for maturity ogive from uterus condition for both species (Fig. 7.4) (Table 7.3).

Maternity parameters were not estimated for *O. halei* because of the lack of females sampled in maternal condition.

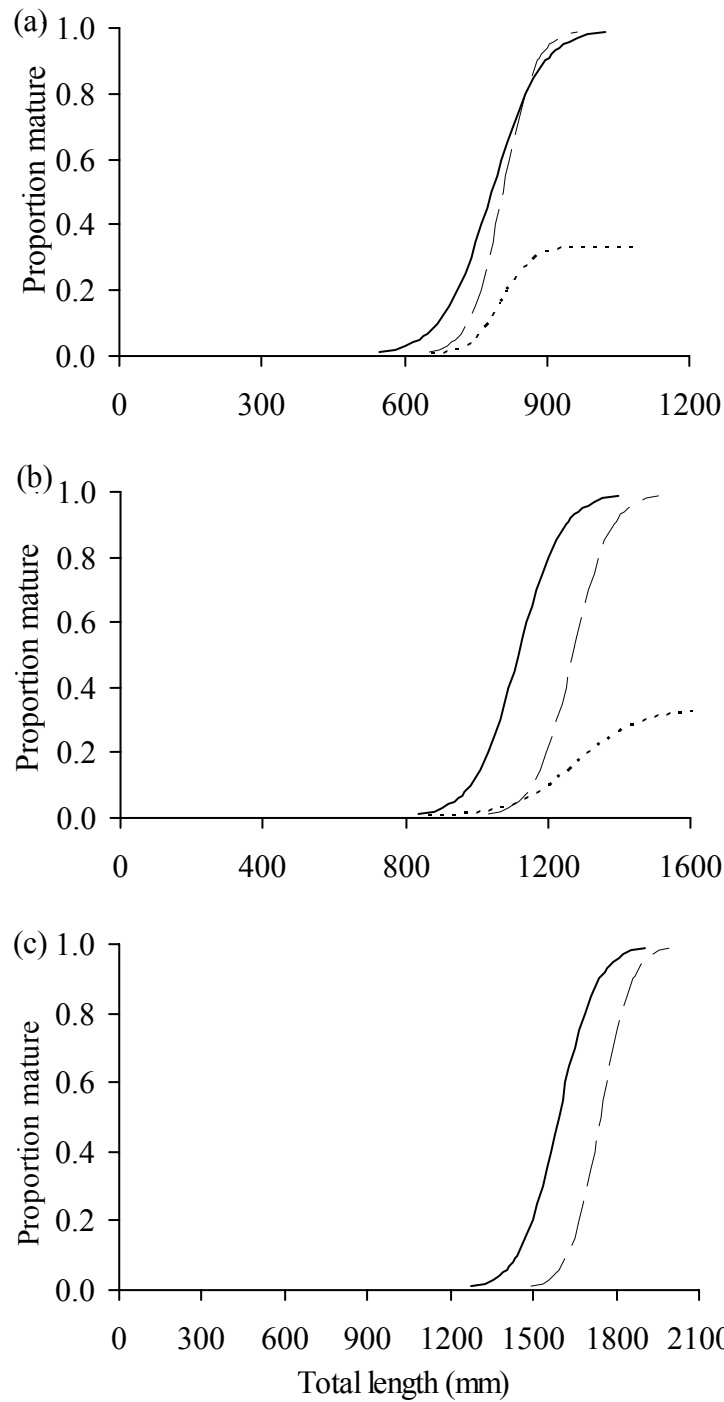


Figure 7.4. Female maturity and maternity ogive of wobbegong sharks in NSW

Proportion of female population with mature ovary (—), mature uteri (—), and in maternal condition (- - -) for (a) *O. ornatus*, (b) *O. maculatus*, and (c) *O. halei*. Ovary and uteri were classed as mature if $OI \geq 2$ and if $UI \geq 3$, respectively. Sharks were classed in maternal condition if females had *in utero* eggs ($UI = 4$) during November or December, females were pregnant with macroscopically visible embryos ($UI = 5$). Values of parameters and statistical quantities are given in Table 7.3.

7.4.2.2 Ovarian cycle

Analysis of the ovarian cycle of *O. ornatus* was based on 202 females; of these, 41 sharks had UI = 1, 17 had UI = 2, and 144 sharks had UI = 3, 4 or 5. Follicles of 30 sharks were measured as <2 mm and excluded from analysis, whereas the LFD of 21 sharks were not measured because of the poor condition of the ovary. Follicles were not developing when uterus condition was UI = 1 (i.e., LFD ranged 5–13 mm, mean 8.5 mm, s.e. 0.6 mm, $n = 12$), or when UI = 2 (i.e., LFD ranged 2–17 mm, mean 9.2 mm, s.e. 1.5 mm, $n = 16$). In contrast, the LFD of sharks with UI = 3–5 exhibited more variability. Individuals with UI = 3 had LFD ranging 5–49 mm (mean 17.2 mm, s.e. 1.5 mm, $n = 84$), whereas those with UI = 4 had LFD ranging 5–58 mm (mean 28.7 mm, s.e. 13.4 mm, $n = 4$) and those with UI = 5 had LFD ranging 0–14 (mean 6.7 mm, s.e. 0.4 mm, $n = 35$).

Growth in LFD differed significantly among reproductive stages in mature females (ANCOVA: slope $F_{df=2} = 55.04$, $P < 0.001$, intercept $F_{df=1} = 65.08$, $P < 0.001$; Fig. 7.5). Mean LFD in pregnant sharks (UI = 5) slowly decreased from *ca.* 8 mm to *ca.* 3 mm throughout pregnancy (linear regression: $F_{df=1, 34} = 9.38$, $r^2 = 0.22$, $P < 0.01$; Fig. 7.5c). The mean LFD of females with pale and translucent follicles (UI = 3), slowly increased from *ca.* 7 mm to *ca.* 13 mm (linear regression: $F_{df=1, 62} = 14.75$, $r^2 = 0.19$, $P < 0.001$). However, large yolky follicles grew much more rapidly than the pale and translucent follicles whereby their mean LFD increased from *ca.* 25 mm to *ca.* 57 mm during a 12-month period (linear regression: $F_{df=1, 62} = 121.44$, $r^2 = 0.87$, $P < 0.0001$; Fig. 7.5a, Table 7.4). Wobbegongs with large yolky follicles (UI = 4) were not included in the regression of LFD against Julian day, but rather only on the timing of ovulation. Sharks with eggs *in utero* (UI = 4) were only observed during November suggesting that ovulation

occurred over a short period of time during November (Fig. 7.5b). The HSI of *O. ornatus* was correlated with LFD, as well as embryo TL indicating an increase of liver mass during follicular development, but a decrease of liver mass during pregnancy (Fig. 7.8a).

Analysis of the ovarian cycle of *O. maculatus* was based on 88 females; of these, 33 sharks had UI = 1, 7 had UI = 2, and 48 had UI = 3 or 5. The follicles of 20 sharks were measured as <2 mm and excluded from analysis, whereas the LFD of 3 sharks was not measured because of the poor condition of the ovary. Follicles were not developing when UI = 1 (i.e., LFD ranged 5–13 mm, mean 7.0 mm, s.e. 0.4 mm, $n = 13$), or UI = 2 (i.e., LFD ranged 2–17 mm, mean 9.4 mm, s.e. 0.2 mm, $n = 7$). In contrast, the LFD of *O. maculatus* with UI = 3–5 exhibited more variability. Individuals with UI = 3 had LFD ranging 4–51 mm (mean 14.5 mm, s.e. 2.2 mm, $n = 32$), whereas those with UI = 5 had LFD ranging 4–12 mm (mean 6.6 mm, s.e. 0.5 mm, $n = 13$).

The only significant regression of LFD significant against Julian day occurred with individuals with large yolky follicles (linear regression: $F_{df=1,2} = 92.02$, $r^2 = 0.98$, $P < 0.05$; Fig. 7.6). This showed that when UI = 5 and when sharks with UI = 3 have pale and translucent follicles with the mean LFD remaining at *ca.* 10 mm (Fig. 7.6b). In contrast when wobbegongs of UI = 3 have large yolky follicles, the mean LFD rapidly increased from *ca.* 32 mm to *ca.* 55 mm during a 12-month period (Fig. 7.6a, Table 7.4). Finally, the HSI of *O. maculatus* was correlated with LFD, but not with embryo TL (Fig. 7.8b).

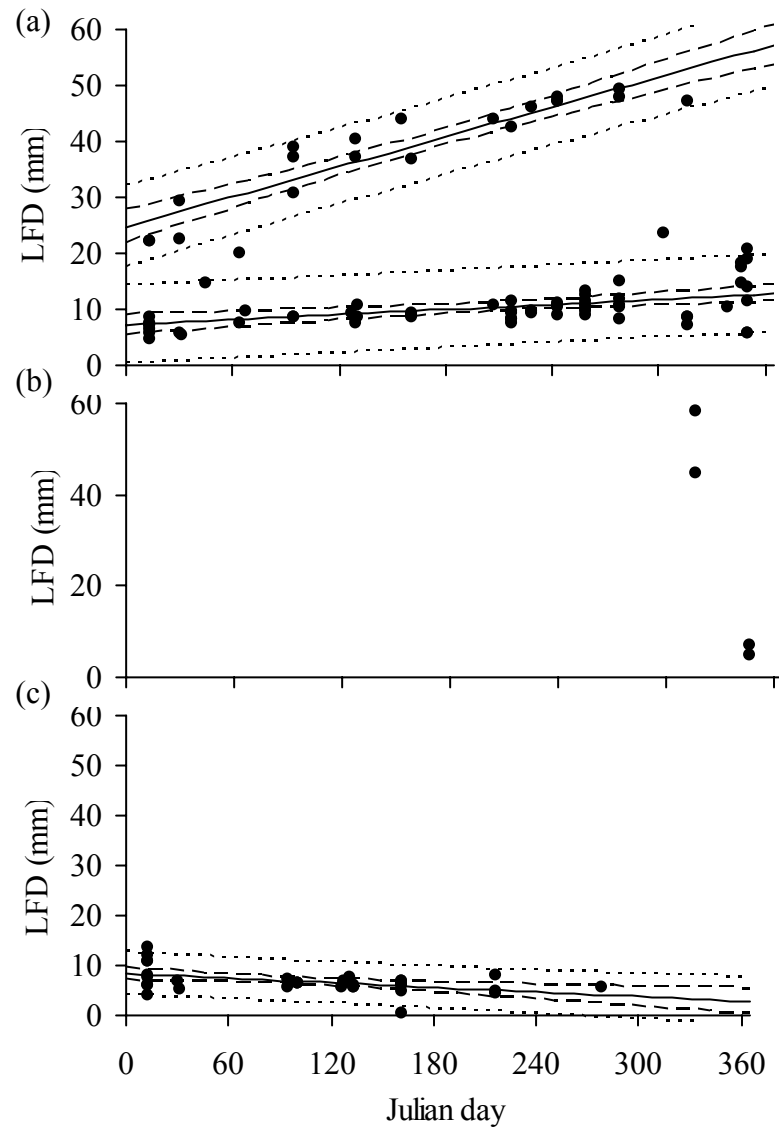


Figure 7.5 Largest ovarian follicle diameter against Julian day for uterus conditions UI=3–5 of *O. ornatus*

Largest follicle diameter against Julian day for each mature uterus conditions (UI = 3–5). Mean largest follicle diameter (—) with 95% confidence limits (---) and 95% prediction limits (- - - -) are presented for (a) non-pregnant animals (UI = 3), (b) animals with *in utero* eggs (UI = 4), and (c) pregnant females (UI = 5). Values of parameters and statistical quantities are given in Table 7.4.

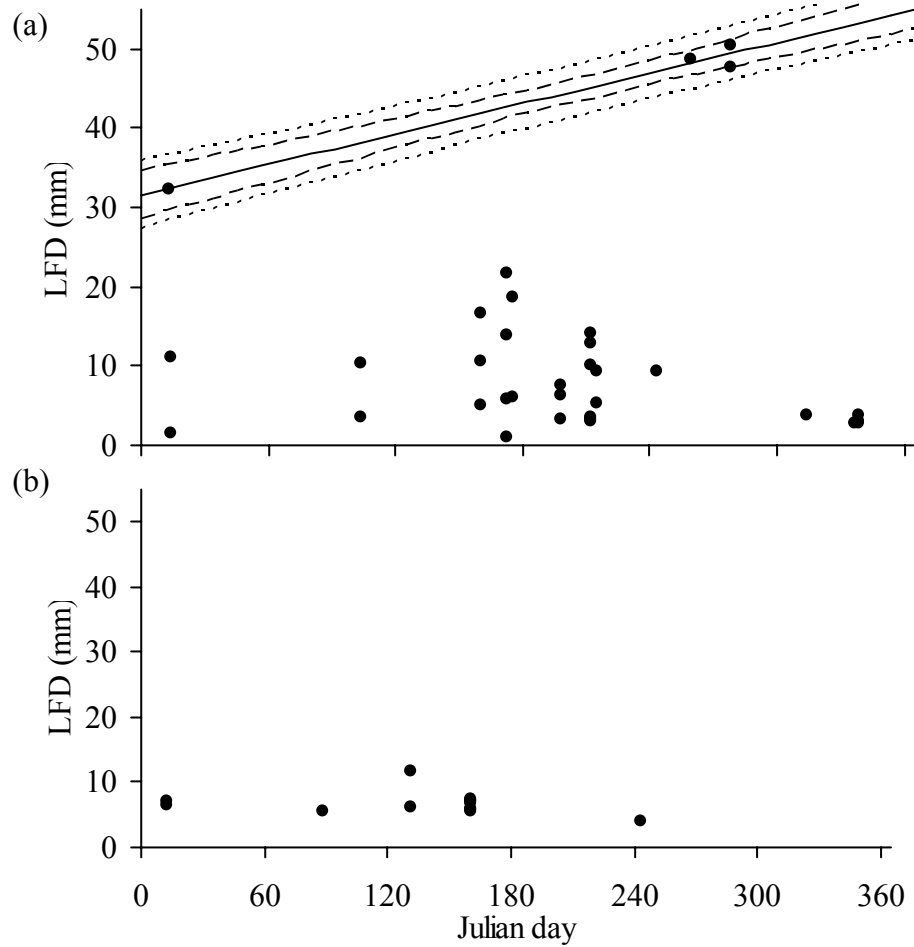


Figure 7.6. Largest ovarian follicle diameter against Julian day for uterus conditions UI=3 and 5 of *O. maculatus*

Largest follicle diameter against Julian day for each mature uterus conditions (UI=3 and 5). Mean largest follicle diameter (—) with 95% confidence limits (---) and 95% prediction limits (- - - -) are presented for (a) non-pregnant animals (UI = 3), (b) pregnant females (UI = 5). Values of parameters and statistical quantities are given in Table 7.4.

Analysis of the ovarian cycle of *O. halei* was based on 179 females; of these, 102 sharks had UI = 1, 13 had UI = 2, and 64 had UI = 3 or 5. The follicles of 81 sharks were measured as <2 mm and excluded from analysis, whereas the LFD of 4 sharks were not measured because of the poor condition of the ovary. Follicles were not developing when UI = 1 (i.e., LFD ranged 5–13 mm, mean 8.6 mm, s.e. 0.3 mm, $n = 26$), or when UI = 2 (i.e., LFD ranged 2–17 mm, mean 9.4 mm, s.e. 0.3 mm, $n = 8$). In contrast, the LFD of sharks with UI = 3–5 exhibited more variability with LFD ranging from 6–52 mm (mean 14.3 mm, s.e. 0.9 mm, $n = 60$).

No pregnant (UI = 5) *O. halei* were obtained and one individual with yolky follicles >50 mm LFD was observed. Consequently, growth of the follicles could only be examined in individuals with UI = 3 and pale and translucent follicles. Analysis (linear regression: $F_{df=1,56} = 11.09$, $r^2 = 0.17$, $P < 0.01$) showed that LFD significantly increased from *ca.* 9 mm to *ca.* 21 mm (Fig. 7.7, Table 7.4). Unlike *O. ornatus* and *O. maculatus*, the HSI of *O. halei* was not correlated with LFD and a possible correlation with embryo TL could not be examined because no pregnant *O. halei* were obtained (Fig. 7.8c, Table 7.5).

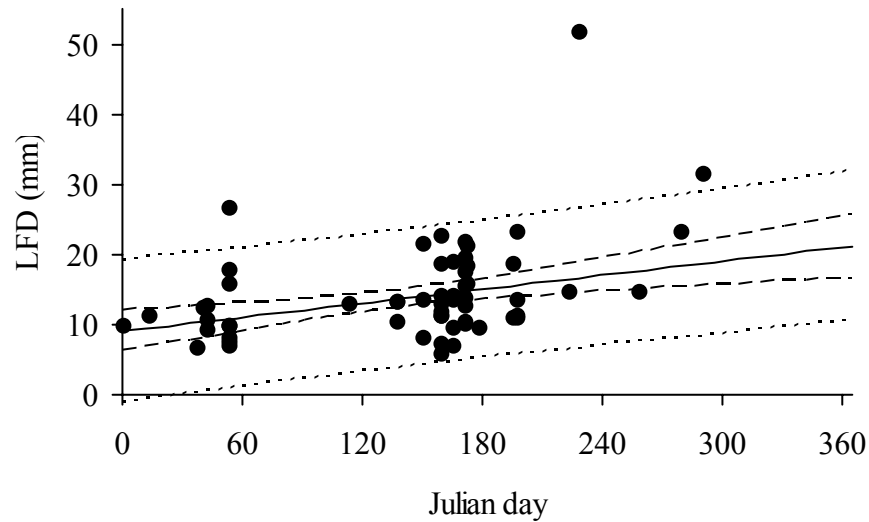


Figure 7.7 Largest ovarian follicle diameter against Julian day for uterus conditions UI=3 of *O. halei*

Largest follicle diameter against Julian day for conditions 3. No females were found in uterus condition 4 or 5. Mean largest follicle diameter (—) with 95% confidence limits (---) and 95% prediction limits (- - - -) are presented for non-pregnant animals (UI = 3). Values of parameters and statistical quantities are given in Table 7.4.

Table 7.4 Largest follicle growth estimates for wobbegongs in NSW

Values for parameters and statistical quantities for the regression equation $LFD = a' + b't$; t is Julian day; LFD is largest follicle diameter; a' and b' are parameters; n is sample size; r^2 is square of regression correlation coefficient; rmse is root mean square error for the regression; and P is probability of statistical significance.

