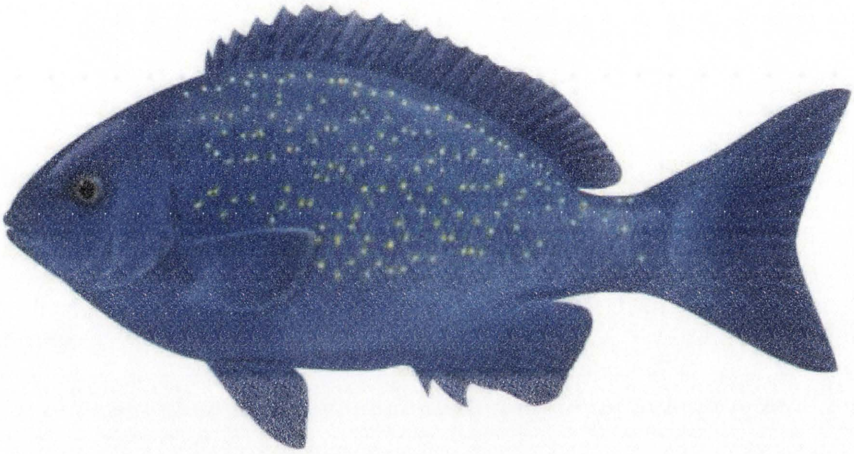
The Life History and Ecology of Bluefish, *Girella cyanea*, at Lord Howe Island



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April 2012

Thesis submitted in fulfilment of the requirements for
the Degree of Master of Science (Research)

UNIVERSITY OF
TECHNOLOGY SYDNEY

Picture source: NSW Department of Primary Industries

Certificate of Authorship & Originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that this thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in this thesis.

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Thesis Abstract

Girella cyanea is a conspicuous member of the reef-fish community in the Lord Howe Island Marine Park (LHIMP), but very little is known about its life history. Rareness of this species on mainland Australian coasts in recent years has initiated a fishing ban across the state of New South Wales, however recreational fishing is still permitted on LHI. Effective management and conservation of this population requires increased information on life history and demographics. Management currently in place for this species is limited. A bag limit of 5 fish person^{-1} day^{-1} is imposed in habitat protection zones across the Marine Park. It is difficult to measure the effectiveness of this strategy, however, without the knowledge of the resource requirements of the species and how these may change throughout the course of life. This study aimed to describe distribution, diet and growth in *G. cyanea* to provide important information for best-practice management of the LHI population.

An extensive literature search was conducted for published life history, ecology and management data on Girellidae, revealing relatively scarce information for the family. A pilot study assessed the utility of a roaming survey method towing a GPS-receiver behind an observer on snorkel/SCUBA. This new method proved effective and was used for size-based assessments of habitat-use at nearshore and offshore locations around the LHI archipelago. Densities of *G. cyanea* were highest in complex rocky intertidal and rocky-reef areas. Dietary analyses helped explain this distribution, with gut contents showing intertidal green algal species (i.e. *Ulva* and *Enteromorpha*) are important food resources for post-settlement fish.

An ontogenetic dietary shift was found, with fish < 40 mm standard length (L_S) found in intertidal habitat having a mainly carnivorous diet and a digestive system without pyloric caeca. In contrast, pyloric caeca were well-developed in fish > 40 mm L_S and diets exhibited increased ingestion of algae.

Age-at-size using otoliths and von Bertalanffy parameters revealed *G. cyanea* is fast-growing and long-lived (up to 41 yrs). It is likely the transition to sexual maturity occurs between 2 and 5 years of age or 200 mm L_S. Size-based observations place fish of this life stage within complex rock habitats at depths < 5 m. Future management policies should ensure adequate (representative) areas of rocky intertidal habitat are within sanctuary zoning to protect *G. cyanea* at this important life stage.

Acknowledgements

My supervisor **Professor David Booth** and co-supervisor **Dr Alan Jordan** gave me the freedom to develop my project in a remote place that I was determined to visit. Thank you for the pep talks when the journey seemed endless and for comments that significantly improved this thesis. Further leadership came from Dr **Will Figuiera** and Dr **Belinda Curley** who deserve a special mention for putting up with my rants and encouraging me onwards and upwards over the years.

To my husband, **Mark Lewis** – you kept the light at the end of the long, dark tunnel always shining bright. Your attempts to teach me a thing or two about project management didn't go unnoticed, even though they must have felt like it at the time! I love you ♥

On two special occasions I was treated to field assistants that are both valued friends and respected colleagues, Dr **Paul York** and **Stephen Summerhayes**. You facilitated some great fieldwork moments, including dancing to ABBA and all the other daggy tunes at the "Bowlo". I hope I helped you experience paradise through the eyes of a bluey ☺

Kerryn Parkinson was always a stable sounding board and a constant source of encouragement, both as a mother and a scientist.

My "Study Buddy", **Cybele Shorter**: a confidante and counsellor that helped me stay productive or get productive more than a couple of times throughout the journey. Thank you, thank you, thank you – I wouldn't have reached the end without you: the sandwiches, the tea breaks, the chocolate. We did it!!!! Undies 'n all!

Dr Matthew Lockett, for adult otolith work and keeping a pregnant lady happy - if you could do it and stay (semi) sane, so could I! ☺ And a special thank you for the time you were allowed to give me during your work hours, as well as the otolith processing equipment of the **NSW DPI Fisheries Research Centre** at Cronulla.

Ashley Fowler helped me get excited about the incy wincy teeny tiniest of fish ear bones and grinding my fingertips down to a painful level. You rock! And thank you also for commandeering the facilities at the **UNSW School of Biological, Earth and Environmental Sciences** laboratories.

Valeriya Komyakova – your volunteer work in the lab was a big help, and you distracted me only at the most appropriate of times ☺

My brother, **Ben Crowther**, who allowed me to convert his Man Cave into my Writer's Retreat. This was more important than you know and, though brief as it was, I really loved the time we spent without the cavalry!

To the LHIMP staff, past and present: **Geoff Kelly**, **Ian Kerr,** and **Sallyann Gudge** . I sincerely thank you for all of your support, feedback, encouragement, and patience.

Thank you to both **Scott Wilson** and **James Thompson** for helping me to find the blueys, for island education, and for trying to teach a fish conservationist how to fish!

Harry, after coming nine weeks early (presumably because he could bare the smell of fish guts no longer), finally learnt to sleep so I could make a come-back. Enjoying your days at school made dropping you off each day so much easier than it could have been. I hope you will be proud of what you helped your mummy achieve.

To my mum who stayed up way past her bedtime to read a lengthy document and saw all the things I could no longer see, and who cheered me on... and on... and on. Thanks **Mum** xox

My BFF **Jemma**, a chic corporate gal that is great at pretending she really is interested in what I do – thanks for accepting me anyway.

Many of my **friends and family** have been accommodating of the times when I have been Absent Without Leave or Missing in Action. For this, and your support in light of this, I thank you. I promise I'll be in touch real soon ☺

This thesis is dedicated foremost to **Uncle Brian**, who had all the makings of a scientist: curiosity, scepticism, eccentricity, and a relentless passion for intellectual improvement. I just wish you got to read it.