Species	Uterus condition	n	a' (s.e.)	b' (s.e.)	rmse	r^2	P
<i>O. ornatus</i>	UI = 5	35	8.32 (0.64)	-0.015 (0.0049)	2.10	0.22	<0.01
	UI = 3 large	20	24.81 (1.49)	0.089 (0.0081)	3.37	0.87	<0.001
	UI = 3 small	64	7.23 (0.92)	0.023 (0.0035)	2.80	0.19	<0.001
<i>O. maculatus</i>	UI = 5	13	7.52 (1.18)	-0.006 (0.0080)	1.76	0.06	ns
	UI = 3 large	4	31.61 (1.57)	0.064 (0.0067)	1.50	0.98	<0.05
	UI = 3 small	28	11.85 (2.06)	-0.010 (0.0098)	4.09	0.04	ns
<i>O. halei</i>	UI = 3	58	9.07 (1.55)	0.033 (0.0099)	4.95	0.16	<0.05

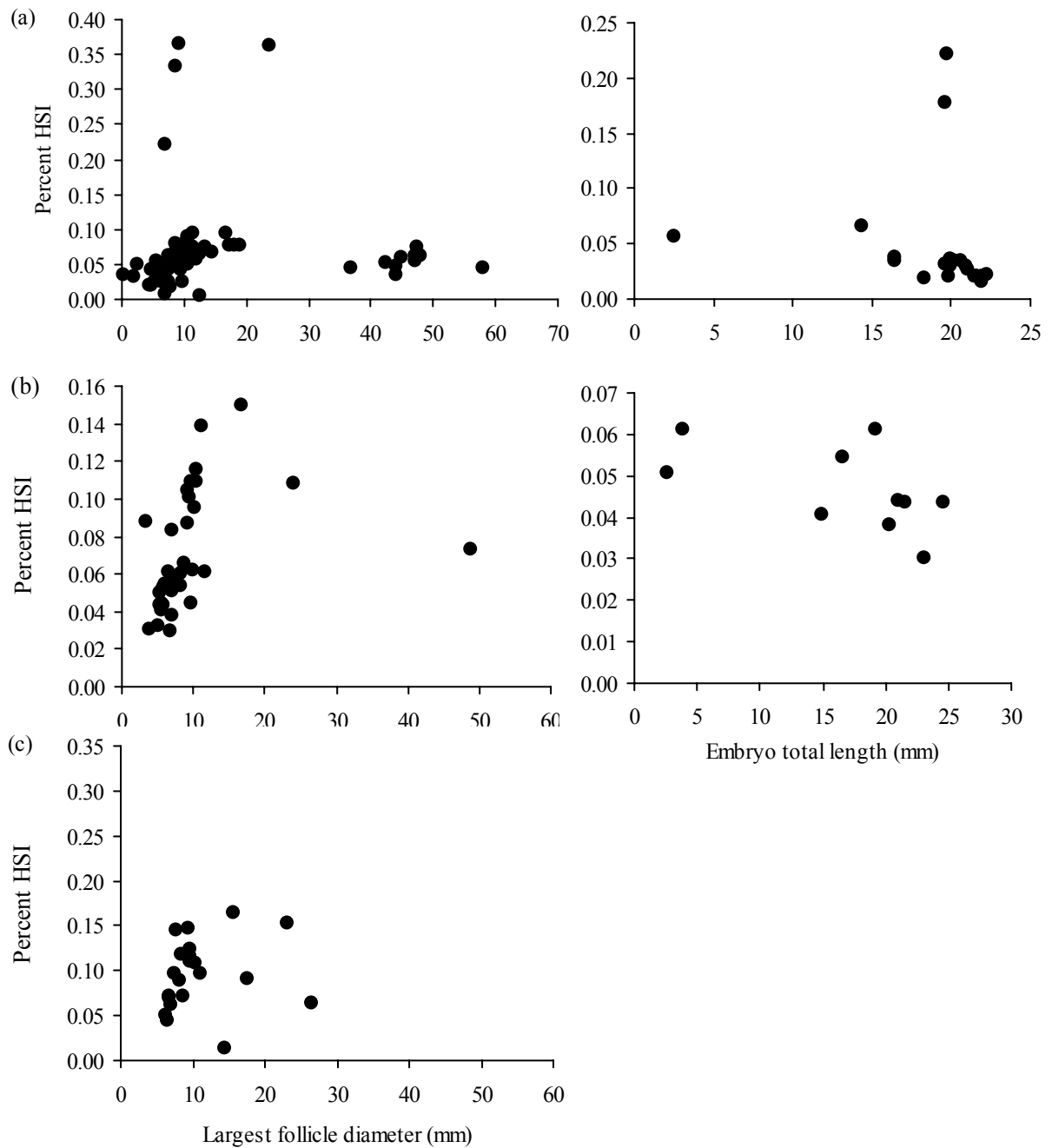


Figure 7.8 Percent HSI against largest ovarian follicle diameter and embryo total length of wobbegongs in NSW

Spearman correlation between hepatic somatic index and ovarian largest follicle diameter (left), and between hepatic somatic index of pregnant females and embryo total length (right) for (a) *O. ornatus*, (b) *O. maculatus* and (c) *O. halei*.

Table 7.5 Liver mass correlations for wobbegongs in NSW

Correlations estimated using Spearman rank correlation between hepatosomatic index (HSI)–largest follicle diameter (LFD) and HSI–embryo total length (TL). P is the probability of statistical significance.

Species	<i>n</i>	correlation	Correlation coefficient	P
<i>O. ornatus</i>	118	HSI–LFD	0.55	<0.01
	22	HSI –embryo TL	–0.05	ns
<i>O. maculatus</i>	38	HSI –LFD	0.73	<0.01
	10	HSI –embryo TL	–0.65	<0.01
<i>O. halei</i>	21	HSI –LFD	0.36	ns

7.4.2.3 Period of gestation and embryonic growth

Forty-three pregnant *O. ornatus* and 13 pregnant *O. maculatus* yielded 236 and 135 embryos, respectively, and were used to investigate embryonic growth. The embryonic development of *O. ornatus* was similar to that of *O. maculatus*. *In utero* eggs of *ca.* 50 mm mean diameter (mass 46 g) were observed during November–December with embryos of *ca.* 30 mm TL (0.3 g) visible during January. Initial embryonic growth was very rapid with embryos attaining 150 mm TL within 3–4 months, whereas it took another 5 months for the embryos to grow a further 70 mm. Embryos reached *ca.* 220 mm TL (70 g) in *O. ornatus* and *ca.* 230 mm TL (80 g) in *O. maculatus* during September–October when parturition occurred. External yolk sacs depleted rapidly and were mostly exhausted or absent by June–July when the embryos were *ca.* 190 mm TL (60 g). This corresponded to the time of decreased embryonic growth. Internal yolk sacs started to increase during April–May and reached a peak during June with a mean diameter of *ca.* 25 mm (11 g) before decreasing to a mean diameter of *ca.* 15 mm (4 g) during September. Internal yolk sacs persisted in embryos immediately prior to parturition (Fig. 7.9).

Most pregnant wobbegongs (34 *O. ornatus* and 12 *O. maculatus*) were caught at Nambucca Heads with a further 9 pregnant *O. ornatus* caught off Port Stephens and 1 *O. maculatus*, caught off Terrigal. The rate of embryonic development did not differ significantly between locations for *O. ornatus* (ANCOVA: slope $F_{df=1} = 0.00$, $P > 0.05$, intercept $F_{df=1} = 3.16$, $P > 0.05$). However, small sample sizes precluded a comparison of the rate embryonic development of *O. maculatus* between locations.

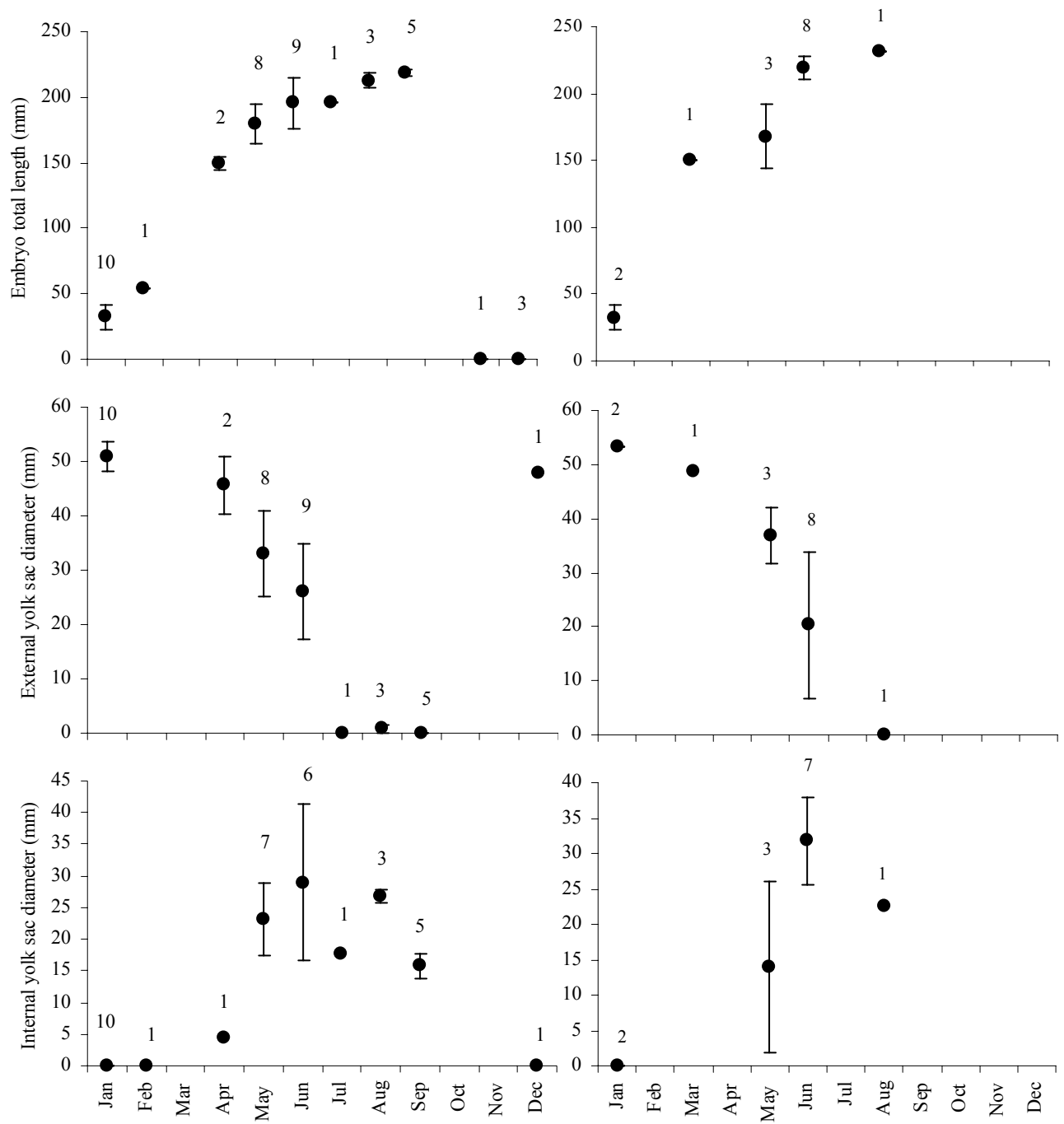


Figure 7.9 Embryonic development through time

Mean (•) monthly development per pregnant female with standard error (bar), for embryo total length, external yolk sac diameter, and internal yolk sac diameter for (left) *O. ornatus* and (right) *O. maculatus*; number above bar is monthly sample size.

7.4.2.4 Sex ratio of embryos and distribution of *in utero* eggs and embryos

Embryos were found in 43 *O. ornatus*. Male claspers became distinguishable at a TL of 130 mm. As a result, 117 *O. ornatus* embryos were classed as ‘unknown sex’ due to being in an early stage of development. Assuming that external sexual characteristics became evident at 130 mm TL, the number of male embryos per uterus (mean 3.1, s.e. 0.4, $n = 133$) did not differ significantly (t-test: $t = -1.60$, $P > 0.05$) from the number of female embryos per uterus (mean 3.6, s.e. 0.4, $n = 156$). The number of *O. ornatus* embryos in the left uterus (mean 4.8, s.e. 0.3, $n = 208$) did not differ significantly (t-test: $t = 1.24$, $P > 0.05$) from that in the right uterus (mean 4.6, s.e. 0.2, $n = 198$). *In utero* eggs without visible embryos were present in seven *O. ornatus*. The number of *in utero* eggs could only be estimated in two females because *in utero* eggs were extremely fragile and usually broke when females were dissected. Both females had nine eggs in their uteri.

Embryos were found in 13 *O. maculatus*. Male claspers also became distinguishable at a TL of 130 mm. As a result, 71 *O. maculatus* embryos were classed as ‘unknown sex’ due to being in an early stage of development. However, assuming that external sexual characteristics of *O. maculatus* also became evident at 130 mm TL, the number of male (mean 8.1, s.e. 1.6, $n = 106$) and female (mean 7.7, s.e. 1.4) *O. maculatus* embryos per uterus did not differ significantly (t-test: $t = 0.6$, $P > 0.05$). *Orectolobus maculatus* also had similar numbers of embryos in the left (mean 10.5, s.e. 0.9, $n = 137$) and right (mean 10.8, s.e. 0.8, $n = 140$) uteri ($t = -0.41$, $P > 0.05$). Neither *O. maculatus* nor *O. halei* had *in utero* eggs without visible embryos. No pregnant *O. halei* were collected during the sampling period.

7.4.2.5 Litter size–maternal length relationship

Litter size was recorded for 43 *O. ornatus* females with numbers ranging 4–18 embryos (mean 9, s.e. 0.5). Litter size of *O. ornatus* increased significantly in larger females (linear regression: $F_{df=1, 40} = 16.44$, $r^2 = 0.29$, $P < 0.001$; Fig. 7.10a). Neither TL nor TM of near-term embryos with sizes 197–222 mm TL (mean 214 mm, s.e. 0.3 mm) from 8 pregnant female *O. ornatus* were significantly related to maternal TL (linear regressions: TL, $F_{df=1, 6} = 4.92$, $r^2 = 0.45$, $P > 0.05$; Fig. 7.11a and TM, $F_{df=1, 6} = 4.4$, $r^2 = 0.42$, $P > 0.05$; Fig. 7.11b). The number of ovarian follicles when OI = 4 ranged 8–17 (mean 11.9, s.e. 0.6), and was significantly related to maternal TL (linear regression: $F_{df=1, 15} = 21.98$, $r^2 = 0.59$, $P < 0.001$; Fig. 7.11c). However, the number of follicles when OI = 4 was higher than litter size at any TL (ANCOVA: slope $F_{df=1} = 1.02$, $P > 0.05$, intercept $F_{df=1} = 10.24$, $P < 0.01$; Fig. 7.11d, Table 7.6) suggesting that not all follicles are ovulated.

Litter size in 13 *O. maculatus* females ranged 8–31 embryos (mean 21, s.e. 1.55). However, there was no significant increase in litter size with increasing maternal size (linear regression: $F_{df=1, 11} = 0.55$, $r^2 = 0.05$, $P > 0.05$; Fig. 7.10b, Table 7.6), and this may have been due to the small sample size.

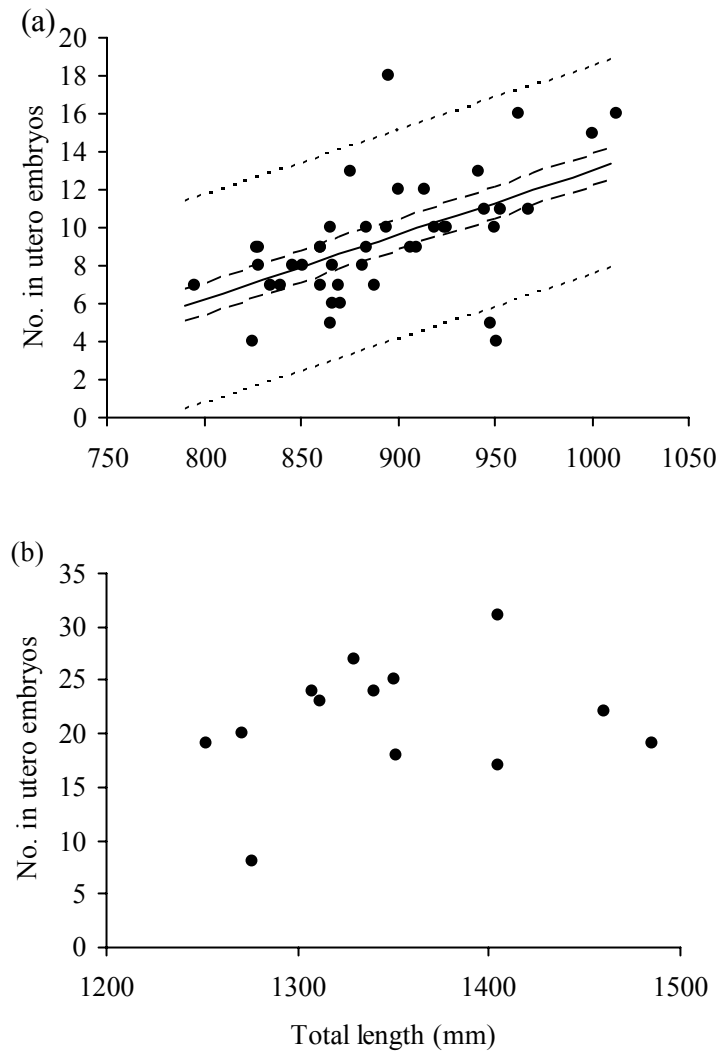


Figure 7.10 Relationship between litter size and maternal total length

Mean embryos number (—), 95% confidence limits (---), 95% prediction limits (- - -), and raw data (●) are plotted against maternal total length of pregnant females (UI = 5) for (a) *O. ornatus*, and (b) *O. maculatus*. Values of parameters and statistical quantities are given in Table 7.6.

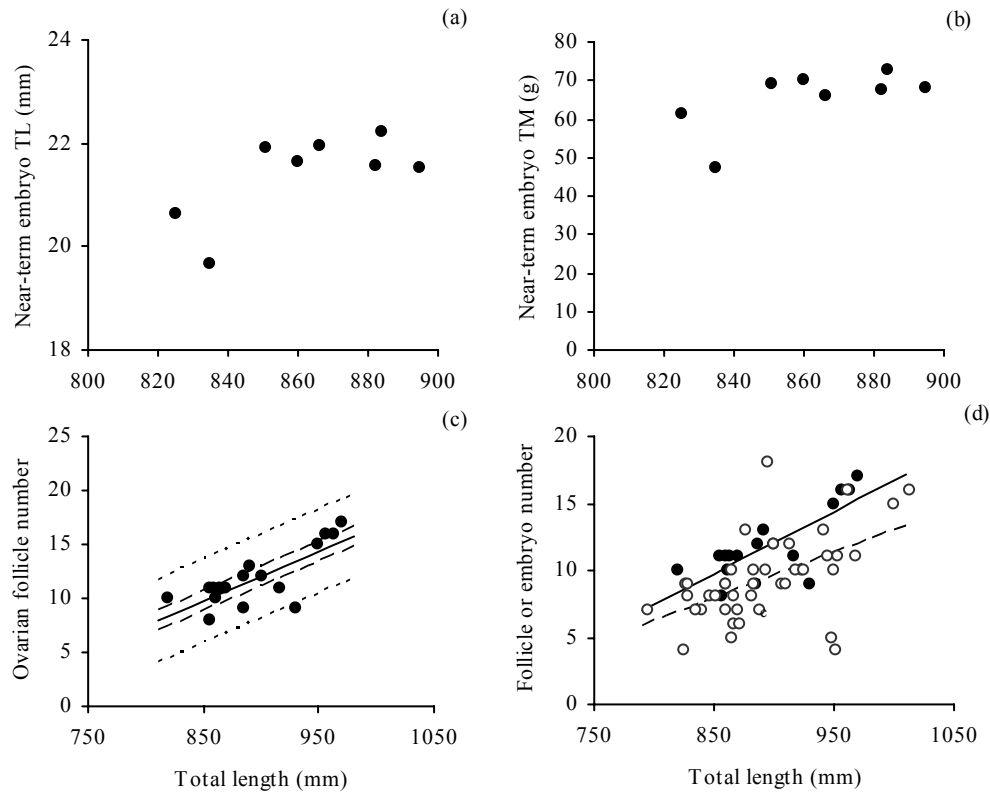


Figure 7.11 Relationship between different variables and maternal total length of *O. ornatus*
 (a) Mean near-term embryo TL, (b) mean near-term embryo TM, and (c) mean number of follicle in ovary when OI = 4 (—), 95% confidence limits (---), 95% prediction limits (· · ·), and raw data (●) are plotted against maternal total length of females with embryo being classified as near-term when external yolk sac is absent. Values of parameters and statistical quantities are given in Table 7.6. (d) Comparison between the number of ovarian follicles when OI = 4, data (●), regression (—); and the litter size, data (○), regression (---) against maternal total length of *O. ornatus*.

Table 7.6 Fecundity relationships for wobbegongs in NSW

Values of parameters and statistical quantities for the equation $p=a'+b'L$; L is maternal total length measured in millimetres; p is fecundity variable; a' and b' are parameters; No follicle OI = 4 is the number of follicle when females have large yolked follicles >30 mm; n is sample size; r^2 is square of regression correlation coefficient; rmse is root mean square error; and P is the probability of statistical significance for linear regression.

Species	Fecundity variable	n	a' (s.e.)	b' (s.e.)'	r^2	rmse	P
<i>O. ornatus</i>	Litter size	42	-20.92 (7.48)	0.034 (0.0084)	0.29	2.69	<0.001
	Embryo TL	8	1.60 (8.93)	0.023 (0.0103)	0.67	1.49	ns
	Embryo TM	8	-116.88 (86.83)	0.211 (0.1006)	0.42	6.53	ns
	No follicles OI = 4	17	-29.56 (8.85)	0.046 (0.0099)	0.59	1.75	<0.001
<i>O. maculatus</i>	Litter size	13	-1.77 (31.14)	0.017 (0.0230)	0.48	5.77	ns

7.5 Discussion

7.5.1 Maturity and maternity ogives

The differences in the L_{50} estimates for female maturity obtained between using ovary condition and uterus condition indicate the importance of explicitly defining maturity (Conrath 2004; Walker 2005). In the three species investigated, maturity determined for ovary condition occurred at a smaller TL than did maturity determined from uterus condition.

Sexual dimorphism is common in many chondrichthyan species, with females exhibiting larger size-at-maturity and a greater maximum TL (Stevens and Wiley 1986; Klimley 1987). Sexual dimorphism in sharks may be due to the requirement, by females, for greater space for internal embryonic development (Klimley 1987) and/or the energetic demands of reproduction resulting in selection pressure for larger body size (Sims 2003). The L_{50} for maturity and maximum TL sampled were similar for males and females, suggesting that sexual dimorphism does not occur in wobbegongs in NSW. The absence of sexual dimorphism has been previously noted in *O. halei* (misidentified as *O. ornatus*) and *O. hutchinsi* in Western Australia (Chidlow 2003).

Wobbegongs can usually be found in rocky and boulder habitats, concealed under rocks (Last and Stevens 1994; Compagno 2001). The evolutionary advantage of females growing to a larger size might have been lost to enhance the occupation of cracks and crevices thus reducing female mortality. Similarly, the absence of sexual dimorphism in *Furgaleus macki* is believed to permit easier access to holes and crevices to feed on octopods (Simpfendorfer and Unsworth 1998).

For *O. halei*, the L_{50} estimated in the present study is similar to a previous estimate of 1750 mm TL (Last and Stevens 1994) and slightly smaller than the L_{50} for *O. halei* in WA (misidentified as

O. ornatus (Chidlow 2003). In contrast, the L_{50} estimates for *O. maculatus* from the present study (i.e. 1280 mm TL) differ with previous estimates of maturity of 600 mm TL (Compagno 2001) and *ca.* 1000 mm TL in WA (Chidlow 2003). Both of which are much less than the TL of the smallest mature *O. maculatus* recorded in NSW. Recent taxonomic evidence suggests the existence of an undescribed species in WA that is similar in appearance to *O. maculatus* in NSW, but matures at a smaller size and has a smaller maximum TL (J. Chidlow and P. Last pers. comm.). It is therefore likely that the smaller TL at maturity for *O. maculatus* in WA was due to species misidentification.

The use of maturity ogives instead of maternity ogives in fishery stock assessment models may bias predicted size- or age-structured recruitment and increases as the duration of the reproductive cycle increases (Walker 2005; Braccini *et al.* 2006a; Walker in review). In NSW, although the parturition cycle of *O. ornatus*, *O. maculatus* and *O. halei* was triennial, the L_{50} for the mature wobbegongs is only slightly smaller than the L_{50} for maternal individuals. However, at any particular time, about a third of mature females are in maternal condition.

7.5.2 Mating period

In NSW, mating period appears to vary with location. *Orectolobus ornatus* is found primarily in northern NSW and is reproductively active during April–June, as determined by the increasing GSI during that period. However, two *O. ornatus* were sighted mating on 1 August, indicating that the mating period might be slightly longer than indicated by the GSI. The hepatosomatic index has been linked to the reproductive cycle, with liver reserves depleting during reproductive activity (Rossouw 1987). The hepatosomatic index was at its lowest during March–July, supporting the mating period suggested by the concurrent peak in GSI. In WA, *O. hutchinsi* and

O. halei appeared to mate in July (Chidlow 2003), but in NSW *O. maculatus* and *O. halei* appeared to be reproductively active during December–January. Further studies will, however, be required to improve our understanding of the timing of mating along the NSW coast, and of the physiological processes linking masses of testes and liver in wobbegongs.

7.5.3 Ovulation season

None of the three species of wobbegong sampled were in the process of ovulating. *Orectolobus ornatus* collected during this study was the only species observed (during November) with eggs *in utero* without macroscopically visible embryos. The existence of individuals within the same population, with either large ovarian follicles or completely ovulated eggs during November suggests that ovulation occurs rapidly at this time of year. Collection of *O. maculatus* specimens with large ovarian follicles at a similar period to *O. ornatus* indicates synchrony between the two species, with ovulation occurring during November in northern NSW. No *O. halei*, were caught with LFD >31 mm, ovulating or with *in utero* eggs in central and southern NSW. However, one specimen was caught in Nambucca Heads with a LFD of 52 mm during August suggesting that *O. halei* may ovulate in synchrony with *O. ornatus* and *O. maculatus* in northern NSW.

As the gonadosomatic index suggests that mating occurs in *O. ornatus* during June–October and that ovulation takes place during November, sperm storage is likely to occur during June–October. Sperm storage between mating and ovulation occurs in many species of chondrichthyes (Hamlett *et al.* 2005). Sperm is stored in the terminal zone of the oviducal gland (Pratt 1993; Hamlett *et al.* 2002; Storrie 2004) and sperm storage periods range from four weeks in the nervous shark (*Carcharhinus caudatus*) (White and Potter 2002b), up to 12 months in blue shark (*Prionace glauca*) (Pratt 1993), and potentially even longer in the chain dogfish (*Scyliorhinus*

rotifer) (Castro *et al.* 1988). Sperm storage has also been suggested in *O. hutchinsi* for ca. 4–6 months (Chidlow 2003). Sperm storage has been hypothesised as a mean of ensuring a supply of sperm for progressive fertilisation of ova released during ovulation over a period of several weeks, or possibly months. Sperm storage provides a mechanism to avoid the problem of accumulating *in utero* eggs obstructing sperm transiting the uteri to the oviducal glands (Walker 2005). This does not appear to be the case for wobbegongs, in which ovulation occurs rapidly and in a triennial cycle, as sperm can pass through the uterus in the absence of *in utero* eggs or embryos during the 2-year period prior to ovulation and gestation. Sperm storage might instead occur to increase the number of males fertilising the litter and thereby, increasing species fitness. This allows females to store sperm from different males, increasing genetic variation as seen in the lemon shark (*Negaprion brevirostris*) and the nurse shark (*Ginglymostoma cirratum*) where three and four fathers, respectively, contributed to one litter (Feldheim *et al.* 2001; Saville *et al.* 2002). However, more accurate estimation of mating period and histology of the female reproductive tract is required to confirm the occurrence of sperm storage in wobbegongs. Genetic analyses should also be conducted to investigate multiple paternity.

7.5.4 Ovarian cycle

Follicular growth and the three reproductive stages observed at Nambucca Heads indicated that *O. ornatus* and *O. maculatus* had a triennial ovarian cycle. Within the same population, three reproductive stages of the ovary were observed in mature females: females with ovaries with pale and translucent follicles <20 mm LFD and not pregnant; females with large yolky follicles ≥20 mm LFD and not pregnant, and pregnant females. The two different reproductive stages observed in non-pregnant females indicate that follicles take two years to mature following parturition. Previous studies have assumed constant follicular growth in chondrichthyans with ovarian cycles

>1 year (Walker 2005; Braccini *et al.* 2006a; Walker in review). However, in the case of wobbegongs, it appears that follicular growth occurs at two different rates. During the 10–12 month gestation (UI = 5) and the first 12 months after parturition (UI = 3 and 6), follicles do not grow. During December–January, *ca.* 12 months after parturition, follicles grow rapidly over the following 10–11 months and are ovulated at *ca.* 50 mm LFD during November. The few *O. halei* collected at Nambucca Heads, combined with anecdotal observations (R. Brislane pers. comm.) suggest an ovarian cycle synchronous with *O. ornatus* and *O. maculatus*.

Other studies of the reproductive cycles of wobbegongs have been less definitive. In WA, mature female *O. hutchinsi* had the same three reproductive stages documented here with 27% of the mature females pregnant (Chidlow 2003). The study suggested a biennial or triennial cycle for *O. hutchinsi*, but could not discern which because of small sample sizes. In NSW, Carraro (2001) proposed a biennial cycle for *O. ornatus* based on behavioural observations of individually identified females over several years. It is plausible that the ovarian cycles differed between northern site off Nambucca Heads (triennial), and the more centrally-located site Port Stephens (biennial). However, dissection of *O. ornatus* obtained off Port Stephens during the current study did not support Carraro's hypothesised biennial cycle, because three reproductive stages of mature females were observed at any one time. Spatial differences in the duration of ovarian cycles of sharks have been observed. For example, the gummy shark (*Mustelus antarcticus*) (T. Walker unpub. data) and the star-spotted dogfish (*M. manazo*) (Yamaguchi *et al.* 2000) are known to exhibit annual or biennial ovarian cycles depending on particular regions within their entire range. The ovarian cycles of *M. antarcticus* and *M. manazo* were correlated with water temperature and slower reproductive cycles occurred in regions with the coldest water temperature (Yamaguchi *et al.* 2000; Walker in review).

Walker (2005) suggests that the duration of the ovarian cycle is related to the LFD and water temperature. Annual ovarian cycles usually occur in species with a LFD less than 30 mm, such as Smooth-hound shark (*M. schmitti*) (Menni 1986) or the Atlantic sharpnose (*Rhizoprionodon terraenovae*) (Parsons 1983b), whereas biennial species such as the spiny dogfish (*Squalus acanthias*) (Hanchet 1988) and the sevengill shark (*Notorynchus cepedianus*) (Ebert 1986) and triennial species such as the school shark (*Galeorhinus galeus*) (Peres and Vooren 1991; Lucifora *et al.* 2004; Walker 2005), the angular angel shark (*Squatina guggenheim*) (Colonello *et al.* in press) and the dusky whaler *C. obscurus* (Branstetter and Burgess 1996; Dudley *et al.* 2005) have $LFD \geq 40$ mm. The long ovarian cycle in chondrichthyans that produce large LFD might be due to the time required for follicles to grow. However, other species such as the Atlantic weasel shark (*Paragaleus pectoralis*), the spotted gully shark (*Triakis megalopterus*), the blacktip shark (*C. limbatus*) and the shortfin mako shark (*Isurus oxyrinchus*) might also have a triennial reproductive cycle, but with a $LFD < 35$ mm (Dudley and Cliff 1993; Smale and Goosen 1999; Mollet *et al.* 2000; Capapé *et al.* 2005). In wobbegongs, the LFD of all three species was recorded as > 50 mm, in line with Walker's generalisation. Wobbegongs differ from *G. galeus* by having a period during which follicles do not develop and remain small similarly to *C. limbatus* (Dudley and Cliff 1993), whereas follicles from *G. galeus* develop at a constant rate over the two years prior to ovulation. In wobbegongs, the period of no follicular growth may be required for restoration of energy reserves in the liver enabling subsequent follicular growth as indicated by a rapid increase in HSI with small LFD growth.

7.5.5 Geographically-dependent reproductive behaviour

Although pregnant wobbegongs or those with large ovarian yolky follicles were collected in the northern NSW region, those caught in the central and southern NSW regions were never pregnant or found with large ovarian yolky follicles. Furthermore, commercial fishers from central and southern NSW, intensively targeting wobbegongs for more than 15 years, have never caught pregnant *O. halei* or *O. maculatus* or individuals with ovaries containing large yolky follicles (J. Moyce pers. comm.; S. Fantham pers. comm.). Differences in size-at-maturity among locations is common in sharks (Menni 1985; Bonfil *et al.* 1993; Parsons 1993b; Mollet *et al.* 2000) and geographic variation in growth, reproduction, and development has been reported among species of teleosts (McCormick 1999). However, latitudinal variation in life history traits among species of chondrichthyan has received little attention (Lombardi-Carlson *et al.* 2003). While the effects of latitude on life history traits have only been investigated in a few species, increases in growth rate, size- or age-at-maturity and the size of near-term embryos have been positively correlated with latitude (Yamaguchi *et al.* 2000; Horie and Tanaka 2002; Lombardi-Carlson *et al.* 2003) and reflect the elasticity of these traits. Geographic variation in reproductive behaviour between locations only 500 km apart has not previously been observed in chondrichthyan species. Latitudinal differences are believed to be an adaptive response to different environmental cues (Levins 1969; Conover and Present 1990). Therefore, variation in water temperature or habitat may explain the differences in reproductive behaviour observed in wobbegongs. Several explanatory models may account for the absence of reproductively active female wobbegongs off Sydney and sites to the south. First, wobbegongs may stop feeding during reproductively-active periods, limiting their capture by baited setlines. Second, wobbegongs may migrate to warmer, northern waters to increase rates of follicular and embryonic development. Third, wobbegongs may move to locations where targeted fishing does not occur (e.g. estuaries or offshore

locations). Locating pregnant females, along with *post partum* females, may elucidate the whereabouts of neonates and existence of nursery areas. Acoustic tagging would enable the localised and migratory movements of females, particularly pregnant individuals, to be documented.

7.5.6 Embryonic development

Embryos were found until the end of August for *O. maculatus* and the beginning of October for *O. ornatus*, implying that parturition occurred during September–October after a gestation of *ca.* 10–12 months. The close embryonic development of *O. ornatus* and *O. maculatus* suggests a high level of synchrony between these species. Although no pregnant *O. halei* were sampled, a pregnant specimen was caught in Nambucca Heads by a commercial fisher during September (R. Brislane pers. comm.). Embryos were about 350 mm TL and did not have visible external yolk sacs, suggesting that *O. ornatus*, *O. maculatus* and *O. halei* have a synchronous period of gestation.

Ovulation, follicular and embryonic development, and parturition occurred simultaneously in *O. ornatus* and *O. maculatus*, and are likely to be similar in *O. halei* (R. Brislane pers. comm.). Reproductive cycles are thus highly synchronous between these sympatric species. Competition for food among pregnant females and neonates can possibly occur if food resources are limited due to a high number of pregnant females and births at similar times. Whereas some fish populations with similar life history traits can coexist with complete resource overlap (McCaan 1998), habitat and diet partitioning are frequently observed in chondrichthyans (White and Potter 2002a; Bethea *et al.* 2004; Pikitch *et al.* 2005). Resource partitioning, such as diet or habitat

differentiation, reduces competition and is likely to increase survival rate of neonates, which can otherwise compete for food or shelter from predators if food resources or habitats are limited.

Near-term embryos of *O. ornatus* and *O. maculatus*, including those aborted by females, were *ca.* 220 mm TL and *ca.* 240 mm TL, respectively. All near-term embryos still possessed internal yolk sacs suggesting that they would have been absorbed during the days after birth to supplement feeding. The collection of wild neonates with internal yolk sacs would be necessary to confirm this suggestion. However, near-term embryos (with internal yolk sacs) excised from a pregnant female during October successfully survived in captivity (C. Huveneers unpub. data).

7.5.7 Litter size–maternal length relationship

Litters of *O. ornatus* increased with female TL, but the length of near-term embryos was not related to maternal TL. There was no relationship between litter size and maternal TL in *O. maculatus*. However, the sample size was small and a short pregnant female (1276 mm TL) carried only 8 embryos, whereas a large female (1405 mm TL) carried 31 embryos. Further studies may also reveal a significant relationship between litter size and maternal TL in *O. maculatus*. In viviparous sharks, where the physical space available in the body cavity is limited, larger females have more space for embryos to develop. There is, therefore, a trade-off between litter size and embryo TL for female chondrichthyans to maximise fecundity and fitness. Whereas certain species produce only a few large embryos (e.g. *Carcharias taurus* with 2 pups biennially), others produce more, smaller young (e.g. *R. taylori* which has a large litter size and smaller size-at-birth than most other carcharhinids (Simpfendorfer 1992)). Litter size and offspring TL increase female reproductive output by increasing the number of offspring likely to survive until maturity, but in different ways. Larger size-at-birth reduces vulnerability to predation, whereas

the production of more offspring increases the probability of survival to reproductive age. In the case of *O. ornatus*, the trade-off of increasing litter size rather than litter TL might be related to the habitat where parturition occurs. Small size-at-birth in wobbegongs enables neonates to hide in small cracks and crevices and reduce predation by larger sharks.

Pregnant *O. halei* producing 30–45 pups have been reported by commercial fishers (R. Brislane pers. comm.), and one preserved pregnant female in the Queensland Museum (I 16013) collected from Southport, Queensland (27° 35'S 153° 17'E) had 36 pups. Furthermore the number of enlarged ovarian follicles in one specimen collected (OI = 4) suggested that *O. halei* has a litter size of *ca.* 30.

When litter size and offspring TL are unavailable, the number of large ovarian follicles (OI = 4) can be used as indication of the number of embryos. Few studies compare fecundity estimated from the number of ovarian follicles and with the number of *in utero* embryos. In *S. acanthias*, *G. galeus*, and *Paragaleus pectoralis*, litter size and number of ovarian follicles increase with female TL, although fecundity derived from the ovarian follicles number is often slightly higher than that derived from the embryo number (Marques da Silva and Ross 1993; Lucifora *et al.* 2004; Capapé *et al.* 2005). Fecundity derived from the number of ovarian follicles in *O. ornatus* is also higher than when derived from embryos and is likely due to the failure of some yolky follicles to ovulate and undergo *atresia*. It is important to note that spontaneous abortions during capture and handling can bias estimates of the number of embryos *in utero*.