I must include **Baby Baxter**, an unexpected tragedy but the blessing you brought me is bigger than anyone knows. You changed my life and gave me a renewed passion for my passions. I hope I make your star shine brighter.

And of course, I wouldn't be me if I did not acknowledge the ultimate sacrifice of the many **bluefish** described in this research. I hope my findings serve them as I intended: in best practice management.

So what did I learn from this process? In the words of American writer Poul Anderson:

"I am yet to see any problem, however complicated,
which when you look at it the right way
did not become still more complicated."

Permissions, Permits and Funding

This study involved a species protected in part of its distributional range, and was conducted within a State and Commonwealth Marine Park listed as a UNESCO World Heritage Site. The study forms part of the Marine Parks Authority (MPA) 2006-2012 Research Work Plan, and was approved and supported by the Lord Howe Island Board.

The following permits apply:

- RNSH & UTS Animal Care & Ethics Committee (ACEC) approval RNS/UTS 0610-038A
- NSW Department of Primary Industries (DPI) scientific collections permit P05/0130-02

Funding support was gratefully received from a number of sources:

- Research Grant - NSW Department of Environment and Climate Change (DECC)
- Grant Award - Project AWARE Foundation
- UTS Department of Environmental Sciences student allocation

Additional in-kind support was provided by the Lord Howe Island MPA

Conference attendance was partially financed by UTS:

- Vice-Chancellor Award
- Faculty of Science Post-graduate International Conference Allocation

Further dissemination of the results was achieved through a scholarship from the University of the Sea aboard the *RV Marion Dufresne*.

Table of Contents

Title Page i

Certificate of Authorship & Originality ii

Thesis Abstract iii

Acknowledgements iv

Permissions, Permits and Funding vi

List of Tables xi

List of Figures xii

Abbreviations xiv

CHAPTER 1 - GENERAL INTRODUCTION 1

1.1 Studying the ecology and life history of fishes 1

1.2 Life history and ecology of the bluefish, *Girella cyanea*, Macleay 1881 2

1.3 Project aims 3

1.4 *Girella cyanea* at Lord Howe Island 4

1.5 Thesis structure 11

(1) What resources do G. cyanea require/use? 12

(2) What life history traits do G. cyanea exhibit? 12

(3) Do the life history and demographic attributes of G. cyanea display ontogenetic change? 13

CHAPTER 2 - LITERATURE REVIEW 14

2.1 Reviewing what we know about the Family Girellidae 14

2.2 Taxonomy 15

2.3 Geographic range 15

Figure 2.1 Worldwide antitropical distribution of Girellidae. Adapted from Yagishita & Nakabo (2003) 18

2.4 Habitat 19

2.5 Biology and behaviour 19

Diet 19

Reproduction 22

Age and growth 22

2.6 Fisheries and populations 23

The Americas 23

Australasia 24

Japanese archipelago 25

2.7 Bibliography (Ch. 2 only) 26

CHAPTER 3 - METHOD DEVELOPMENT 34

3.1 Preface 34

Preliminary Study A: Optimisation of underwater visual survey methods for patchily distributed fish *35*

3.2 Introduction 35

3.3 Materials and Methods 36

3.5 Discussion 39

Preliminary Study B: Determining the accuracy and precision of underwater estimates of fish lengths *47*

3.6 Introduction 47

3.7 Materials and Methods 48

3.8 Results 49

3.9 Discussion 49

CHAPTER 4 - PUTTING BLUEFISH (GIRELLIDAE: *GIRELLA CYANEA*) ON THE MAP: PATTERNS OF ABUNDANCE AND POPULATION SIZE STRUCTURE USING THE ROAMING TRANSECT SURVEY METHOD 53

4.1 Introduction 54

4.2 Materials and methods 54

Study site *54*

Nearshore sampling *55*

Offshore sampling *57*

Data analyses *57*

4.3 Results 59

Habitat partitioning *59*

Depth stratification *63*

Environmental factors *63*

LHIMP zones *63*

4.4 Discussion 67

Distribution of juveniles to adults, from complex intertidal to rocky-reef *67*

CHAPTER 5 - HERBIVORY, PSEUDO-HERBIVORY OR OMNIVORY? THE HIGHLY VARIABLE DIET OF THE BLUEFISH (GIRELLIDAE: *GIRELLA CYANEA*) AT LORD HOWE ISLAND 70

5.1 Introduction 71

5.2 Materials and methods 72

Sample collections *72*

Fish dissection and measurements *73*

Dietary examination *75*

Diet composition and data analyses *76*

5.3 Results 77

Length-weight relationship and morphology 77
Diet composition 78
5.4 Discussion 88
Intertidal algal spp. are an important dietary component for G. cyanea 88
An ontogentic dietary shift occurs in G. cyanea at < 40 mm L_S 91
Omnivory across adult sizes makes G. cyanea a pseudo-herbivore 93
Conclusion 95

CHAPTER 6 - LONG LIVE THE BLUEFISH: SIZE-AT-AGE, GROWTH AND LONGEVITY OF *GIRELLA CYANEA* (GIRELLIDAE) AND INFORMATION FOR THE MANAGEMENT OF THE RECREATIONAL FISHERY AT LORD HOWE ISLAND MARINE PARK **96**

6.1 Introduction 97
6.2 Materials and Methods 100
Samples 100
Otolith preparation 100
Age determination 102
Growth and development 102
Growth and mortality approximations 102
Data analyses 104
6.3 Results 105
Otolith and somatic growth morphometry 105
Life history traits and mortality 108
6.4 Discussion 112
Otoliths as a utility for ageing G. cyanea 112
G. cyanea are long-lived with determinate growth 114
Sexual maturity occurs between 2 and 5 years of age 115
Mortality and harvest of G. cyanea 116
Conclusion 118

CHAPTER 7 – FINAL DISCUSSION **120**

A life history model for Girella cyanea 120
(1) What resources do G. cyanea require/use? 123
(2) What life history traits do G. cyanea exhibit? 123
(3) Do the life history and demographic attributes of G. cyanea display ontogenetic change? 124
Research needed for conservation and management 124
Major conclusions 126

REFERENCES **128**

APPENDICES **151**

Appendix 1: Archived collections of G. cyanea 151

Appendix 2: Dissemination of research results 152

List of Tables

Table 2.1 List of current species recognised in *Girella*. 16

Table 2.2 Diets of adult *Girella* and *Kyphosus* species. Adapted from Clements & Choat (1997) 21

Table 3.1 Defining characteristics of habitat categories used in RTS at North Bay, LHI. 38

Table 3.2 Dependent samples *t*-test of density (number of fish calculated 100m^{-2}) and abundance (number of fish counted per 3min RTS) in each habitat where fish were observed 42

Table 4.1 Description of habitats assessed for *G. cyanea* distributions at locations nearshore on the main island of LHI (RK, AZ, CD, DR, SA, SG), and at offshore islets and dive sites (DI). 58

Table 4.2 Details of total sampling effort and *G. cyanea* abundance across habitat categories surveyed at locations across the LHI archipelago.. 60

Table 5.1 Food items in the diet of sampled *G. cyanea* 82

Table 5.2 Degree of dietary specialization within size classes. 85

Table 5.3 Discriminatory food items contributing to dissimilarity in pairwise comparisons of size classes ... 86