Orectolobus ornatus had the smallest litter of *ca.* 9 pups and grew to a maximum TL of *ca.* 1100 mm. *Orectolobus maculatus* grew to a larger TL (at least 1575 mm) and had litters of *ca.* 21

pups. Finally, the largest wobbegong species sampled, *O. halei* grows to 2065 mm TL and had the largest litter at *ca.* 30 pups. In contrast, *Orectolobus hutchinsi* has litters of *ca.* 23 pups despite having a maximum TL similar to that of *O. ornatus* (Chidlow 2003). Physiological constraints, such as the rate of gas exchange between embryos and uteri (Nammack *et al.* 1985) and other interspecific differences in the structure of the uterine wall (M. Storrie pers. comm.) may also limit litter size in wobbegongs and explain why *O. hutchinsi* can carry a much larger litter to full term.

7.6 Conclusion

The reproductive cycles of *O. ornatus*, *O. maculatus*, and *O. halei* along the NSW coast were synchronous with a triennial ovarian cycle and parturition occurring during October–November following a 1-year gestation period (during which follicles did not grow). Follicles remained small for a year after parturition, prior to rapid growth over a year, allowing follicles to reach a LFD of *ca.* 50 mm prior to ovulation during November. The absence of wobbegongs with embryos or large ovarian yolky follicles in the central or southern NSW regions suggests geographic variation in reproductive behaviour. This regional difference requires further investigation and needs to be taken into account when regulating the fishery. This investigation provides fishery managers with the required information and parameters (e.g. sex ratio and fecundity) to create stock assessment models and determine wobbegong resilience to the current fishing level pressure.

CHAPTER 8: AGE AND GROWTH OF WOBBERGONG SHARKS (GENUS *ORECTOLOBUS*)
IN NEW SOUTH WALES, AUSTRALIA



© Charlie Huveneers (neonates *Orectolobus ornatus* age: 1 day)

8.1 Introduction

The determination of age for large, harvested species such as chondrichthyans is important to the estimation of growth and other key life history parameters such as natural mortality, age-at-maturity, longevity and recruitment (Pauly 1987). Growth rates and age determination are key components of fisheries research (Cailliet and Goldman 2004) and are required for most fisheries stock assessments based on age-structured population models (Pauly 1987). Recent increases in chondrichthyan exploitation around the world (Bonfil 1994; Stevens *et al.* 2000; Lack and Sant 2006) have highlighted the need for life history studies and especially those focusing on age and growth. Crucially, inaccurate age determination can lead to major errors in stock assessment and poor estimation of resilience to fishing pressure leading to overexploitation (Hoenig and Gruber 1990; Hoff and Musick 1990; Officer *et al.* 1996; Musick 1999; Campana 2001).

An assessment of wobbegong resilience to fishing pressure requires accurate determination of age and growth parameters. Concentric growth bands have been documented in the vertebral centra of most chondrichthyans for over 80 years (Ridewood 1921) and are often used to age chondrichthyans. The age and growth of wobbegongs has rarely been investigated and no studies on Australian wobbegongs have been published to date. In contrast, the periodicity of band deposition in captive Japanese wobbegongs (*Orectolobus japonicus*) has been studied, but growth parameters were not produced (Tanaka 1990). This study also showed that a growth band formed annually in spring and there was, on occasion, variable deposition of the band that was more closely linked to the growth of vertebral centra rather than with time. The only study to report growth parameters for Australian wobbegongs (Chidlow 2003) was done off Perth, Western Australia and provided estimates for *O. hutchinsi* and *O. halei* (misidentified as *O. ornatus*).

Estimates of age and growth using vertebrae are subject to many sources of variation including sampling bias, sample size, preparation technique, reader biases and model fitting (Cailliet 1990). Various researchers have attempted to quantify these sources of variation. Sampling biases can be reduced by ensuring that samples are representative of the population and when young individuals are not available, back-calculation is often used. Within and between reader biases can be quantified using the Coefficient of Variation (CV - Chang 1982; Campana *et al.* 1995) or the Average Percentage Error (APE - Beamish and Fournier 1981). However, without age validation, CV and APE only indicate the variability of the readers, but not which is more accurate or if they are biased. Recently, the use of different models has also lead to variations in the estimation of age and growth parameters (Carlson and Baremore 2005; Bishop *et al.* 2006; Braccini 2006). For example, differences in k values obtained by applying various models to the data can lead to six-fold differences in the estimates of natural mortality (Carlson and Baremore 2005).

The techniques used to prepare vertebrae and methods used to count growth bands have not been investigated as often as other sources of variation in age and growth parameters (e.g. Tanaka *et al.* 1990; Officer *et al.* 1996; MacNeil and Campana 2002). Counts using whole vertebrae (WV) and thin sections (TS) can vary (e.g. Moulton *et al.* 1992). Counts of growth bands from thin sections can overestimate actual age of a specimen by including minor growth bands in the counts (Tanaka *et al.* 1990; Officer *et al.* 1996), whereas counts from whole vertebrae can underestimate age in old sharks due to the increased difficulty of distinguishing growth bands close to the vertebral edge (MacNeil and Campana 2002). As a result, differences in growth

curves between separate locations can be masked by variability due to methods (Tanaka *et al.* 1990; Moulton *et al.* 1992; Henderson *et al.* 2003).

In this chapter, growth parameters of wobbegong sharks were obtained using whole vertebrae and thin sections. The growth parameters are compared using observed lengths-at-age and four back-calculated equations, and applied to four different growth models. Validation and verification of the periodicity of growth band deposition was also attempted using edge analysis, chemical marking (OTC) and physical measurement of captive sharks.

8.2 Materials and methods

8.2.1 Collection of samples

Vertebrae were collected from sharks caught either on-board commercial hook and line fishing vessels, or captured while scuba-diving over the period June 2003–May 2006 at six main locations in NSW (Nambucca Heads, Port Stephens, Newcastle, Terrigal, Sydney and Eden).

One to four vertebrae were taken from the post-cranium region (vertebral numbers 1–4) of each specimen. Removal of vertebrae anterior to the first dorsal fin (i.e. the largest vertebrae) was not done because it lowers the carcass market value. Each shark was identified to species (Huveneers 2006; Chapter 2) and sex was determined by noting the presence of claspers in males. The following length measurements were recorded to the nearest 1 mm before dissection: total length (TL), snout to anal insertion length (SAL), partial length from the pectoral-fin insertion to the base of the caudal fin (PL), and total mass (TM) to the nearest 200 g. Vertebrae were stored on ice before being placed in a freezer at -20°C until further analysis.

Numerous techniques have been used to enhance the visibility of growth bands in chondrichthyan vertebrae. The success of each technique is species dependent and slight modifications of the method can enhance results (Goldman 2005). Therefore, several techniques were tested on wobbegong vertebrae to identify a method for elucidating the clearest growth bands on WV and TS. Alizarin red (LaMarca 1966; Gruber and Stout 1983) and crystal violet (Johnson 1979; Schwartz 1983) were used to stain whole and sectioned vertebrae and a pencil method was also tested on WV (Parsons 1983a; 1985; Carlson and Parsons 1997). Neither staining nor the use of the pencil improved the clarity of growth bands. Thus, vertebrae were instead prepared as follows.

8.2.2 Vertebral preparation

Vertebrae were thawed, excess tissue was removed and individual centra separated using a knife before immersion in 5% sodium hypochlorite solution to remove any remaining flesh. Soaking time varied with vertebral size and ranged from 30 minutes for adult *O. ornatus* (ca. 10 mm in diameter) to two immersions of one hour each for adult *O. halei* (ca. 25 mm in diameter).

Excessive soaking was avoided because it tends to dissolve the centra and makes the articulating surfaces brittle and crumbly (Francis and Ó Maolagáin 2000). Vertebrae were then placed in running fresh water for at least 30 minutes or left soaking overnight. Cleaned vertebrae were stored in a –20°C freezer until sectioned or used whole for age determination.

Prior to embedding, cleaned vertebrae were left to dry in an oven at 55°C. Centra were then embedded in clear polyester casting resin blocks. A thin layer of resin was poured on to the base of a silicon mould and left to partially cure for ca. 30–60 minutes to avoid vertebrae displacement within the block when drying. Resin was then poured into the bloc until vertebrae were

completely covered. Blocks were first left to air-dry for about one hour to avoid formation of air bubbles before placing them in an oven at 55°C. Vertebrae were sectioned sagittally through the centra, perpendicular to the longest diameter to standardise the plane of cut, using a Gemmasta lapidary saw fitted with a diamond-impregnated blade. Up to five transverse sections of *ca.* 350 µm thick were taken ensuring that the focus of the centra of each vertebra was included. The two best sections were rinsed in water and cleaned with alcohol prior to mounting onto a glass slide (50 x 75 mm). A cover-slip was placed over the section to avoid damage during handling and storage.

8.2.3 Reading of growth bands

Whole vertebrae and thin sections were viewed under a dissecting microscope (Olympus SZH) with a 0.75X lens connected to a Sony camera (DFW-X700). Images were visualised on an Imac computer (Apple, Cupertino, California, USA) using the BTVPro software Version 5.4.1 (Ben Software, London, England). Whole vertebrae were illuminated with a fibre optic light source projecting light through the side of the vertebra (Fig 8.1a). Thin sections were illuminated with transmitted and reflected light (Fig. 8.1b). A growth band was defined as the narrow, translucent bands.

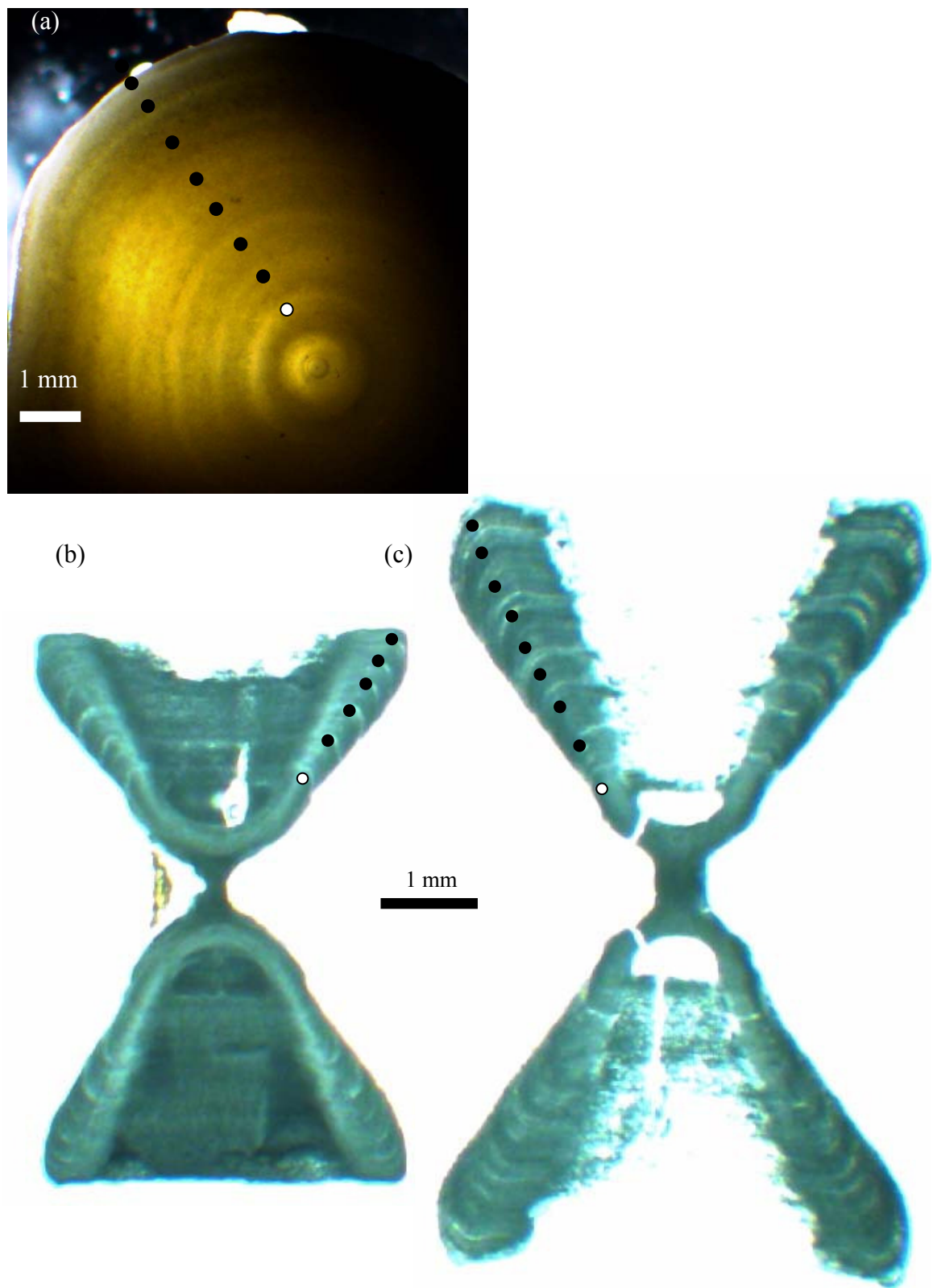


Figure 8.1 Example of growth bands observed on *O. ornatus* vertebrae

(a) whole vertebra of a 729 mm TL with seven growth bands; (b) thin sections of a 507 mm TL with five growth bands; and (c) thin sections of a 691 mm TL with eight growth bands; (○) indicates birth marks; (●) indicates growth bands.

Growth bands of each WV and TS were counted on two occasions after being chosen at random and without knowledge of the size or sex of the specimen. When present, notches along the outside edge of the *corpus calcareum* helped counts by providing an additional ageing feature (Goldman 2005). The angle change on the centrum face, a result of the difference between fast intra-uterine and slower post-natal growth (Walter and Ebert 1991), was considered as the birth mark and assigned as growth ring 0. Any ring observed before this birth mark was defined as a pre-birth mark (Allen and Wintner 2002).

Each processed vertebra was assigned a 'readability score' of 1–6 based on the degree of difficulty in interpreting the arrangement of the vertebral bands (adapted from Officer *et al.* 1996, Table 8.1). Vertebrae and sections with readability score greater than 4 were excluded from further analysis. The consensus count for each individual was determined as the mean between the two readings. If the mean was between half a ring count, the vertebra or section was randomly assigned either reading. Readings differing by more than 3 growth bands were also excluded from analysis.

Table 8.1 Description of vertebrae readability.

Readability	Description
1	Bands of exceptional clarity, unambiguous count
2	Bands of good clarity, but 1 difficult to interpret
3	Bands observable, but 2 or 3 difficult to interpret
4	Bands observable, but several difficult to interpret
5	Bands pattern visible but impossible to interpret
6	No count possible and recorded as 'unreadable' or vertebra broken

The radius of each vertebra was measured on the *corpus calcareum* along a straight line through the focus of each vertebra with the ‘Optimate’ software (version 6.5). Vertebral radius (VR) was plotted against wobbeong TL and tested for a linear relationship.

8.2.4 Precision and accuracy

The precision of band counts was calculated using the APE (Beamish and Fournier 1981) and the CV (Chang 1982; Campana *et al.* 1995). Within reader bias was determined from percent agreement (Cailliet 1990) and age-bias plots of band counts (Campana *et al.* 1995). Difference of APE between WV and TS was tested by a paired t-test to determine if precision differed between the methods used (i.e. WV vs. TS).

8.2.5 Models

Several alternative models were fitted to the length-at-age data to generate growth curves that were biologically plausible and that provided the best fit to the data. Four models were used: the traditional von Bertalanffy growth model (VBGM - von Bertalanffy 1938), a two-parameter modified form of the VBGM forced through the length-at-birth (estimated using the largest near-term embryo, Chapter 7) (2P VBGM - Fabens 1965), the two-parameters Gompertz growth model (2P Gompertz - Gompertz 1825; Ricker 1975), and the logistic model (Ricker 1979) (Table 8.2). Model parameters were estimated by least-squares non-linear regression using the function SOLVER in the Microsoft Excel software (Microsoft, Redmond, Washington, USA).

Table 8.2 Growth models fitted to lengths-at-age data.

Model	Equation
Von Bertalanffy growth model	$L_t = L_\infty (1 - e^{-k(t-t_0)})$
Two-parameters von Bertalanffy growth model	$L_t = L_\infty (1 - be^{-kt}), b = \frac{L_\infty - L_0}{L_\infty}$
Two-parameters Gompertz growth model	$L_t = L_0 (e^{G(1-e^{-kt})}), G = \ln(\frac{L_\infty}{L_0})$
Logistic growth model	$L_t = \frac{L_\infty}{1 + e^{-k(t-\alpha)}}$

Where L_t = mean length at time t

L_0 = length-at-birth

L_∞ = mean maximum age at infinite length

k = growth coefficient

t_0 = theoretical age at zero length

α = time at which the absolute rate of increase in length begins to decrease, or the inflection point of the curve

Due to the small sample size of pup and juvenile wobbegongs, back-calculated estimates of length at previous age were calculated using four different equations. The best back-calculated equation was determined by comparing observed and back-calculated lengths-at-age. Observed lengths-at-age data, and a combination of back-calculated lengths and sample data were each separately fitted to the four growth models and the resulting parameter estimated compared.

Back-calculated lengths were not calculated using regression methodologies as they can overestimate fish length at capture (Francis 1990). Instead, four proportion-based back-calculation methods were investigated and compared (Table 8.3): the Dahl-Lea direct proportions method (Carlander 1969), the linear-modified Dahl-Lea method (Francis 1990), the quadratic-modified Dahl-Lea method (Francis 1990), and the size-at-birth-modified Fraser-Lee method (Campana 1990) (Table 8.3).

Table 8.3 Proportion-based back-calculation details.

Method	Equation
Dahl-Lea direct proportions method	$L_t = VD_t \left(\frac{L_c}{VD_c} \right)$
Linear-modified Dahl-Lea method	$L_t = L_c \left[\frac{a + bVD_t}{a + bVD_c} \right]$
Quadratic-modified Dahl-Lea method	$L_t = L_c \left[\frac{a + bVD_t + cVD_t^2}{a + bVD_c + cVD_c^2} \right]$
Size-at-birth-modified Fraser-Lee method	$L_t = L_c + \left[\frac{(VD_t - VD_c)(L_c - L_{birth})}{VD_c - VD_{birth}} \right]$

Where a , b and c = linear fit parameter estimates

L_t = length at growth band t ,

L_c = length at capture

L_{birth} = size-at-birth

VD_t = vertebral diameter at growth band t

VD_c = vertebral diameter at capture.

VD_{birth} = vertebral diameter at birth.

For each species and vertebrae preparation, the best fitting model was determined using Akaike's (1973) Information Criterion (AIC).

$$AIC = n \ln (\sigma^2) + 2p$$

Where n = sample size,

σ = Residual sum of squares/ n , and

p = number of parameters

For model comparisons, the delta AIC (ΔAIC) and Akaike's weights (w_i) were calculated (Burnham and Anderson 2002). The ΔAIC is a measure of each model relative to the best model and is calculated as

$$\Delta AIC = AIC_i - \min AIC$$

Where AIC_i = AIC for model i , and

$\min AIC$ = AIC value of the best model

Akaike's weights (w_i) represent the probability of choosing the correct model from the set of candidate models and are calculated as

$$w_i = \frac{\exp(-\Delta AIC/2)}{\sum_{r=1}^R \exp(-\Delta AIC / 2)}$$

Where R = number of candidate models.

Once the best model was determined, a likelihood ratio test (Kimura 1980; Cerrato 1990) was also used to test for differences between growth curves of males and females (Haddon 2001).

8.2.6 *Validation and verification*

Several methods were compared to verify and validate the periodicity of growth band deposition: edge and marginal increment analyses, growth rate of captive sharks, and the chemical marking of captive sharks.

8.2.6.1 Edge and marginal increment analyses

The periodicity of band formation was evaluated using two methods of centrum edge analysis. The last deposited band was classified as translucent or opaque and related to the month of capture (Kusher *et al.* 1992). Marginal increment analysis was undertaken by measuring the distance from the last band to the edge of the centrum as a proportion of the distance between the last and the penultimate bands for vertebrae that have clear band patterns and undamaged centrum edges (Branstetter and Stiles 1987; Cailliet 1990):

$$\text{MIR} = (\text{VR} - \text{GB}_n) / (\text{GB}_n - \text{GB}_{n-1})$$

where MIR is the marginal increment ratio, VR is the vertebral radius, GB_n the distance from the centra to the last band and GB_{n-1} is the distance from the centra to the penultimate band.

Temporal variation of MIR was examined using a Kruskal-Wallis test.

8.2.6.2 Growth rate of captive wobbegongs

Specimens of all three species were held captive to assess growth rates. Sharks were held in indoor aquariums ranging from 1000 to 2.2 million litres capacity depending on the size and number of wobbegongs held captive. Wobbegongs were subjected to natural variation in water temperature and the photoperiod artificially mimicking the natural, diel cycle. Sharks were fed a combination of whiting, pilchards, yellowtails, trevally, squid and octopus at least twice a week and up to six days/week. Sharks were identified using photo-identification of dorsal markings

such as spot position and shape of saddles and measured monthly for TL, SAL, and TM to the nearest 1 mm. Sharks of similar TL and born or captured together were grouped together. If the age of animal was known, the final TL was plotted against age and compared with observed lengths-at-age estimated using counts from WV and TS.

8.2.6.3 Chemical marking of captive wobbegongs

Captive sharks that could be sacrificed were also injected with oxytetracycline (OTC). Sharks were measured, weighed and injected with 25 mg/kg of OTC before being released in the aquarium (McFarlane and Beamish 1987). After approximately a year, three of the eleven sharks initially injected were re-injected with another 25 mg/kg OTC. Sharks were later sacrificed by pithing and were measured, weighed and dissected to collect vertebrae using the methods described above. The number of growth bands following OTC marks was counted and the temporal periodicity of the formation of growth bands was estimated by comparing known dates of OTC injection with the number of growth bands counted after OTC marking.

8.3 Results

8.3.1 Collection of samples

During the sampling period, vertebrae from 702 wobbegongs (275 *O. ornatus*, 174 *O. maculatus* and 253 *O. halei*) were excised and processed to count growth bands. As a result of poor readability or count difference ≥ 3 , whole vertebrae from 201 *O. ornatus*, 108 *O. maculatus*, and 178 *O. halei*; and thin sections from 201 *O. ornatus*, 120 *O. maculatus*, and 188 *O. halei* were retained and used for age and growth analysis (Table 8.4).

All three species had a significant linear relationship between VR and shark TL, indicating that the vertebrae were a suitable structure for age determination (Fig. 8.2, Table 8.5). The mean radius of the birth band was 1.2 (s.e. 0.01), 1.4 (s.e. 0.02) and 1.5 mm (s.e. 0.02) for *O. ornatus*, *O. maculatus* and *O. halei*, respectively. Similarly, the mean vertebral radius of near-term embryos was 1.1 and 1.2 mm for *O. ornatus* and *O. maculatus*, respectively.

Table 8.4 Number of wobbegongs sampled and number of vertebrae and sections used in analyses

n is sample size; WV and TS are the number of whole vertebra and thin section retained for analysis.

Species	Sex	<i>n</i>	WV	TCS
<i>O. ornatus</i>	Male	123	91	97
	Female	150	109	104
	Unknown	2	1	1
	Total	275	201	201
<i>O. maculatus</i>	Male	92	57	63
	Female	79	51	57
	Unknown	3		
	Total	174	108	120
<i>O. halei</i>	Male	114	84	87
	Female	131	90	97
	Unknown	8	4	4
	Total	253	178	188
Species combined		702	487	509

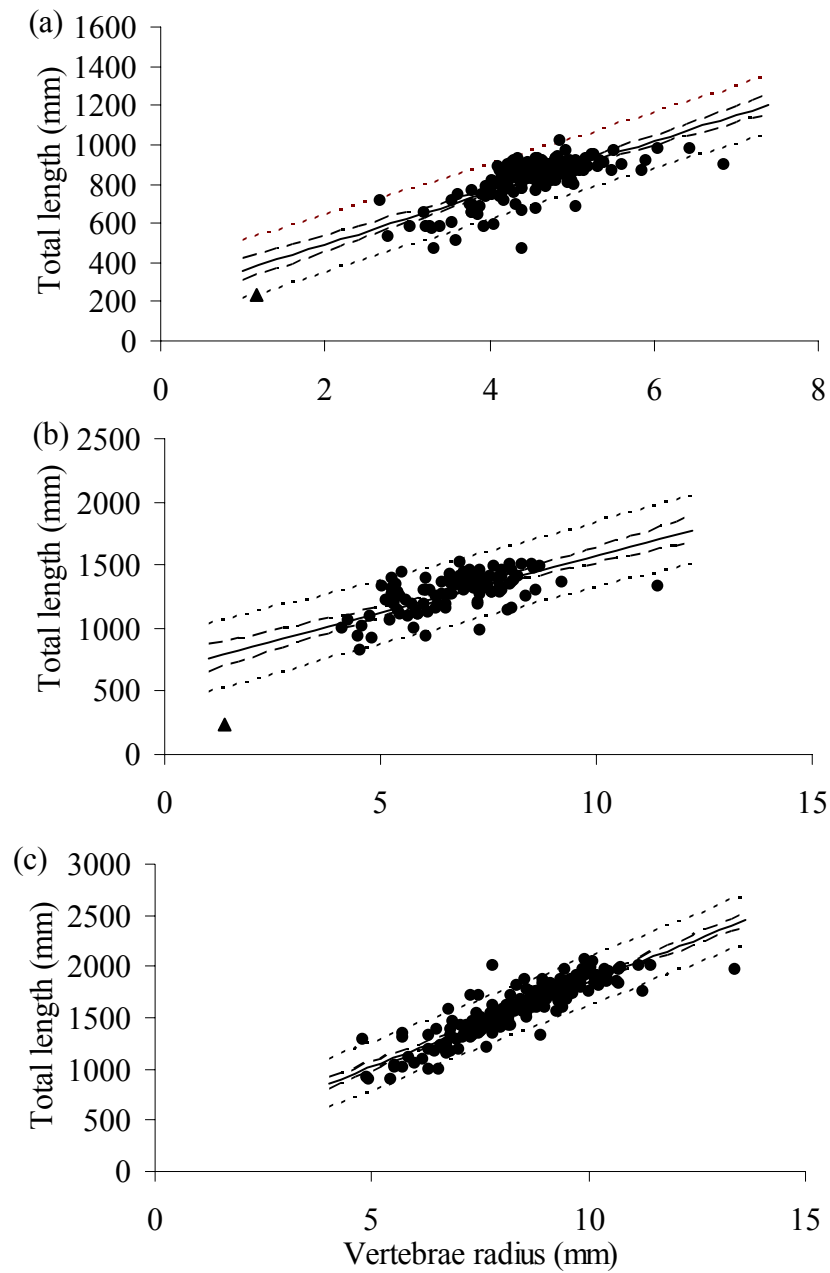


Figure 8.2 Relationship between vertebral radius and wobbegong total length

Shark total length (—), 95% confidence limits (---), 95% prediction intervals (- - -), raw data (●), and (▲) near-term embryos are plotted against vertebral radius for (a) *O. ornatus*, (b) *O. maculatus*, and (c) *O. halei*.

Table 8.5 Relationship between vertebral radius and wobbegong total length

Values of parameters and statistical quantities for the equation $TL=a'+b'VR$; VR is vertebral radius; TL is shark total length; a' and b' are parameters; n is sample size; r^2 is square of regression correlation coefficient; rmse is root mean square error; and P is the probability of statistical significance.

Species	$a' (\pm s.e.)$	$b' (\pm s.e.)$	n	r^2	rmse	P
<i>O. ornatus</i>	229.6 (38.1)	131.4 (8.4)	202	0.56	5131	<0.001
<i>O. maculatus</i>	666.0 (64.8)	91.0 (9.8)	121	0.45	16496	<0.001
<i>O. halei</i>	191.9 (53.2)	165.8 (6.2)	188	0.79	14342	<0.001

8.3.2 Precision and accuracy

All APE were lower than 5%, whereas all CV were lower than 6% (Fig. 8.3). APE for counts made using WV did not differ significantly from APE for counts made using TS for *O. ornatus* (paired t-test: $t_{df=169} = -0.53$, $P > 0.05$), *O. maculatus* (paired t-test: $t_{df=99} = 0.77$, $P > 0.05$), and *O. halei* (paired t-test: $t_{df=139} = 1.08$, $P > 0.05$). Percent agreement did not indicate any strong biases between the two readings with 91.87%, 89.21% and 89.94% of the counts similar within ± 2 growth band for *O. ornatus*, *O. maculatus* and *O. halei*, respectively. Similarly, within reader bias was not observed in age-bias plots when using WV or TS to count growth bands (Fig. 8.3).

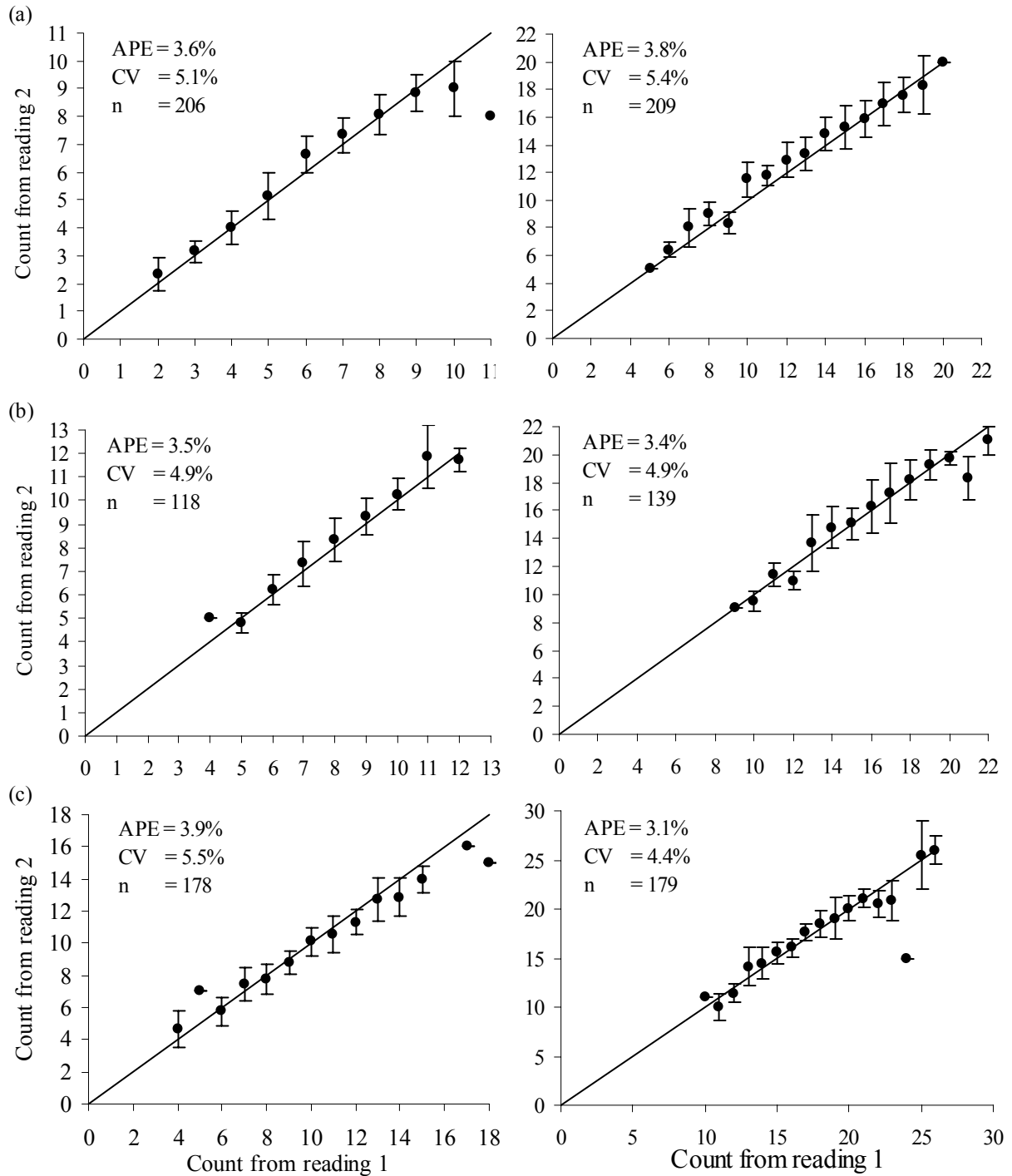


Figure 8.3 Age-bias plots of band counts for wobbegong sharks in NSW

(●) mean; bars, standard error; APE average percent error; CV coefficient of variation; n sample size using whole vertebrae (left) and thin cut sections (right) for a) *O. ornatus*, b) *O. maculatus*, and c) *O. halei*

8.3.3 Models

Back-calculated lengths obtained from the Dahl-Lea linear proportion method were similar to the mean observed lengths-at-age, but were higher than other back-calculated lengths in young sharks. They also overestimated the size-at-birth of all three species, with the largest overestimate occurring in *O. maculatus*. The quadratic-modified Dahl-Lea method was more variable. While it gave a good length-at-age estimation for adult and large juvenile *O. ornatus*, it slightly underestimated size-at-birth. The quadratic-modified Dahl-Lea method was influenced by an outlier at growth increment 9 in *O. maculatus* and underestimated the entire range of *O. halei* (Fig. 8.4). The back-calculated lengths obtained using the Dahl-Lea direct proportion and the modified Fraser-Lee method gave estimates closest to mean observed lengths-at-age and size-at-birth for all three species. The Dahl-Lea direct proportion equation was preferred over the modified Fraser-Lee equation because the latter did not follow back-calculation hypotheses and is based on a misuse of linear regression (Francis 1990). Therefore, lengths-at-age calculated using the Dahl-Lea direct proportion equation was used when combining observed and back-calculated lengths-at-age. Using this equation, back-calculated size-at-birth was similar to measured TL of near-term embryos, whereas mean observed lengths-at-age were also similar to mean back-calculated lengths (Table 8.6). This suggested that back-calculated lengths obtained from the Dahl-Lea direct proportion method provided good length-at-age estimation for wobbegongs where TL was not obtained.

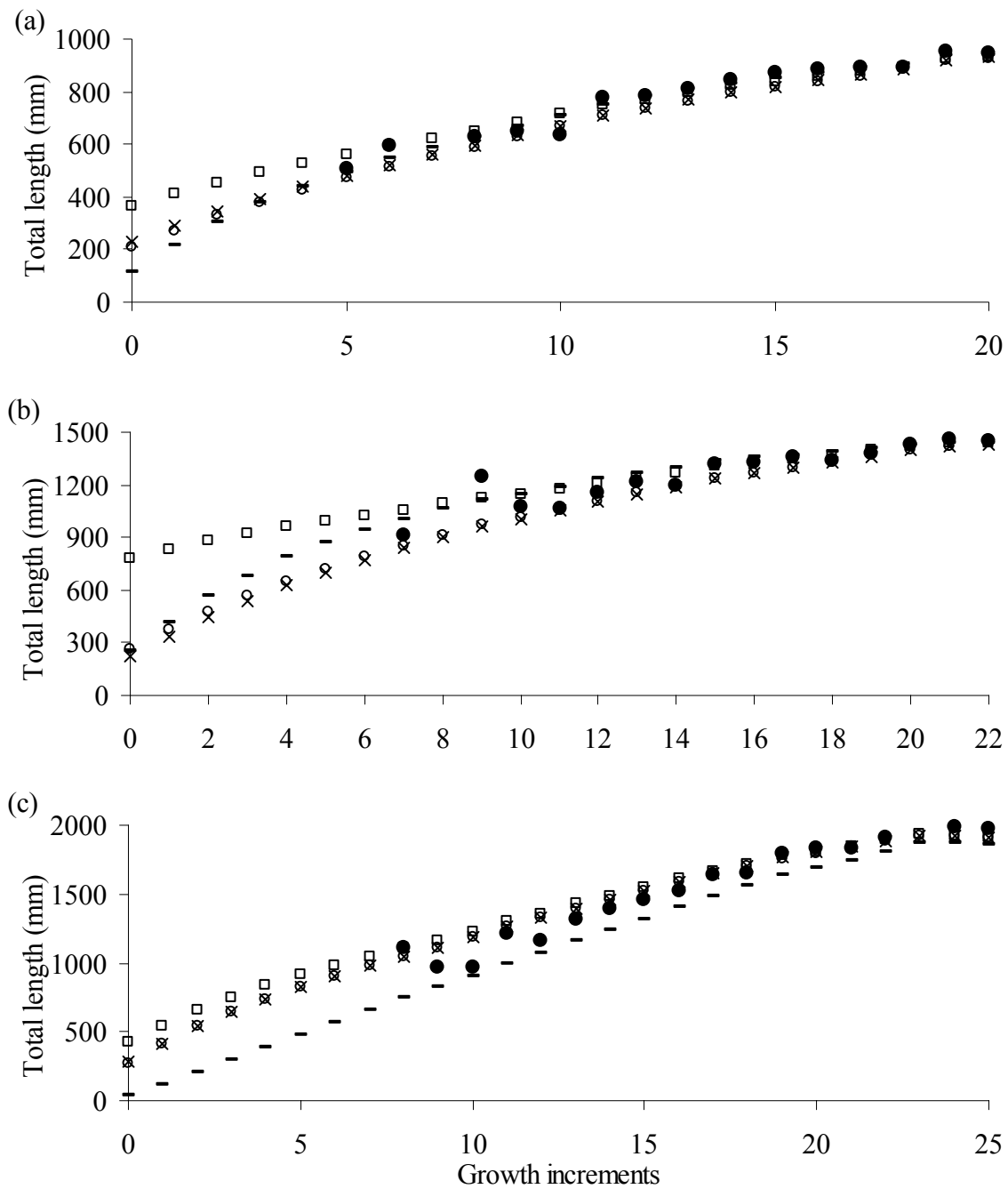


Figure 8.4. Back-calculated lengths-at-age estimates for wobbegongs in NSW

Back-calculated length-at-age using measurement obtained on thin sections and the Dahl-Lea (○), the Dahl-Lea Linear (□), the Dahl-Lea Quadratic (—), and the size-at-birth modified Fraser method (×) compared to sample mean length-at-age (●) for (a) *O. ornatus*, (b) *O. maculatus*, and (c) *O. halei*.