Table 6.1 Mean age of size classes. 107

Table 6.2 Growth parameters derived from the von Bertalanffy growth model and population characeteristics 110

List of Figures

Figure 1.1 Map of the global distribution of *G. cyanea* 5

Figure 1.2 The Lord Howe Island archipelago 6

Figure 1.3 Location of Lord Howe Island within the south-west Pacific Ocean, and expanded to show the LHI archipelago 7

Figure 1.4 Oceanic currents of the south-west Pacific Ocean. From: Schiel et al. (1986). 9

Figure 2.1 Worldwide antitropical distribution of Girellidae. Adapted from Yagishita & Nakabo (2003) 18

Figure 3.1 Schematic of the roaming transect survey (RTS) technique showing swathe dimensions and field of view of the observer. 37

Figure 3.2 Distance covered during a three-minute RTS per habitat at North Bay, LHI 40

Figure 3.3 Distance (*d*) versus Speed (*s*) of each RTS conducted over a three minute interval 41

Figure 3.4 Density (number of fish calculated per 100m^2) and abundance (number of fish counted per three minute RTS) for each habitat that *G. cyanea* were observed 43

Figure 3.5 A: Accuracy of model fish size estimations in the field. B: Size class categories used to assign fish length estimates ad hoc. 50

Figure 3.6 Precision of model size estimations in the field 51

Figure 4.1 Sampling locations within the LHI archipelago 56

Figure 4.2 Mean densities (± S.E.M) of *G. cyanea* in nearshore habitats, recorded from RTS swims pooled across locations 62

Figure 4.4 Depth distributions of *G. cyanea* 64

Figure 4.5 Occurrence of four environmental factors associated with *G. cyanea* sightings. 65

FIGURE 4.6 SEGREGATION OF RTS-OBSERVED *G. CYANEA* ACROSS LHI MARINE PARK ZONES....................................... 66

FIGURE 5.1 SAMPLING LOCATIONS OF *G. CYANEA* AT LORD HOWE ISLAND 74

FIGURE 5.2 THE RELATIONSHIP OF LENGTH AND WEIGHT IN *G. CYANEA* 79

FIGURE 5.3 SCHEMATIC DRAWINGS OF THE DIGESTIVE TRACT OF *G. CYANEA* 80
FIGURE 5.4 THE RELATIONSHIP BETWEEN THE LENGTH OF DIGESTIVE TRACT AND TWO MEASURES OF BODY SIZE 81

FIGURE 5.5 VOLUME OF MAJOR FOOD GROUPS IN DIGESTIVE TRACT AND RELATIVE GUT LENGTH PER SIZE CLASS................. 87

FIGURE 5.6 GUT LENGTH STANDARDISED FOR BODY MASS, EXPRESSED AS ZIHLER'S INDEX (ZI). 89

FIGURE 5.7 SEASONAL FREQUENCY OF THE MOST COMMON DIETARY ITEMS IN PLANT (*ULVA* SPP.) AND ANIMAL (*EUPHAUSID* SP.) CATEGORIES FOUND IN GUT CONTENTS. TOTAL ANIMAL TISSUE IS ALSO DISPLAYED.. 90

FIGURE 6.1 TRANSVERSELY SECTIONED SAGITTAL OTOLITH OF A FOUR YEAR OLD *G. CYANEA*, SHOWING A DENSE CENTRAL OPAQUE REGION (F) AND A SUBSEQUENT ALTERNATING SEQUENCE OF OPAQUE AND TRANSLUCENT BANDING. 101

FIGURE 6.2 LINEAR GROWTH OF OTOLITHS IN RELATION TO OPAQUE BANDS (PRESUMED AGE IN YRS) IN *GIRELLA CYANEA* . 106

FIGURE 6.3 TEMPORAL PATTERNS OF REPRODUCTIVE DEVELOPMENT ACROSS SIZE CLASSES (A), AGES (B) AND MONTHS (C). 110

FIGURE 7.1 DIAGRAMMATIC REPRESENTATION OF HORIZONTAL (HABITAT) AND VERTICAL (DEPTH) PARTITIONING IN *G. CYANEA* THROUGH ONTOGENY 122

Abbreviations

ANOVA	Analysis of Variance
DPI	Department of Primary Industries
EAC	East Australian Current
EAUC	East Auckland Current
GLM	General Linear Model
HPZ	Habitat Protection Zone (some fishing permitted, see p. 10)
LHI	Lord Howe Island
LHIMP	Lord Howe Island Marine Park
L_T	Fish total body length (rostrum to caudal fin tip)
L_F	Fish body length (rostrum to fork)
L_S	Fish standard body length (rostrum to last vertebrae)
MHWM	Mean high water mark
MLL	Minimum Legal Length
MPA	Marine Park Authority
NSW	New South Wales
QLD	Queensland
RTS	Roaming Transect Survey
SZ	Sanctuary Zone (no-take reserve)
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UTS	University of Technology, Sydney
UVC	Underwater Visual Census
VBGM	von Bertalannfy Growth Model

Chapter 1 - General Introduction

1.1 Studying the ecology and life history of fishes

Ecology is the study of an organism and its surrounding environment, including all the abiotic and biotic influences it is subjected to. These may or may not change as the organism progresses through the course of its life or "ontogeny" (e.g. Werner & Gilliam 1984, Mittlebach 1986, Olson 1996, Muñoz & Ojeda 1998). Life history is a term that encompasses the biological traits of an organism throughout its lifetime, namely: early metamorphosis, feeding, growth and development, ageing, and longevity. Many fishes display ontogenetic changes in these traits that are important for understanding guild structure and resource use (see Werner & Gilliam 1984 for a review). Length and age-based information has been identified as a central parameter in the assessment of exploited populations and of potential management strategies (Ricker 1975, Megrey 1989, Campana 2001). Unfortunately, knowledge of basic life history is lacking for many species and even families (Pogonoski et al. 2002).

The fundamentally important questions for fish ecologists are no different to those asked by terrestrial researchers, notably: *why are species found where they are; are communities structured by food limitation, competition, and habitat availability; what mechanisms contribute to historical and present distributions* (Krebs 1978)? Although we tend to look at these factors in light of the complex interactions involved, and hence on a "bigger picture" basis, the importance of species-specific information of phylogeny and biological attributes cannot be overlooked for conservation of populations.

Our understanding of fish life history was historically assumed to encompass the traits observed from small-bodied species that were important contributors to commercial harvests (e.g. anchovies, sardines, and herring). Such species were often from pelagic, cold temperate marine habitats and were believed to exhibit fast growth, early maturation and short life spans (i.e. highly productive populations) and hence supposedly indestructible stocks. Extrapolation of these characteristics to fisheries models and harvest strategies lead to ineffective management of deeper-water species that were later found to possess much longer life spans and exhibit slower growth than once thought (Caillelier et al. 2001, Munk 2001, Berkeley et al. 2004) Over time, we have learnt that life histories in fish are as diverse as the taxa themselves. Techniques used to age fishes in the past (e.g. using scales) have been shown to greatly underestimate age and therefore maturation and longevity growth parameters (Beamish & McFarlane 1983, Campana 2001, Berkeley et al. 2004). It is now clear that fish assemblages in all habitats, tropical and temperate, harbour a great deal of ecological diversity that includes a range of life spans, growth rates and size structures. More recent work has shifted our attention to species that occur in lower latitudes where it has been recognised that large bodied, long lived herbivores contribute significantly to large scale ecosystem functioning. Their important role in grazing benthic marine macrophytic algae has been shown to be of vital importance in the settlement and subsequent colonisation of corals in tropical ecosystems (Hixon & Brostoff 1996).