Table 8.6 Back-calculated length (BC) and Observed length (OL) with standard deviation (s.d.) and sample size (*n*) for *O. ornatus*, *O. maculatus*, and *O. halei*.

Age	<i>O. ornatus</i>			<i>O. maculatus</i>			<i>O. halei</i>		
	<i>n</i>	OL \pm s.d.	BC \pm s.d.	<i>n</i>	OL \pm s.d.	BC \pm s.d.	<i>n</i>	OL \pm s.d.	BC \pm s.d.
0	0		206 \pm 29	0		265 \pm 50	0		277 \pm 46
1	0		271 \pm 33	0		375 \pm 58	0		413 \pm 60
2	0		329 \pm 37	0		475 \pm 69	0		536 \pm 66
3	0		380 \pm 39	0		563 \pm 78	0		644 \pm 72
4	0		428 \pm 39	0		650 \pm 81	0		740 \pm 79
5	1	507	473 \pm 41	0		722 \pm 84	0		828 \pm 80
6	3	593 \pm 76	513 \pm 44	0		789 \pm 85	0		906 \pm 82
7	0		551 \pm 48	2	912 \pm 121	853 \pm 84	0		980 \pm 87
8	6	630 \pm 58	590 \pm 51	0		913 \pm 83	1	1105	1049 \pm 90
9	10	650 \pm 111	628 \pm 54	1	1245	972 \pm 82	2	964 \pm 65	1112 \pm 93
10	1	638	666 \pm 50	4	1077 \pm 165	1010 \pm 85	5	969 \pm 70	1185 \pm 97
11	8	774 \pm 72	706 \pm 50	4	1069 \pm 94	1057 \pm 80	5	1207 \pm 126	1260 \pm 99
12	10	786 \pm 73	736 \pm 47	5	1154 \pm 34	1109 \pm 81	5	1156 \pm 105	1324 \pm 99
13	31	813 \pm 76	767 \pm 45	12	1217 \pm 129	1153 \pm 84	13	1315 \pm 86	1396 \pm 99
14	28	847 \pm 37	794 \pm 42	12	1200 \pm 140	1193 \pm 78	13	1400 \pm 127	1459 \pm 101
15	42	869 \pm 51	818 \pm 43	14	1313 \pm 99	1238 \pm 68	14	1462 \pm 75	1522 \pm 101
16	25	882 \pm 23	840 \pm 44	15	1328 \pm 79	1270 \pm 60	21	1522 \pm 119	1587 \pm 106
17	18	892 \pm 33	860 \pm 51	11	1359 \pm 35	1299 \pm 54	20	1634 \pm 118	1646 \pm 105
18	5	890 \pm 34	883 \pm 56	8	1341 \pm 52	1327 \pm 61	17	1650 \pm 143	1702 \pm 102
19	2	951 \pm 94	917 \pm 64	11	1381 \pm 85	1364 \pm 58	22	1796 \pm 92	1760 \pm 92
20	2	947 \pm 47	929 \pm 41	8	1429 \pm 41	1340 \pm 46	17	1830 \pm 83	1800 \pm 90
21				3	1455 \pm 54	1422 \pm 52	11	1835 \pm 131	1839 \pm 91
22				1	1445	1434	10	1915 \pm 51	1885 \pm 66
23							1	2015	1925 \pm 69
24							3	1987 \pm 64	1924 \pm 66
25							1	1968	1908

Models fitted the observed lengths-at-age better than data combining observed and back-calculated lengths-at-age, except for the VBGM in *O. ornatus* and *O. maculatus*, and the 2P VBGM in *O. halei*. Therefore, models using a combination of observed and back-calculated lengths-at-age were not investigated further. The logistic model slightly overestimated size-at-birth in *O. ornatus* and *O. halei* when counts were made using WV, and in *O. maculatus* when counts were made using TS. By contrast, the VBGM slightly underestimated size-at-birth using both techniques and greatly underestimated size-at-birth of *O. maculatus* when counts were made using WV and *O. halei* when counts were made using TS. Growth curves obtained from the VBGM and 2P VBGM had smaller L_{∞} and higher k than curves obtained from the 2P Gompertz and the logistic models. The 2P VBGM had the largest estimates of L_{∞} and the smallest estimate of k , whereas the logistic model estimated the smallest L_{∞} and the largest k compared to the other models. The maximum TL sampled was similar to the L_{∞} estimated by the VBGM and the 2P VBGM, but was slightly larger than the L_{∞} estimated by the 2P Gompertz and logistic models (Table 8.7).

Counts obtained from WV were always smaller than counts obtained from TS for all three species (Fig. 8.7). Growth parameters estimated from counts undertaken using WV were therefore different from those obtained using TS. The L_{∞} estimated from counts obtained using WV were smaller than those estimated using TS for all models in all three species with the exception of two models (i.e. 2P VBGM and 2P Gompertz) in *O. maculatus*. By contrast, k estimated from counts obtained using WV were higher than those estimated using TS for all models in all three species (Table 8.7, Fig. 8.5).

With *O. ornatus*, the logistic growth function fitted the observed lengths-at-age best when increments were counted using WV and TS. In *O. maculatus*, the VBGM fitted observed lengths-at-age best when increments were counted using WV followed by the logistic growth function, whereas the 2P VBGM followed by the logistic growth model fitted observed lengths-at-age best when increments were counted using TS. With *O. halei*, the 2P VBGM fitted observed lengths-at-age best when increments were counted using WV followed by the logistic growth model and the VBGM, whereas the logistic growth model fitted observed lengths-at-age best when increments were counted using TS. The logistic growth function provided the best or second best model for the data for both techniques and all three species (Fig. 8.5 and Table 8.7).

There were no statistical differences between males and females using both techniques of vertebral preparation with all three species. However, the χ^2 value was higher for all three species when counts were undertaken using TS than when using WV (Table 8.8).

Table 8.7 Growth parameters for *O. ornatus*, *O. maculatus* and *O. halei* calculated from counts using whole vertebrae, thin sections, and a combination of back-calculated and observed lengths-at-age, and using the von Bertalanffy growth model (VBGM); the two-parameter modified form of the VBGF forced through the length-at-birth (2P VBGM), the two-parameters Gompertz growth model (2P Gompertz), and the logistic model. L_{∞} is mean maximum age at infinite length; k is growth coefficient; t_0 is theoretical age at zero length; α is time at which the absolute rate of increase in length begins to decrease, or the inflection point of the curve; RSS is residual sum of squares; and w_i is Akaike's weight.

Species	Technique	Sample	VBGM					2P VBGM				2P Gompertz				Logistic				
			L_{∞}	k	t_0	RSS	w_i	L_{∞}	k	RSS	w_i	L_{∞}	k	RSS	w_i	L_{∞}	k	α	RSS	w_i
<i>O. ornatus</i>	whole vert.	samples only	102.17	0.24	-0.44	4947	0.16	107.81	0.19	4999	0.06	97.49	0.35	4933	0.29	96.22	0.42	2.11	4921	0.49
	Sectionned vert	samples only	109.88	0.10	-1.09	3763	0.01	119.26	0.07	3803	0.00	102.21	0.15	3724	0.27	99.86	0.19	5.06	3688	0.71
		back-calculated	125.02	0.07	-2.33	3743	1.00	122.56	0.07	4128	0.00	102.81	0.15	3992	0.00	98.71	0.20	5.25	3955	0.00
<i>O. maculatus</i>	whole vert.	samples only	159.30	0.24	1.38	34490	0.32	193.47	0.11	34771	0.13	161.30	0.25	34548	0.26	151.36	0.39	3.88	34515	0.29
	Sectionned vert	samples only	172.17	0.09	-1.12	5653	0.21	176.40	0.08	5664	0.45	153.72	0.16	5805	0.01	155.45	0.17	5.91	5631	0.33
		back-calculated	179.48	0.07	-2.00	5597	1.00	176.52	0.08	5960	0.00	152.11	0.16	6422	0.00	153.85	0.18	5.97	5955	0.00
<i>O. halei</i>	whole vert.	samples only	232.64	0.12	0.26	31501	0.09	270.46	0.08	31284	0.80	214.50	0.20	31546	0.07	209.09	0.25	4.98	31641	0.04
	Sectionned vert	samples only	240.07	0.09	4.66	24999	0.23	1681728	0.00	25073	0.36	275.08	0.08	26412	0.00	212.77	0.20	10.96	24918	0.41
		back-calculated	717632	0.00	-4.79	26902	0.00	1385866	0.00	24093	1.00	271.40	0.09	28216	0.00	257.16	0.12	12.69	27175	0.00

Table 8.8 Likelihood ratio test testing differences of growth curves between males and females for wobbegong sharks in NSW

Species	Technique	Model	χ^2	P
<i>O. ornatus</i>	whole vertebrae	Logistic	3.32	>0.05
	thin sections	Logistic	7.49	>0.05
<i>O. maculatus</i>	whole vertebrae	VBGM	0.89	>0.05
	thin sections	2P VBGM	7.29	>0.05
<i>O. halei</i>	whole vertebrae	2P VBGM	0.93	>0.05
	thin sections	Logistic	7.19	>0.05

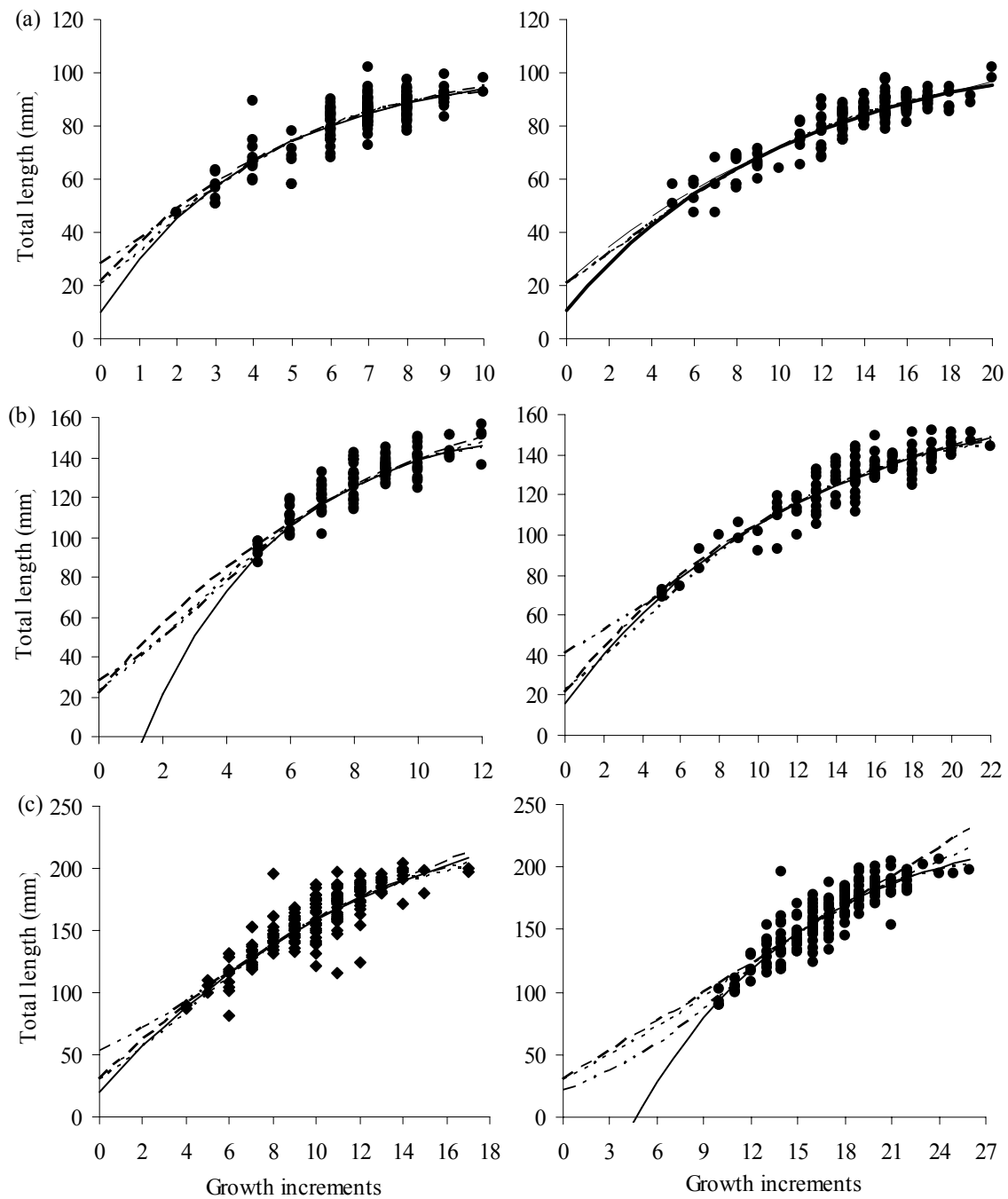


Figure 8.5 Growth curves for wobbegongs in NSW

Growth curves generated from whole vertebrae (left) and thin sections (right) for (a) *O. ornatus*, (b) *O. maculatus*, and (c) *O. halei*. Growth curves were fitted to the observed lengths-at-age data using the von Bertalanffy growth model (—), the two-parameters von Bertalanffy growth model (---), the two-parameters Gompertz growth model (·····), and the logistic growth model (- · - ·).

8.3.4 Validation and verification

8.3.4.1 Edge and marginal increment analyses

Categorisation of growth bands at the edges of the vertebrae as opaque or translucent was difficult for WV and TS. No clear pattern in the last growth band was detected for any of the three species (Fig. 8.6). Small sample sizes prevented statistical tests.

Departure of homogeneity of variance for Marginal Increment Ratio (MIR) calculation was significant for *O. ornatus* (Levene test: $F_{df=8, 168} = 2.7$, $P < 0.01$) and *O. maculatus* (Levene test: $F_{df=9, 100} = 4.0$, $P < 0.001$), but not for *O. halei* (Levene test: $F_{df=11, 169} = 1.2$, $P > 0.05$). MIR differed significantly among months (ANOVA: $F_{df=11, 169} = 3.00$, $P < 0.01$) for *O. halei*, but not for *O. ornatus* (Kruskal-Wallis test: $\chi^2_{df=10} = 15.12$, $P > 0.05$) nor for *O. maculatus* (Kruskal-Wallis test: $\chi^2_{df=10} = 6.83$, $P > 0.05$). No clear pattern was detected in the mean monthly MIR for *O. ornatus* or *O. maculatus*. However, in *O. halei* the mean MIR was highest during March–April and September, and lowest during May and November.

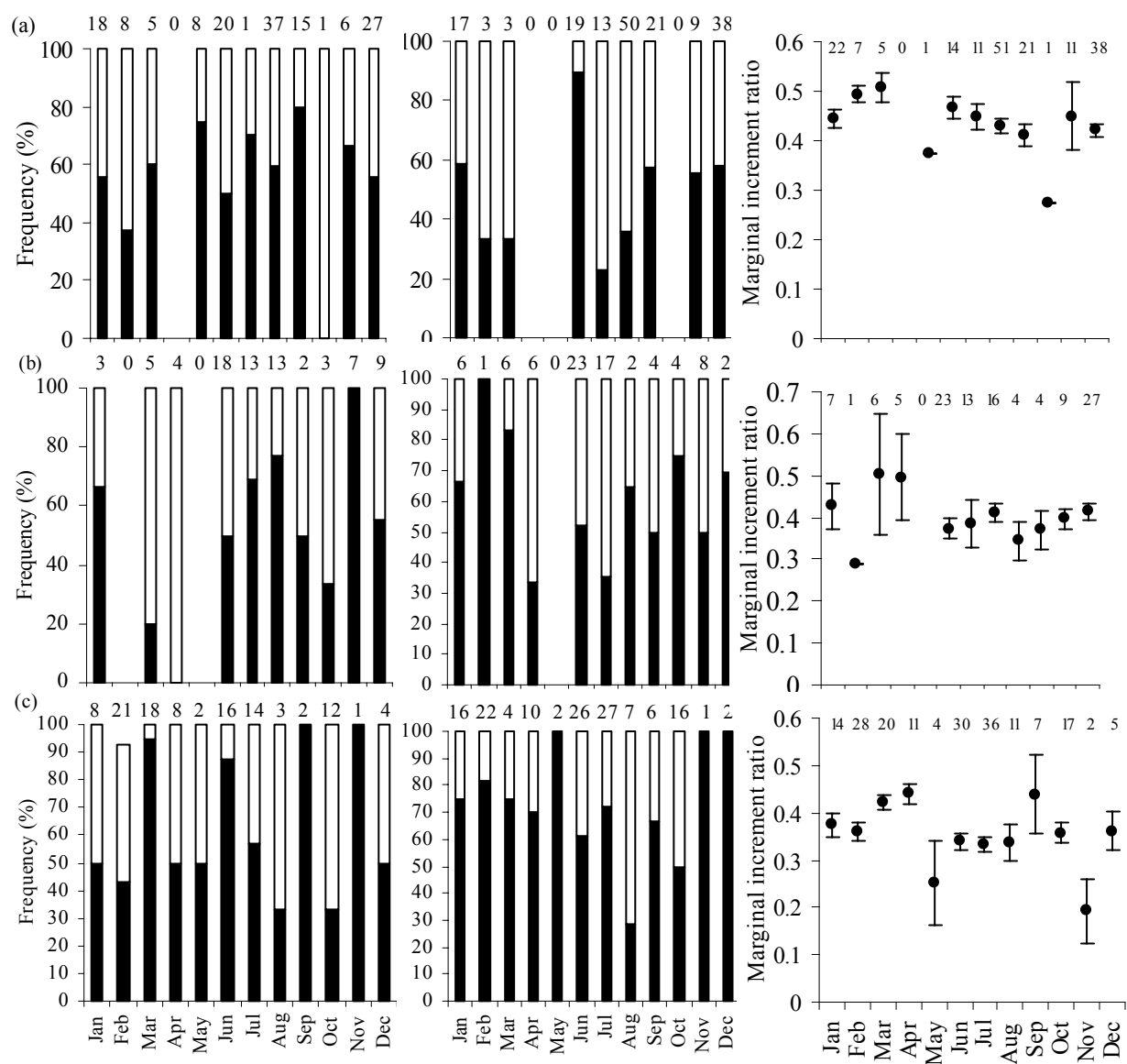


Figure 8.6 Monthly variation of vertebra edge and Marginal Increment Ratio (MIR)
 Monthly frequency of translucent (□) and opaque bands (■) determined from whole vertebrae (left) and thin sections (centre), and monthly variation of mean marginal increment ratio (right) for (a) *O. ornatus*, (b) *O. maculatus* and (c) *O. halei*. Sample size is indicated on top of the graphs; (●) mean monthly MIR; bars, standard error for monthly value.