1.2 Life history and ecology of the bluefish, *Girella cyanea*, Macleay 1881

Girella cyanea (a.k.a. bluefish or blue drummer) is a member of the persiformes Girellidae family of marine fishes that are thought to be mainly herbivorous inhabitants of temperate and subtropical rocky reef in parts of Australia, New Zealand, Japan and southern America (see Chapter 2 for review). Relatively little is known of their ecology and life history (Kingsford 2002).

Pogonoski et al. (2002) were first to raise concerns that *G. cyanea* may have been overfished on mainland Australia, suggesting that the insufficient information available to determine the conservation status should therefore warrant a Near-Threatened listing by the Australian Fish Species Board (AFSB). Until then, *G. cyanea* had received very little attention and descriptions of the species were often surmised from other species' descriptions or used anecdotally from fishing guides (i.e. Roughley 1916, Doak 1978, Ayling & Cox 1982, Francis 1988 & 1996, Kuiter 2000, Francis 2001). Of the few quantitative studies including *G. cyanea*, dietary requirements for the species were suggested from samples of six and thirteen individuals (Clements & Choat 1997, Clements & Zemke-White 2008, respectively) and preliminary estimates of age and growth were obtained from 95 discarded fish frames (Ferrell 2005). Hence, our limited knowledge of life history in bluefish has been based upon extremely small sample sizes and opportunistic research.

Whether *G. cyanea* are naturally rare or have become rare from over-fishing and/or other environmental pressures is unclear. Information on the habitat requirements, environmental tolerances, population dynamics and other aspects of the life history and ecology of *G. cyanea* has been recognised as a high priority by the New South Wales (NSW) Fisheries Scientific Comittee (FSC). This committee operates under Part 7A of the *Fisheries Management Act 1994* as an independent scientific body, and is responsible for the listing of threatened species and preparation of their 'Priority Action Statement and Recovery Plans' for the NSW Department of Primary Industries (DPI). Although the FSC acknowledges an absence of important scientific data on distribution, abundance, habitat and ecology of *G. cyanea,* no recovery plan has ever been drafted.

The present study began at the commencement of a temporary fishing closure on *G. cyanea*. It is now fully protected from all methods of fishing within NSW state waters, excluding Lord Howe Island - where it may be fished recreationally to a bag limit of 5 per person per day (DPI 2006). Additionally, at the time of writing, *G. cyanea* is under review for a recreational boat limit (S. Gudge pers. comm.). Such management measures may be interpreted as further concern for the ongoing exploitability and sustainability of the species.

1.3 Project aims

This project is organised around building a framework for the sustainable management of *G. cyanea*. In light of the paucity of information on the species, the present study investigated the life history and ecology of *G. cyanea* through an integrative analysis of abundance and distribution (Chapters 3 and 4), feeding ecology (Chapter 5), and age and growth of the species (Chapter 6) in the strongest part of its biogeographic range, Lord Howe Island (Chapter 1). Such baseline data provides information required for best practice management of the species in all parts of its range (Chapter 7) and contributes to our knowledge of girellids worldwide (Chapter 2 and 7). Three major questions concerning their life history and ecology were particularly important to answer: (1) What resources do *G. cyanea* require/use? (2) What life history traits do they exhibit? and (3) Do such attributes display ontogenetic change?

1.4 *Girella cyanea* at Lord Howe Island

In 1916, a leading Australian ichthyologist TC Roughley published a book known as much for its observations of fish, as it was for its exquisitely coloured plates. Fortuitously, this body of work forms many of the first population records of fishes found in waters in and around Sydney Harbour. Roughley (1916) reported that *Girella cyanea* were "rarely seen in the Sydney fish markets" and thus concluded that they did not occur in any abundance on the NSW coast. Collections by the Australian Museum, anglers and spearfishers (Appendix I.) indicate that *G. cyanea*, at least at certain times, have occupied areas from Flinders reef in QLD to Eden in southern NSW. Several studies have included observations of *G. cyanea* when conducting underwater surveys in the Kermadecs (Schiel 1986, Cole et al. 1992), Poor Knights (Meekan & Choat 1997, Brook 2002, Denny et al. 2003), Norfolk Island (Francis 1993) and Lord Howe Island (Oxley et al. 2004, Aquenal 2010). Figure 1.1 shows a distributional map marking the localities of these areas. Densities of *G. cyanea* have been considered relatively low in New Zealand (Meekan & Choat 1997, Denny et al. 2003, K. Clements pers. comm.) and mainland Australia (DPI 2006), and some locations have had no reports - anecdotally or otherwise - for some time (e.g. Norfolk Island; S. Adams pers. comm.).

On Lord Howe Island (LHI), *G. cyanea* are considered to occur in numbers reasonable enough to maintain a recreational fishery. Because they are no longer harvested elsewhere in NSW, assessment of the LHI population is important (Ferrell 2005).

The oceanic archipelago of the Lord Howe Island Group (Fig. 1.2) is located approximately 600 km off eastern Australia at 31°33'S, 159°05'E. The main island (LHI) is inhabited by approximately 350 residents and covers some 11 km in length and 3km in width, with a shallow coral-fringed lagoon on its western coast (Fig. 1.3). The pinnacle of Ball's Pyramid lies approximately 23 km to LHI's south-east, separated by an oceanic trough averaging 600 m deep (EA 2002). LHI and Ball's Pyramid, together with Middleton and Elizabeth Reef (approx.150 km north), form part of a chain of nine

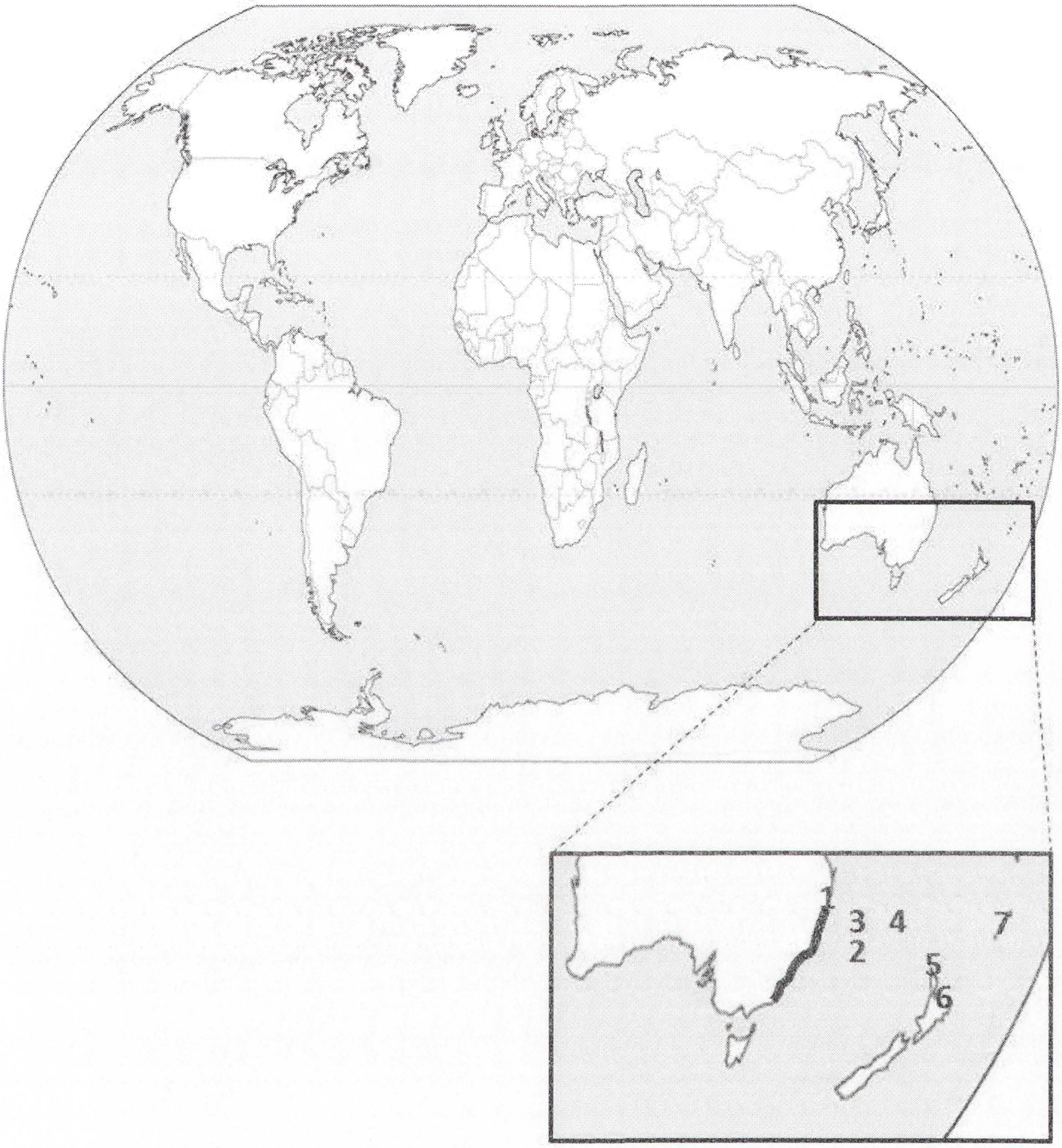

Figure 1.1 Map of the global distribution of *G. cyanea*; insert is the Tasman Sea. Occurrences denoted as 1(plus line). SE Queensland to Eden; 2. Lord Howe Island; 3. Middleton and Elizabeth reefs; 4. Norfolk Island; 5. Three Kings Islands; 6. Poor Knights Islands; 7. Kermadec Islands. Data are sourced from Schiel 1986, Cole et al. 1992, Meekan & Choat 1997, Brook 2002, Denny et al. 2003, Francis 1993, Oxley et al. 2004, Aquenal 2010, and Appendix 1.

Figure 1.2 The Lord Howe Island archipelago. View is looking south. Note Ball's Pyramid in the distance. Photograph used with permission from the LHI Marine Parks Authority.

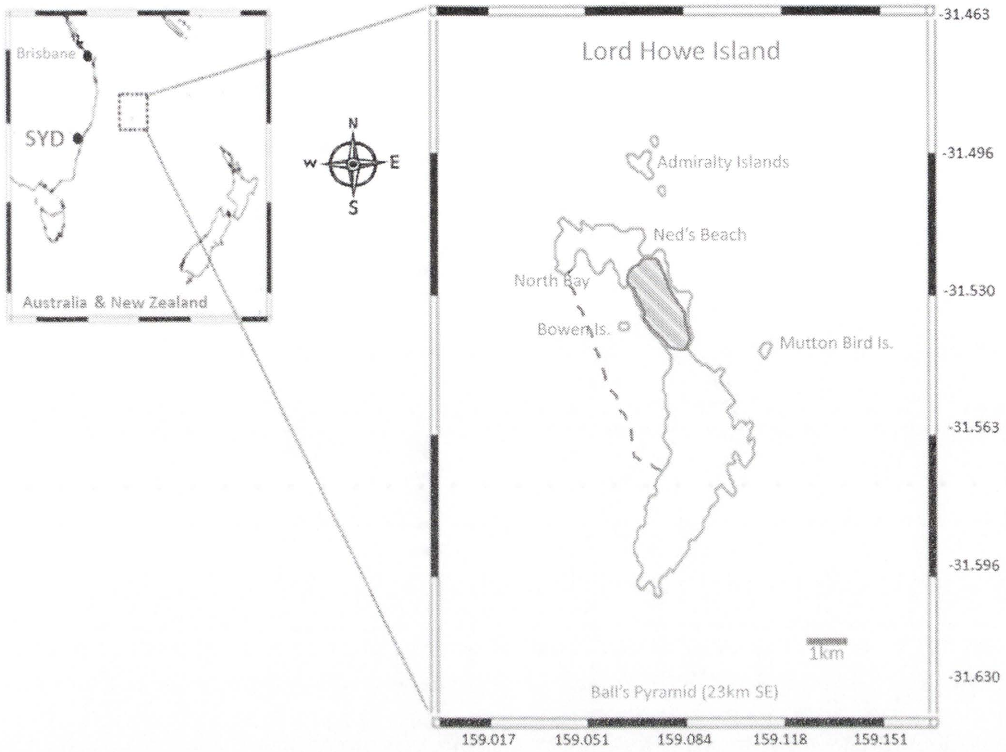

Figure 1.3 Location of Lord Howe Island within the south-west Pacific Ocean, and expanded to show the LHI archipelago. Dashed line represents the fringing reef, delineating the shallow lagoon. Shaded area denotes the settlement area.

seamounts extending over 1000 km along the Lord Howe Rise (Sutherland & Ritchie 1977). The formation of this seamount system is akin to the Hawaiian chain of shield volcanoes (Hill et al. 2000).

LHI harbours a unique combination of tropical and temperate marine flora and fauna due to its location at the convergence of tropical (Coral Sea) and temperate (Tasman Sea) water masses of the 'Tasman Front'. The seasonal north-south movements of the Tasman Front (Nilsson & Cresswell 1981) facilitate an oceanic transition zone between temperate and tropical biomes (Kennedy et al. 2002), with water temperatures ranging from 17°C in winter to 25°C in summer (Hutton 1986). Often described as subtropical, LHI is also influenced by the warmer waters of the East Australian Current (EAC): a western boundary current alongside mainland Australia, from a latitude of 22°S to as far as 38°S (Church & Craig 1998). The extreme latitude of this warm water separating from the eastern Australian coast as eddies (Bowen et al. 2005) allows LHI to be the southernmost true coral reef in the world (Allen et al. 1976). Moreover, there is strong evidence for the role of the EAC in the transport and expatriation of fish larvae (see Booth et al. 2007). The eddies eventually run into the same trajectories modelled for the East Auckland Current (EAUC[1]; Fig. 1.4) and help explain the supply of subtropical and warm temperate species, including *G. cyanea,* around north-eastern New Zealand (Clements & Zemke-White 2008) and the Kermadec Islands (Cole 2001).