8.3.4.2 Growth rate of captive wobbegongs

Three *O. ornatus*, 18 *O. maculatus* and two *O. halei* were kept in captivity between 6–22 months. All sharks in captivity grew at rates decreasing with increasing TL (Table 8.9). The neonate *O. ornatus* grew *ca.* 350 mm in nearly two years averaging a monthly growth rate of 16 mm/month. However, the two mature *O. ornatus* of TL close to known maximum TL did not grow as fast and grew only *ca.* 2 mm/month. In *O. maculatus*, rate of growth rate also decreased with increasing TL. Neonates of *ca.* 310 mm TL grew *ca.* 22 mm/month, whereas neonates of *ca.* 400 mm TL grew *ca.* 19 mm/month as did two juvenile of *ca.* 500 mm TL. Five *O. maculatus* of *ca.* 700 mm TL grew *ca.* 8.5 mm/month and provide the slowest growth rates recorded. Both immature *O. halei* grew *ca.* 12 mm/month. Known size-at-age fitted the growth curves estimated from WV better than curves estimated from TS for *O. ornatus* and *O. maculatus* (Fig. 8.7).

Table 8.9 Growth rate details of captive wobbegongs

Group is sharks of similar TL, and born or captured together; *n* is sample size; TL is total length at which sharks were born or captured (mm); Growth is total growth during study (mm); Period is period of study; Ave growth is average monthly growth (mm/month); Ave growth is average yearly growth (mm/year).

Species	Group	<i>n</i>	TL mean (s.e.)	Growth mean (s.e.)	Period month	Ave growth mean (s.e.)	Ave growth mean (s.e.)
<i>O. ornatus</i>	1	1	231	352	22	16	192
	2	2	925 (20.0)	20.5 (5.5)	11	1.9 (0.5)	22.4 (6.0)
<i>O. maculatus</i>	3	5	311.5 (5.0)	249.7 (14.2)	12	22.4 (1.3)	268.4 (5.0)
	4	6	404 (5.5)	283 (6.2)	14	19.5 (0.4)	234.2 (5.0)
	5	1	414	430	24	17.9	215
	6	1	571	256	13	19.7	236.3
	7	5	663.8 (8.6)	55.4 (4.0)	6	8.5 (0.6)	102.3 (7.0)
<i>O. halei</i>	8	2	1223 (49.0)	210.5 (15.5)	18	11.7 (0.9)	140.4 (10.1)

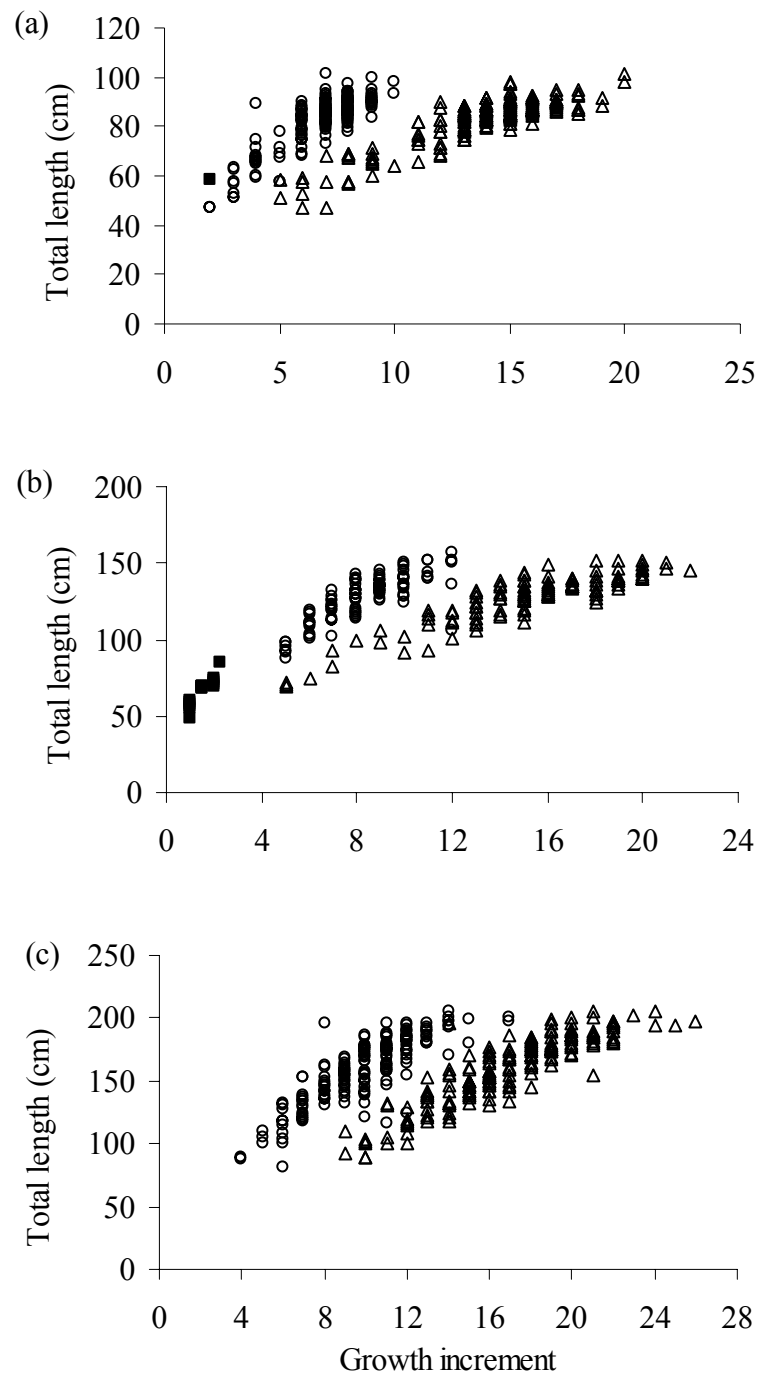


Figure 8.7 Observed length-at-age from whole vertebrae (\circ), thin sections (Δ) and known length-at-age of captive sharks (\blacksquare) for (a) *O. ornatus*, (b) *O. maculatus*, and (c) *O. halei*.

8.3.4.3 Chemical marking of captive wobbegongs

Although not all OTC injections resulted in incorporation into the vertebrae, most sharks injected with OTC showed a fluorescent band when viewed under ultraviolet light (e.g. Fig. 8.8). Growth bands after OTC marks were more difficult to observe on WV than on TS.

One neonate and two mature male *O. ornatus* were injected with OTC. Date of birth of the neonate was known because it was removed from a female uterus as near-term embryo. The neonate shark was injected with OTC after two years and again four months prior to being euthanased. Four growth bands were observed after the birth band in TS, whereas three bands were observed on WV. One opaque band was seen after the OTC mark when using TS. Both adult *O. ornatus* were injected one year before being euthanased. In TS, a narrow opaque band was observed after the OTC mark, whereas no OTC mark was observed on WV.

Five *O. maculatus* were injected with OTC, but died six months later due to accidental death. In all five sharks, an opaque band was discerned after the OTC mark in TS. Some sharks had an opaque and a translucent band present after the OTC mark, but poor readability of the vertebrae made it difficult to categorise growth bands. No growth band was seen after the OTC mark on WV. Another *O. maculatus* was injected with OTC on two occasions: one year and four month prior to being euthanased. However, only one OTC mark was discernable close to the edge of the vertebrae, followed by an opaque band in TS. Again no growth band could be seen following the OTC mark on WV.

Two immature *O. halei* were injected with OTC 18 months prior to being euthanased. In both individuals, an OTC mark was highly visible and two growth bands (two opaque and two

translucent bands) were observed after the OTC mark in TS. On the other hand, one growth band (two opaque and one translucent band) was seen following the OTC mark on WV.

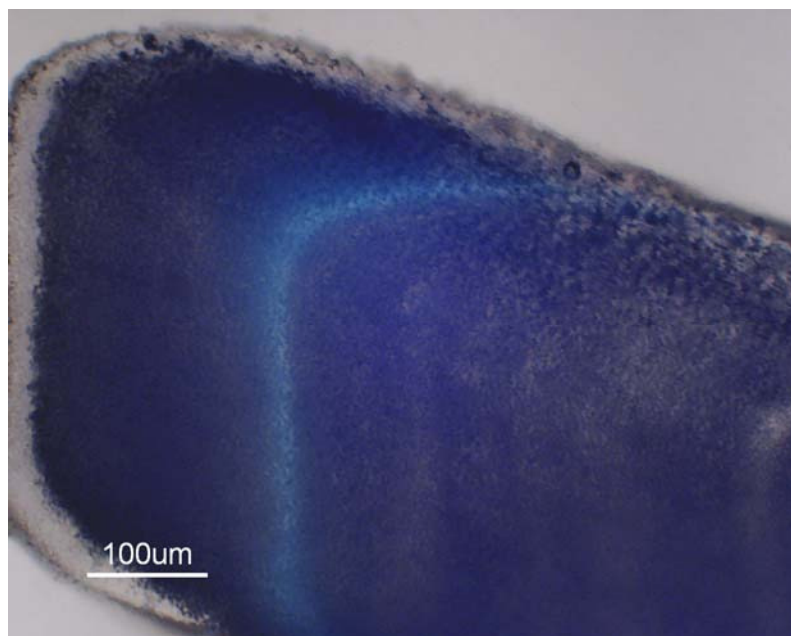


Figure 8.8 Example of OTC mark visible using ultraviolet light on a vertebra of *O. haley*.

8.4 Discussion

Close agreement between the mean vertebral birth band radius of wobbegongs, and the mean radius of near-term embryos indicated that the birth band was identified correctly. APE and CV of all three species were sufficiently low to indicate reproducible counts and high precision between the two readings (Campana 2001). Age-bias plots also indicated that within reader precision was constant throughout the age classes sampled. The low APE and the close similarity between APE from WV and from TS indicated that precision was both high and similar between the two methods.

Counts obtained using WV or TS are sometimes similar (e.g. Carlson *et al.* 1999). However, in the present study, counts obtained using WV produced consistently lower counts than those obtained from TS. Age and growth studies of *Carcharhinus plumbeus* showed a similar pattern with higher counts obtained using TS (Sminkey and Musick 1995) compared to those obtained using WV (Joung *et al.* 2004). The discrepancy between the two methods may arise from underestimation when using WV or overestimation in TS. Underestimation of growth bands in WV can occur in older sharks because of the increased difficulty in distinguishing growth bands close to the vertebral edge (Cailliet 1990; MacNeil and Campana 2002; Skomal and Natanson 2003). On the other hand, overestimation of growth bands in TS can occur because of the counting of false checks or split bands in the *corpus calcareum* (Moulton *et al.* 1992; Oshitani *et al.* 2003; Goldman 2005); also referred to as ‘minor bands’ (Tanaka *et al.* 1990; Officer *et al.* 1996; Simpfendorfer *et al.* 2000). As a result, the growth parameter estimates can differ between the two methods. Correct estimation of age and growth of wobbegongs necessitates the identification of the technique that provides the most accurate age estimate. Size-at-maturity in *O.*

ornatus, *O. maculatus* and *O. halei* was estimated at *ca.* 800, 1250 and 1250 mm TL, respectively. This was equivalent to an age-at-maturity of *ca.* 6, 8 and 11–13 years for *O. ornatus*, *O. maculatus* and *O. halei*, respectively, using WV. By contrast, age-at-maturity would be *ca.* 12–13, 14 and 18–20 years for *O. ornatus*, *O. maculatus* and *O. halei*, respectively, using TS. This represents a large difference with size-at-maturity nearly doubling when using counts from TS. Growth parameters were also influenced by the vertebral preparation with L_{∞} increasing and k decreasing with counts from TS. Such difference in age-at-maturity and growth parameters can have important impacts on stock assessments and fishery models (Hoenig and Gruber 1990; Hoff and Musick 1990; Officer *et al.* 1996; Musick 1999; Campana 2001). The determination of which method provides the most accurate estimation of age and growth parameters is necessary to create fisheries models that correctly assess stock variation and resilience to fishing pressure.

Wobbegongs with known length-at-age and captive growth rates fitted better with counts from WV than did the counts from TS. Those sharks were, however, born and kept in captivity. For some species, captive growth can be as much as nine or ten times faster than natural growth (and *Carcharhinus amblyrhynchos* - Waas 1971; e.g. *Negaprion brevirostris* - Gruber and Stout 1983) whereas, other species do not show accelerated growth in captivity (e.g. *Sphyrna tiburo* - Parsons 1993a). Therefore, if accelerated growth in captive wobbegongs occurred, the sharks with known size at age would have had a better fit with the counts from TS. Assessments of the differences in growth rates between captive and wild sharks may help determine which technique (i.e. WV or TS) provides more accurate estimates of age in wobbegongs.

In some of the wobbegongs injected with OTC, the band was visible in TS, but could not be observed on WV. When close to the edge, the OTC band may not be readily observed as is often

the case with ordinary growth bands. Counts at the edge can be difficult to obtain with accuracy and this can give rise to discrepancies between methods and underestimation with WV. However, it is possible that the lack of visibility of the OTC band on WV was not due to its proximity to the edge, but to OTC marks being less visible on WV than on TS and independent of the location of the OTC mark on vertebrae.

Growth parameters estimated for *O. halei* in WA using counts obtained from x-rays applying the VBGM on observed lengths-at-age combined with back-calculated lengths (using Dahl-Lea direct proportion method) were 0.099 for k , and 222.9 cm for L_{∞} (Chidlow 2003). The present study obtained similar estimates ($k = 0.09$ and $L_{\infty} = 240.1$ cm) when using the VBGM and counts from TS. However, the maximum age of individuals sampled was less in the present study (26 increments) compared to individuals from WA (32 increments). Using the model with the best fit to the data and taking into account biologically meaningful estimations of L_{∞} and k , growth parameters obtained using counts from WV were for L_{∞} : 962, 1593 and 2705 mm TL and for k : 0.42, 0.24 and 0.08 for *O. ornatus*, *O. maculatus*, and *O. halei*, respectively. Growth parameters obtained when using counts from TS were for L_{∞} : 999, 1764 and 2128 mm TL and for k : 0.19, 0.08 and 0.20 for *O. ornatus*, *O. maculatus*, and *O. halei*, respectively.

The present study could not determine which method (i.e. WV or TS) was the most accurate for estimating growth increments in wobbegongs. Further verification and validation studies will be necessary to determine the best method with wobbegongs. Similarly, simple demographic analysis combining estimated fecundity, age-at-maturity and longevity may help determine which parameters are more biologically sound by comparing reproductive output. Comparison of the distance between the centra and each growth increments would help determine: (1) why growth

counts using WV and TS differ to such an extent; (2) assess if overestimation occurs in TS or if underestimation occurs in WV; and thereby (3) confirming which method provides the most accurate count. Finally, count of wobbegong growth bands by a different reader on WV and TS is required to assess subjectivity and difficulty involved in counting wobbegong growth bands.

Several authors (e.g. Beamish and McFarlane 1983; Cailliet 1990; Cailliet and Goldman 2004) have stressed the need to validate the periodicity of band deposition and of the absolute age for accurate age estimation. Various methods were attempted to validate the periodicity of band deposition in wobbegongs. Edge analysis did not show patterns indicating any periodicity for all three species. Similarly, MIR did not show patterns of periodicity in *O. ornatus* or *O. maculatus*. Although a significant difference was obtained in *O. halei*, it did not provide a clear trend of low and high periods with low standard deviations of means during the months when a new zone was forming (Lessa *et al.* 2004). This was most likely due to the difficulty in categorising the edges of the *corpus calcareum* in WV, and the small sample sizes in any particular month (Cailliet 1990). To overcome the difficulty of measuring the width of the last growth band in older sharks (Allen and Wintner 2002), and because MIR conducted over all age classes can be different when restricted to a single age (Campana 2001), MIR calculations can be done on juveniles <4 years old only (Killiam and Parsons 1989; Neer *et al.* 2005). This was not feasible in this study due to the minimal numbers of neonates and small juveniles. Although marginal increment ratios are frequently used as validation techniques, it does not often result in periodicity being determined (e.g. Carlson *et al.* 1999; Allen and Wintner 2002; Wintner *et al.* 2002; Lessa *et al.* 2004; Santana and Lessa 2004) and chemical marking is frequently recommended to validate periodicity in growth band deposition. OTC can be incorporated into wobbegong vertebrae (Tanaka 1990), but the small number of sharks injected with OTC and the short period between injection and

euthanasia prevented the periodicity of growth band deposition to be determined in the present study. Furthermore, chemical marking was undertaken on captive sharks and handling can produce irregular growth band deposition or ‘disturbance check marks’, biasing periodicity estimates (Walker *et al.* 1995).

Previous studies have also been unable to validate growth band deposition in wobbegongs. Although growth band deposition seemed to be annual, the OTC injection in captive *O. japonicus* did not clearly show periodicity in growth band deposition (Tanaka 1990). Furthermore, ontogenetic variation in growth band deposition is thought to occur in *O. hutchinsi* with neonates producing up to three growth bands in their first year, whereas adults form less than one band per year, averaging growth band periodicity to one per year (Chidlow *et al.* in review). Wobbegongs also share similar biological and ecological characteristics to *Squatina* species including benthic behaviour (Compagno 2001) and a triennial reproductive cycle (*Squatina* - Colonello *et al.* in press and wobbegongs - ; Huveneers *et al.* in review-b, Chapter 7). Importantly, growth bands in *Squatina* are not formed in a temporally predictable manner, but are related to somatic growth (Natanson and Cailliet 1990). Growth of wobbegongs may also be similar to growth of *Squatina* species and not show any periodicity in their increment deposition.

The inconsistent results from the age validation studies suggest that other techniques need to be used to determine the periodicity of growth band deposition or the lack of temporal pattern. The bomb radiocarbon method (Druffel and Linick 1978) as a method for age validation is not applicable for wobbegongs because samples during the C¹⁴ increase (1955–1970) are not available. However, electron microprobe analysis of calcium and phosphorus weight-fraction concentration or OTC injection of wild wobbegongs with recapture after a period of at least two

years is likely to provide good information on the periodicity of band deposition. The latter is the most promising because wobbegong movements are limited and acoustically tagged individuals have been found within the same area for two years (Huveneers *et al.* in press, Chapter 4).

Several publications indicate that sectioning is more accurate than using WV (Cailliet and Goldman 2004). This method is now commonly used and accepted in the literature and studies have published growth parameters obtained using TS without validation (e.g. Lessa *et al.* 2004). However, preparation of WV is easier and images can be acquired in a short period of time using less specialised equipment than that required for TS. The present study showed that in chondrichthyans, growth parameter estimates can differ widely between counts made from WV and TS. Even when growth increments are visible on TS, it does not necessarily mean that such counts are accurate and growth parameters should not be assumed to be correct without validation. Counts of growth increments from WV should also be attempted and compared to those obtained from TS to assess which counts make more biological sense and accurately estimate the age of an individual.

CHAPTER 9: GENERAL DISCUSSION



© Charlie Huveneers (*Orectolobus halei* being processed to be sold as “flake”)

In the last 20 years, interest in the resilience of chondrichthyans to fishing pressure has increased because of their susceptibility to overexploitation and previous population collapses (Hoff and Musick 1990; Bonfil 1994; Camhi *et al.* 1998; Lack and Sant 2006). This has immediate relevance in the Australian context for a number of shark species, including wobbegongs. The decline in the reported commercial catch of wobbegongs in NSW has lead to concerns over the sustainability of the wobbegong fishery (NSW Fisheries 2001; Cavanagh *et al.* 2003). However, there are minimal current management strategies specifically regulating the fisheries. Those currently in place directly applying to wobbegongs are a recreational bag limit of two wobbegongs per day, gear limit of no more than ten lines each with a maximum of six hooks when setlining within three nautical miles of the coast, and *de facto* protection given to shared critical habitats with the grey nurse shark (*Carcharias taurus*) (Fisheries Management (General) Regulations 2002, <http://www.legislation.nsw.gov.au/maintop/scanact/inforce/NONE/0>)

This thesis has provided critical biological and ecological information on the three species of wobbegong in NSW waters. The enhanced understanding of their biology and ecology arising from this work identifies the future research that is needed for population assessments and sustainable fishing practices. This will, in turn, inform future management policies for the commercial wobbegong fishery.