The shelf area surrounding the seamounts of LHI extends to approximately 3-6 nmi offshore reaching depths up to 200 m. It then drops off steeply to over 2000 m, forming a major discontinuity between the shallow shelf and deep sea environments (Anon. 2002). The deep slopes created by the steep drop-off maximises LHI's exposure to ocean currents from all directions (Smith et al. 1989, Pichon 1995). The perturbations (i.e. eddies, tides, trapped waves, and freely propagating internal waves) generated around seamounts contribute to enhanced productivity and biodiversity: important factors in the formation of a 'hotspot' (Roberts et al. 2002 *sensu* Myers 1988).

The western side of LHI, flanked by a fringing coral reef, forms a shallow sheltered lagoon (Dickson & Woodroffe 2005). Water exchange within the lagoon occurs at four

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[1] To avoid confusion, we refer to these currents using the acronyms EAC and EAUC respectively, as both may be referred to in the literatre as the 'EAC'.

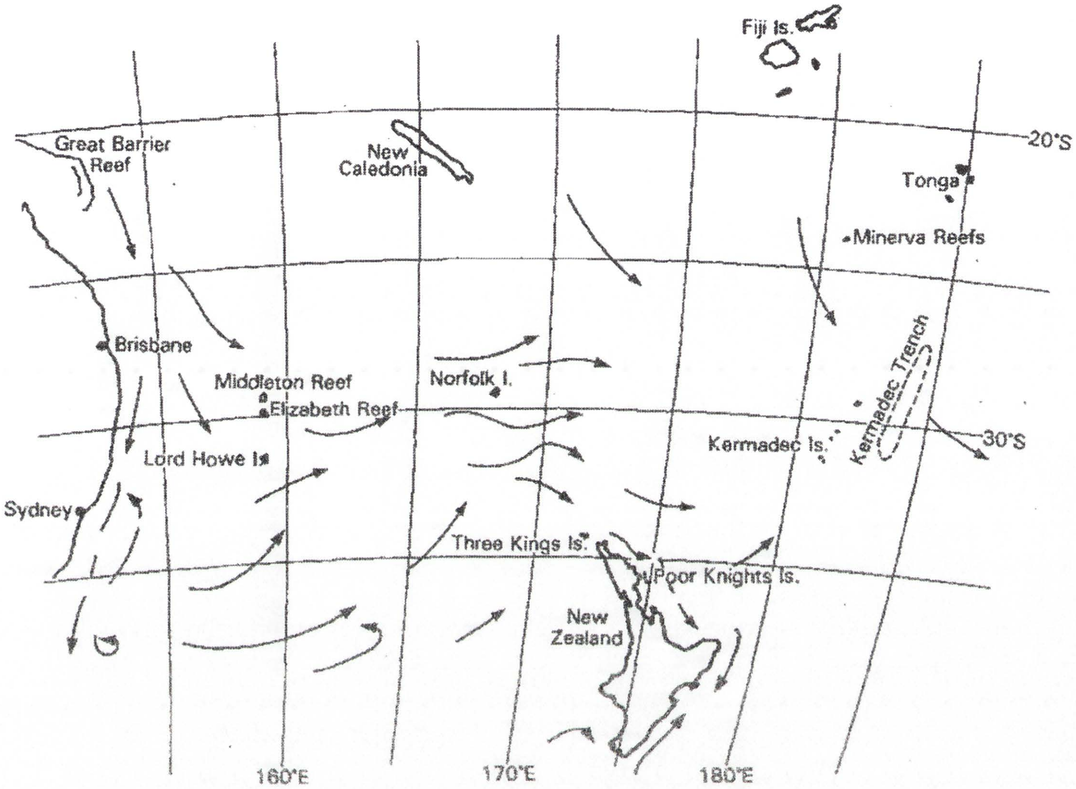

Figure 1.4 Oceanic currents of the south-west Pacific Ocean. Arrows indicate trajectories. Note the location of Lord Howe Island. From: Schiel et al. (1986).

deeper water passages up to 6 m in depth (Allen et al. 1976), but how wave- and wind-driven circulation patterns affect larval dispersion into the lagoon is not yet known (MPA 2010).

The diversity of marine flora and fauna on LHI is remarkably high, with an associated high endemicity. Of the 305 known species of benthic algae, 15 % are considered endemic to the island (Millar & Kraft 1993, 1994a,b); and of the 433 recorded species of fish, approximately 4 % are endemic to the region (including Norfolk Island: 29°02'S, 167°57'E), 10 % are found only at LHI, southern Australia, and/or New Zealand, and 32 % are restricted to the south-western or southern Pacific Ocean (Allen et al. 1976). Additionally, many of the island's coral communities include populations of tropical species at the southern end of their distributional limits and subtropical species that are rare or absent on tropical reefs (Harriott et al. 1995), and some appear to be relicts of groups from the Mesozoic age (Richer de Forges et al. 2000). The rich and unusual biodiversity of LHI has been officially recognised for its importance on several levels:

1. Globally - with its inclusion on the UNESCO World Heritage List in 1982;
2. Locally - with the declaration of the LHI Marine Park (State Waters) in 1999;
3. Federally – with proclamation of the LHI Marine Park (Commonwealth Waters) in 2000.

Fishing is considered an important leisure activity and provides an important food source for the locals on LHI (EA 2002). Under the current zoning scheme, 73 % of the 46 000 ha of the state marine park is managed as Habitat Protection Zones (HPZs) that allow recreational and charter fishing but exclude spearfishing, trawling, long-lining, dredging and most traps and nets. Seven Sanctuary Zones (SZs) that prohibit all fishing and extraction of marine life comprise 27 % of the total marine park area. The additional 300 000 ha of Commonwealth Waters protect offshore areas from all long-lining and trawling activities. Fishing pressure on the island is considered low compared to mainland Australia (Aquenal 2010). Nearshore fishing activities have used mainly handline/rod and reel practises even prior to the multiple-use zoning scheme in 2004. Moreover, three locations (Comet's Hole and Erscott's Hole in the lagoon, and Ned's Beach on the NNE coast) have served as *defacto* sanctuary zones by local residents for over 40 years (Edgar et al. 2009). Nine charter vessels are permitted to sell

fished products locally, with all commercially caught fish consumed on the island (ie. no export). *G. cyanea*, once served in restaurants on the island, are now prohibited from commercial harvest (DPI 2006).
Tourism is considered a very important component of the island's inherent value and economy, thus controlled fish feeding occurs in two locations (Ned's Beach and North Bay), both of which are SZs. *G. cyanea* are conspicuous participants in the bread feeding frenzy at both locations.

The accepted date of LHI's discovery is 17th February 1788, when Lieutenant Henry Lidgbird Ball, Commander of the *Supply*, was en route to establish a penal colony at Norfolk Island. Prior to his party landing three weeks later, there appears to be no evidence of human settlement, indigenous or otherwise (Nichols 2006). Settlement was prompted five decades later, when LHI became a known port of call for American whaling ships (Nichols 2006). Despite the small human population (348 ppl; ABS 2008) human-induced disturbance on the marine habitat is evident. Cyanobacteria and filamentous algae on seagrass beds in some locations (Edgar et al. 2009) is most likely a reflection of elevated nutrient levels and/or decreased grazing of herbivores (McCook 1999, Szmant 2002, Fabricius et al. 2005). Similarly, Edgar et al. (2009) also note increased epiphytic growth in areas in close proximity to the settlement area (see Fig. 1.3), and suggest causes including seepage of nutrient-enriched groundwater, and waste-management inefficiency.

The small human population and relatively recent settlement, combined with the inherent marine conservation value of the archipelago, makes the LHI bluefish population particularly useful for the study of life history, biology and ecology of the species.

1.5 Thesis structure

Chapter 2 is the first detailed review of the Family Girellidae. The collation of taxonomic and ecological research provides a framework for the baseline data required to help fill in some of the knowledge gaps of the family. Chapter 3 details two pilot studies. The first, Part A, was designed to test the efficacy of the roaming transect method employed to assess the distribution and abundance of *G. cyanea*. The second, Part B, was a test of the accuracy and precision of the author's *in situ* identification of each individual fish and determined effective size classes for ontogenetic comparisons in the proceeding data chapters. Data from Chapters 4 to 6 answer questions important for management recommendations made in Chapter 7. Each chapter, however, stands alone and offers new information on each of the major topics discussed. The chapters are organised around the three major questions outlined in the project aims:

(1) What resources do *G. cyanea* require/use?

Chapter 4

Densities are visually assessed across depth-stratified habitats at nearshore and offshore locations. Associations between particular habitat and size class categories are determined. Other factors, such as nearby shelter and congenerics, are briefly investigated also.

Chapter 5

Specimens are collected from various fishing expeditions throughout the LHI archipelago. Feeding guild is evaluated using gut morphology combined with dietary analyses. Markers of an ontogenetic phase shift are investigated.

(2) What life history traits do *G. cyanea* exhibit?

Chapter 6

Otolithic microstructure is used to calculate annuli. Data is supplemented with that of Ferrell (2005) to increase sample sizes. Presumed age is combined with body length to estimate von Bertalanffy growth parameters and longevity for the population. Levels of mortality are approximated from key empirical equations. A limited temporal assessment of gonadosomatic indices aids in estimating spawning activity.

(3) Do the life history and demographic attributes of *G. cyanea* display ontogenetic change?

Chapter 7

Length and age based information from preceding chapters is brought together to develop a demographic model of *G. cyanea* that will aid in effective management strategies for the conservation of the Lord Howe Island population. Some suggestions are put forward regarding future management strategies and research directions.

Chapter 2 - Literature Review

2.1 Reviewing what we know about the Family Girellidae

Knowledge of the life history of girellids (Actinopterygii: Perciformes) remains scant and insufficient, and few data exist on their ecology (Kingsford 2002) and exploitation (Gray et al. 2010). This is surprising given their apparent importance to recreational angling (Kingsford et al. 1991, Stephens 2001, Anon. 2005, MPA 2010) and commercial harvest (Fitch & Lavenberg 1971, Gray et al. 2000, Scandol et al. 2008, Gray et al. 2010). Most research has concentrated on their placement within feeding guilds (e.g. Anderson 1986, Clements & Choat 1997, Davis 2000, Clements & Zemke-White 2008), owing mainly to their specialized dentition (Yagishita & Nakabo 2003) and alimentary morphology (Johnson & Fritzsche 1989, Kanda & Yamaoka 1994, 1997). Their frequent occurrence in tide pools along the Chilean and Australian coasts has also been noted (Davis 2000, Silberschneider & Booth 2001, Griffiths et al. 2004, Pulgar et al. 2006); and they have received some attention from studies of recruitment and post-settlement processes (Worthington et al. 1992, Trnski 2002, Smith & Sinerchia 2004).

This review provides, as far as we know, the first significant collation of girellid research (but see Curley et al. (in prep.) for detailed reviews of *G. tricuspidata* and *G. elevata* specifically). As is often the case in a review, ours brings together the hard to access articles of less mainstream publications with the main references for species that we base upon much of our current understanding of the genus. We located literature by searches of the ASFA Database, Google Scholar (www.google.com), and references in Fishbase (www.fishbase.org) using the search engine prefix "girell*" for all searches. Literature gathering was episodic over the period of June 2005 to January 2011 to account for institutional conversions of traditional paper-based articles to modern digital copies. Additional references were located within articles acquired during the previous searches. Where citations are used for more general purposes, care has been taken to include only articles that also contain information on *Girella* spp. The list of references at the conclusion of this chapter thus forms a comprehensive and useful bibliography for future girellid research.

2.2 Taxonomy

The systematic positioning of the closely related girellids, kyphosids, microcanthids, and scorpidids remains unsettled despite early recognition of distinct families (see Fowler 1933, Hubbs et al. 1979, Johnson 1984 *versus* Robins et al. 1980). Occasionally, articles will still unite species of the *Girella* and *Kyphosus* genera under the family name Kyphosidae (e.g. Pulgar et al. 1999, Watson et al. 2005, Itoi et al. 2007Tolentino-Palico et al. 2009). Fishbase also lists girellids as Kyphosidae. For the purpose of the current study, we follow the nomenclature of Johnson & Fritzsche (1989) allocating girellids their own family of Girellidae, and including two genera: *Girella* Gray, 1835 and *Graus* Philippi, 1887.

A limited availability of study material further adds to the confusion at family level as it has "prevented an adequate understanding of species' variability and subsequent taxonomic relationships" (Yagishita & Nakabo 2000). Sixteen species of *Girella* are currently listed in Fishbase (Table 2.1). Although meristic and morphological revisions have been undertaken (Norris & Prescott 1959, Orton 1989, Yagishita & Nakabo 2000), genetic data is limited (but see Orton et al. 1987, Terry et al. 2000, Yagashita & Nakabo 2003, Curley & Gillings 2006, Umino et al. 2009) often focussing on population connectivity rather than systematics. Further morphological and phylogenetic research coupled with quantified population studies may alter the girellid species list in the future.

2.3 Geographic range

The worldwide distribution of girellids appears anti-tropical in temperate and subtropical waters spanning the Indo-Pan Pacific and eastern Atlantic Ocean (Yagishita & Nekabo 2000). Up to six species are known to co-exist in approximately five regions

Table 2.1 List of current species recognised in *Girella*.

Scientific Name	Authority
G. albostriata	Steindachner, 1898
G. cyanea	Macleay, 1881
G. elevata	Macleay, 1881
G. fimbriata	(McCulloch, 1920)
G. freminvillii	(Valenciennes, 1846)
G. laevifrons	(Tschudi, 1846)
G. leonina	(Richardson, 1846)
G. mezina	Jordan and Starks, 1907
G. nebulosa	Kendall and Radcliffe, 1928
G. nigricans	(Ayres, 1860)
G. punctata	Gray, 1835
G. simplicidens-but see Terry et al 2000	Osburn and Nicols, 1916
G. tephraeops	(Richardson, 1846)
G. tricuspidata	(Quoy and Gaimard, 1824)
G. zebra	(Richardson, 1846)
G. zonata	Günther, 1859

Note: Compiled from species recognised on Fishbase (as Kyphosidae), accessed 2011.