The biology and ecology of wobbegongs was investigated by determining which species of wobbegongs occur in NSW and redescribing two species previously known as the ornate wobbegong (Chapter 2); investigating the distribution and relative abundance of wobbegongs along the NSW coast using recreational diver survey (Chapter 3); assessing localised movements

and residence time of wobbegongs (Chapter 4); determining predictive morphological relationships between carcasses and whole wobbegongs (Chapter 5); quantifying and comparing the diet of NSW wobbegong species (Chapter 6); and by describing and contrasting the reproductive characteristics (Chapter 7) and growth parameters of NSW wobbegongs (Chapter 8).

9.1 Taxonomy uncertainties and redescription

The present study focused on wobbegongs from NSW and resolved identification problems by redescribing easily confusable species and providing an identification key for all species found in NSW waters (Huveneers 2006; Chapter 2). Prior to this study, management of the commercial wobbegong fishery was based on the notion that there were only two species (combined under the name “wobbegong”). It is essential that species are correctly identified, and that catches are reported by species because of the biological and ecological differences between the three species of wobbegongs occurring in NSW (Maximum size - Chapter 2; distribution - Chapter 3; diet - Chapter 6; litter size and size-at-maturity - Chapter 7, and growth parameters - Chapters 8).

Maximum total lengths of *Orectolobus ornatus* and *O. halei* can exhibit 3-fold differences (Huveneers 2006; Chapter 2). Considering that mass is used to quantify and describe the wobbegong fishery (Pease and Scribner 1993; 1994; Pease and Grinberg 1995) and the much smaller mass of *O. ornatus* compared to the two other species, the number of individuals in the total catch could be grossly underestimated if based on two species rather than on the three species identified in this study. The identification key that was developed allows fishers to correctly identify wobbegongs to species level and to report their catch accordingly. Correct

species identification and catch reports allows the implementation of species-specific regulations and the management of individual species in the fishery, previously not possible.

In addition to the redescrptions provided in this study, two new species of wobbegongs from Western Australia have recently been identified (P. Last and J. Chidlow pers. comm.). New material from Indonesia (W. White pers. comm.), Borneo (Manjaji 2002) and the Philippines (Compagno *et al.* 2005) also indicates that additional species exist in the Indo-West Pacific. Moreover, specimens from Japan suggest there might be several species currently synonymised with *O. japonicus* (P. Last pers. comm.). A full revision of the Orectolobidae family is therefore required. Genetic investigation of the Orectolobidae phylogeny has already started (Corrigan and Huveneers, in progress). The first stage of this genetic research project has already confirmed the divergence between wobbegong species found in NSW as suggested by the redescription in Chapter 2 (Corrigan *et al.* in review).

9.2 Distribution and morphological relationships of wobbegongs

The commercial catches during sampling for this study combined with the recreational diver survey suggested differences in distribution between the three species. *Orectolobus ornatus* is only found north of Sydney, whereas *O. maculatus* and *O. halei* occur along the entire NSW coast. The abundance of *O. maculatus* is smaller around Eden, whereas the abundance of *O. halei* is lower at lower latitudes (Chapter 3 and 5). As a result, the impact and effectiveness of management regulations might vary spatially. For instance, closure of areas south of Sydney would not assist recovery of the *O. ornatus* population because its distribution is restricted to regions north of Sydney.

No neonates and very few small juvenile wobbegongs were found in the recreational diver survey or in the catches from commercial fishers. Although gear selectivity could explain the absence of neonates, it is unlikely to explain the absence of juveniles because *O. ornatus* of 700–1000 mm TL are commonly caught using the same gear and in the same areas, whereas only a few *O. halei* smaller than 1300 mm TL are caught. It seems more likely that small wobbegongs are not available to the fishery because they live within different habitats. This suggests that spatial separation as a function of size might occur in wobbegongs.

Therefore, management regulations based on size segregation and spatial preferences could be an effective tool to protect specific life stages of wobbegongs. Demographic analyses have suggested that juveniles are the most vulnerable stage implying that management regulations should protect immature sharks to rebuild stocks (Cortés 1995; 1999b; Brewster-Geisz and Miller 2000; Frisk *et al.* 2002; Otway *et al.* 2004). The restriction of commercial fishing to habitats and regions similar to regions where fishing effort currently occurs would ensure that neonates and small juveniles remain inaccessible to extensive fishing mortality.

Tagging of pregnant females close to parturition period (October–November - Chapter 7) using archival tags will enable the detection of preferred pupping location and habitat, and potential nursery areas, and enable management based on size segregation and spatial preferences. Strategic sampling of areas not targeted by commercial fishers such as deeper waters using trawlers or estuaries using gillnets could also help find neonates and juveniles missing in the commercial fishery.

As sharks are commonly landed as trunks, length and mass composition of the fishery for management purposes is difficult (FAO 2000). The relationships between carcass and whole shark measurements provided in this thesis will permit managers to convert carcass mass or partial length to total mass and length to use in fisheries assessments.

9.3 Localised movements and residence time of wobbegongs

Residence time in areas where fishing is allowed is a critical parameter to measure when trying to evaluate the effectiveness of an area closure for shark conservation (Chapman *et al.* 2005). Site fidelity occurs in at least some wobbegongs with residency of two years and with only short excursions during that period (Chapter 4). The long residence time of wobbegongs suggests that commercial fishers could potentially deplete a wobbegong population by continued targeting of small reefs. There is a growing awareness that MPAs and other forms of area closure will play an important role in shark conservation, especially for the protection of site-attached species (Bonfil 1999a; Heupel and Simpfendorfer 2005). The long-term residency pattern observed in some wobbegongs suggests that temporal fishing closures or marine protected areas may be effective tools for the management and conservation of local populations.

Diel patterns were also observed in wobbegong species with more sharks present during daylight hours than at night (Chapter 4). Diel movement patterns are common in chondrichthyans with a diurnal pattern in many species related to feeding (Bray and Hixon 1978; Nelson and Johnson 1980; Holland *et al.* 1993). Wobbegongs may change their primary mode of foraging from ambush predation during the day to active predation at night. Reports of divers observing active predation at night are consistent with this switch (R. Harcourt pers. comm.). Management of the wobbegong fishery may need to incorporate these diel behavioural differences into fishing

management practice, although it might not be financially viable due to the low value of the fishery. Fishing regulations should account for day and night ranges when mobile species with diel feeding patterns are the targeted species (Heupel and Simpfendorfer 2005) by increasing habitat protection to include the nighttime excursions.

The extent of wobbegong movements and the frequency of excursions are important considerations when assessing the effectiveness of area closures for the protection of wobbegongs. The use of archival tags would be beneficial in assessing the extent of wobbegong excursions. Furthermore, the recent deployment of a receiver array along the NSW coast to study the movement and migration of grey nurse sharks could also be used to detect acoustic tags implemented on wobbegongs, allowing passive tracking of individuals.

9.4 Diet and feeding ecology of wobbegongs

This thesis provides the first quantitative assessment of the dietary composition of the three species of wobbegongs in NSW. Wobbegongs primarily fed on bony fishes cephalopods and some chondrichthyans (Cochrane 1992; Last and Stevens 1994; Compagno 2001; Chidlow 2003). Surprisingly, crustaceans, which have previously been reported as a component of wobbegong diet (e.g. Last and Stevens 1994; Compagno 2001) were not found in this study. Wobbegongs are often caught in lobster pots, However, they seem to be attracted to the bait and octopuses attracted by the lobsters, rather than by the lobsters themselves. Wobbegongs and lobsters are indeed regularly found sharing the same pot (R. Brislane pers. comm.; J. Moyce pers. comm.; C. Huveneers pers. obs.). If wobbegongs commonly fed on lobsters, then remains would have been found in the stomachs of the many sharks caught by lobster traps.

Sex and ontogenetic differences are frequently observed in chondrichthyans (Cortés and Gruber 1990; Lowe *et al.* 1996; Simpfendorfer *et al.* 2001; Ebert 2002). Sexual dimorphism in sharks may be due to the requirement for greater space for internal embryonic development in females (Klimley 1987) and/or the energetic demands of reproduction resulting in selection pressure for larger body size (Sims 2003). Ontogenetic changes are potentially associated with behaviour, changes of habitat use (i.e., when neonates and juveniles leave nursery areas), mouth dimension, energetic requirements and prey selection as larger sharks may be more efficient at catching faster prey (Wetherbee *et al.* 1990; Simpfendorfer *et al.* 2001). In wobbegongs, diet did not differ between males and females, and the absence of small wobbegongs in the sample prevented ontogenetic differences from being tested. The absence of differences in diet between males and females wobbegong might be related to their lack of sexual dimorphism (Chapter 7). However, diet composition was significantly different between species with the largest difference in diet occurring between species with the largest TL differences (Chapter 6). Large wobbegongs such as *O. halei* fed more on pelagic species and chondrichthyans than the other species, possibly due to increased motility (Wetherbee *et al.* 1990; Simpfendorfer *et al.* 2001), whereas small wobbegongs such as *O. ornatus* fed more on cephalopods. The smaller adult size of *O. ornatus* allows them to capture octopus in small holes and crevices not accessible to the larger-sized *O. maculatus* and *O. halei*.

The impact of fishing on wobbegongs could have flow on effects within their local ecosystems (Stevens *et al.* 2000; Kitchell *et al.* 2002) and needs to be assessed. The removal of top predators has, in some cases, lead to individual species declines and changes in community structure due to competitive (Fogarty and Murawski 1998) and predatory releases (Baum *et al.* 2003; Shepherd and Myers 2005; Ward and Myers 2005). Whether removal of large numbers of resident

wobbegongs through fishing may have similar effects remains to be determined. Multi-species models such as Ecopath (Pauly *et al.* 2000) can use dietary information along with fishing effort and catch composition to determine the effect of commercial wobbegong fishing on the ecosystem and in turn allow an assessment of the importance of wobbegongs within the NSW marine ecosystem.

In 2005 and 2006, the lack of specific strategies directed at wobbegong commercial fishing together with the decline in catches resulted in concerns of the fishery sustainability.

Consequently, a review of NSW Recreational Freshwater & Saltwater Fishing Rules and the Environmental Impact Assessment of the NSW Ocean Trap and Line Fishery proposed a minimum size limit for wobbegongs sharks of 130 cm.

In this study, it was shown that over 80% of wobbegongs caught are stomach-hooked. Although wobbegongs are known to be robust, post release mortality rate after capture and handling is likely to be high because of anatomical injuries caused by hooking and septicaemia.

Consequently, future research should examine the effects that J-shaped and circle hooks have on catches and post-release mortality of individuals under this recommended size. It is imperative that these studies be done prior to the introduction of size limits because the results of this study suggest that a minimum size limit will result in unquantified, fishing-related mortality. Such a management action could not be considered to be one that adheres to the principles of ecological sustainable development nor would it be in line with the objectives of the National Plan of Action for the Conservation and Management of Sharks in Australian waters (Shark Advisory Group and Lack 2004).

Moreover, size limits will affect the three species of wobbegongs differently. Small *O. maculatus* and *O. halei* are rarely caught and *O. ornatus* is the only species caught in substantial numbers at a size smaller than 130 cm (Chapter 5). Results indicate that the maximum size of this species is approximately 110 cm. Therefore, the proposed size limit of 130 cm would completely prohibit landing from this species. Furthermore, this would only impact the fishery north of Sydney as *O. ornatus* distribution does not extent further south than Sydney (Chapter 5).

This research shows that wobbegongs not only interact with fishing gear from the hook and line fishery, but also interact with lobster pots. All wobbegongs caught in lobster pots were still alive and could easily be released with a high expectancy of survival. A zero bag limit for wobbegongs caught with pots would be an effective supplementary management regulation as survival is likely to be significantly higher than for wobbegongs caught using hook and line (Chapter 6).

9.5 Reproductive characteristics and growth parameters

Wobbegong reproductive biology is very slow with a triennial reproductive cycle (Chapter 7). Such low parturition frequency is not common in chondrichthyans with only a few species showing similar parturition frequency (Dudley *et al.* 2005; Walker 2005; Colonello *et al.* in press). However, litter size is relatively high with *ca.* 10 pups for *O. ornatus*, *ca.* 20 pups for *O. maculatus* and probably *ca.* 30–35 pups in *O. halei*, which might compensate for the low parturition frequency of wobbegongs. The importance of species-specific management is further illustrated by the difference in litter size and size-at-maturity between species. *Orectolobus halei* might be able to sustain heavier fishing pressure than *O. ornatus* because of the larger litter size in *O. halei*. Size-at-maturity is also different between species ranging from *ca.* 80 cm in *O. ornatus* to *ca.* 175 cm in *O. halei* (Chapter 7). Minimum size limits protecting immature *O.*

ornatus would therefore not be applicable to either *O. maculatus* or *O. halei* which mature at a much larger TL.

Spatial differences in reproductive behaviour is also observed in wobbegongs with no pregnant wobbegongs or mature females with large yolky follicles found around or south of Sydney (Chapter 7). Female wobbegongs may potentially migrate to warmer northern regions to enhance the rate of follicular and embryonic development, or they may be moving into areas where targeted fishing does not occur (e.g. estuaries or offshore locations). The location of females in such reproductive condition is unknown. The migrations and whereabouts of pregnant and mature females with large, yolky follicles around and south of Sydney could be determined using archive tags to obtain a more complete understanding of wobbegong reproductive biology. This spatial segregation based on reproductive stage can affect management regulations. The protection of pregnant females could be achieved by imposing a ban on wobbegong fishing anywhere north of Sydney while still allowing fishing to occur in and south of Sydney.

The slow parturition cycle of wobbegongs might be compensated by a rapid growth and an early onset of maturity. Two vertebral preparations (whole vertebrae and thin sections) and four different models were used to determine age and growth of wobbegongs in NSW. The calculated growth parameters varied according to vertebral preparation used and models applied to the observed lengths-at-age. Neither method of preparation could conclusively be described as being the most accurate. Size-at-maturity and growth parameters were affected by the vertebral preparation. Differences of size-at-maturity and growth parameters estimates can have important impacts on stock assessments and fishery models (Hoenig and Gruber 1990; Hoff and Musick 1990; Officer *et al.* 1996; Musick 1999). These parameters are necessary to undertake stock

assessments and demographic analyses. It is therefore crucial to determine which vertebral preparation provides the most accurate growth band counts to create fisheries models that correctly assess stock variation and resilience to fishing pressure. A comparison of the distance from the centra to each growth band between whole vertebrae and thin sections along with chemical marking of the vertebrae would enable to assess if underestimation or overestimation occurs.

Verification and validation of the periodicity of growth band deposition was attempted using marginal increment ratio, edge analysis, and growth rate and chemical marking of captive wobbegongs. No conclusion over growth band deposition could be determined. Electron microprobe analysis of calcium and phosphorus weight-fraction concentration or OTC injection of wild wobbegongs with recapture after a period of at least two years is likely to provide good information on the periodicity of band deposition. The latter is the most promising because wobbegong movements are limited and acoustically tagged individuals have been found within the same area for two years (Huveneers *et al.* in press; Chapter 4).

9.6 Conclusion

Stock assessment and demographic analysis needs to be undertaken using results from the present study along with information obtained from suggested future research to estimate wobbegong resilience to fishing pressure and recommend the most suitable management regulations to ensure sustainability of the wobbegong commercial fishery.

The data presented in this thesis provide guidance for future research, together with the taxonomic, distribution, relative abundance, residence time, morphometric relationships, dietary,

reproductive output, and age and growth information of wobbegong sharks in NSW. This critical ecological and biological information is required to recommend suitable management regulations, and warrant sustainable fishing practice. These are necessary to ensure that wobbegongs are resilient to fishing pressure and to adhere to the principles of ecological sustainable development highlighted in the objectives of the National Plan of Action for the Conservation and Management of Sharks in Australian waters (Shark Advisory Group and Lack, 2004).

ANNEXE

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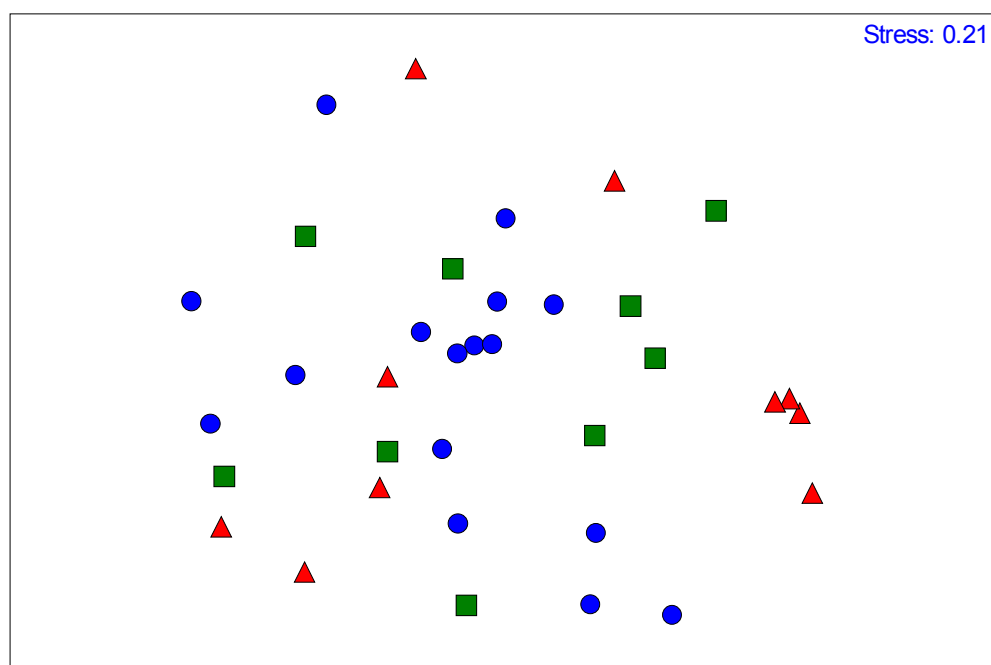
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APPENDIX A



MDS plot of wobbegong diet by species

Non-metric multidimensional scaling of the mean gravimetric percentage dietary data for (●) *O. ornatus*, (▲) *O. maculatus* and (■) *O. halei*; each point represents mean data for groups of four or three that were randomly selected within each species.

APPENDIX B

HUVENEERS, C. (2006). REDESCRIPTION OF TWO SPECIES OF WOBEGONGS
(CHONDRICHTHYES: ORECTOLOBIDAE) WITH ELEVATION OF *ORECTOLOBUS HALEI* WHITLEY
1940 TO SPECIES LEVEL *ZOOTAXA* **1284**, 29–51.