(Fig 2.1). Distributions of individual species are often described from fishing guides or historical sightings both in the grey literature and peer-reviewed articles (e.g. Roughley 1916, Francis 1988: *G. cyanea*; Hutchins & Swainston 1986: *G. tricuspidata*; Kuiter 2000: *G. elevata).* Some descriptions of distribution appear pervasive and assumed, as suggested by the many publications that fail to give any authority when defining the geographical range. These articles are then often used as the citation for more recent works. This is a worrying trend, given that this mostly occurs under the context of population management, especially in Australia.

Data on the driving forces that shape global girellid distribution are scarce. Some species are considered numerically abundant with large effective population sizes in at least parts of their range (e.g. *G. laevifrons:* Varas & Ojeda 1990, *G. tricuspidata*: Curley 2007, *G. elevata:* Last et al. 2011), yet others are seen only on occasion (e.g. *G. fimbriata:* Francis 2001). Indeed, some descriptions of geographical range are based on identifications of vagrant individuals that may not be attached to breeding populations (e.g. *G. leonina* in Randall & Stender 2002). The extent to which this occurs is difficult to ascertain, given that several species are susceptible to translocation by oceanic currents and other phenomena, such as the southern oscillation index (see Francis 1996, Clements & Zemke-White 2008). Reports of established populations in regions bathed by two water masses of differing temperature (*G. nigricans*: Norris 1963, Terry et al. 2000, *G. fimbriata*: Francis 1996, *G. cyanea*: Edgar 2009, *G. elevata*: Last et al. 2011) may suggest that at least some girellids are particularly adapted for eurythermal conditions as adults, occupying the niche transition zone between cold and warm thermal regimes. Indeed, their resilience to the thermal extremes of tide pools is documented; several species appear to select tide pools highest on the shoreline, where large variabilities in environmental conditions exist (Thomson & Lehner 1976, Griffiths et al. 2003). Whether girellids have physiological or behavioural adaptations that allow them to tolerate these extremes is an important consideration eluding the literature (but see Norris 1963).

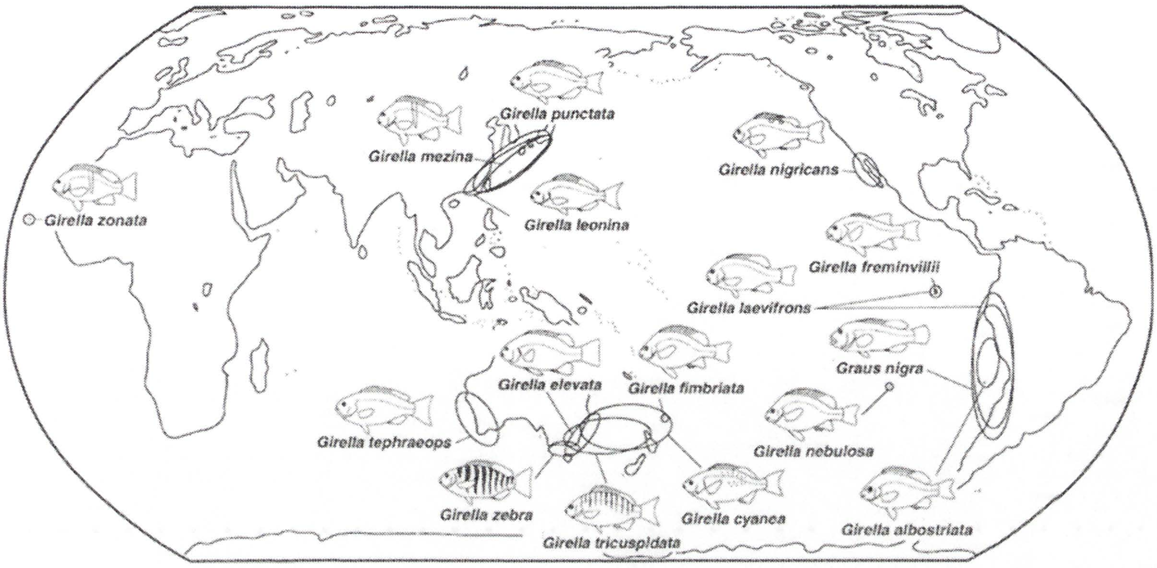

Figure 2.1 Worldwide antitropical distribution of Girellidae. Adapted from Yagishita & Nakabo (2003)

2.4 Habitat

The fishes of Girellidae are often referred to as rocky reef species, typically occupying the intertidal zone and nearshore areas up to 30 m (Thomson & Lehner 1976, Stevens et al. 1989, Yagishita & Nakabo 2000, Francis 2001). Complex environments offering shelter appear important, including kelp (Stevens et al. 1989), seagrass (Gray et al. 1996), boulders and caves (Willan et al. 1979, Hutchins & Swainston 1986, Kuiter 1996), coastal marinas (Clynick 2008), artificial reefs (Fowler in prep.), and drifting objects (Limbaugh 1955, Dempster & Kingsford 2004). However, girellids in subtropical areas (e.g. LHI, Kermadecs, Japan) appear not to utilise coral. Juveniles recruit to tide pools in many species (Stepien 1990, Muñoz & Ojeda 1998, Pulgar et al. 1999, Griffiths 2003 & 2004) where they stay until they are approximately 2yrs old (Norris 1963, Stevens et al. 1989). *G. tricuspidata* are known to make use of tide pools (Morrison 1990) as well as shallow estuarine habitats, such as mangroves (Davenport 1979) and seagrass (Hannan & Williams 1998, Smith & Sinerchia 2004) from which they migrate towards coastal areas at approximately 2 yrs old (~150-200 mm fork length (L_F): Morrison 1990).

Their known association with intertidal areas is likely the result of an adequate food supply, since many of the algal species found within their guts are known to inhabit intertidal zones (e.g. Davenport 1979, Clements & Choat 1997, Clements & Zemke-White 2008).

2.5 Biology and behaviour

Diet

Girellids were recognized for their alimentary tract specializations early into the era of fish nutritional research (e.g. Horn 1989; Johnson & Fritzsche 1989) and appear to have largely herbivourous diets. Anderson (1986) showed that, whilst *G. tricuspidata* had the circular muscles in the oesophagus and stomach consistent with herbivory, they exhibit other "ultrastructural features…similar to those described in carnivorous fish and appear to show no specialization for herbivory".

More recent work has given more weight to the often significant portions of animal material found within gut samples of various girellid species. Indeed, Clements & Choat (1997) found remarkable differences to help resolve the kyphosid /girellid phylogenetic dilemma (refer 1.1): kyphosids appear to benefit from microbial fermentation akin to that seen in ungulates and other terrestrial obligatory herbivores, but girellids lack this exogenous mode, complementing the readily-available energy of algae with protein from invertebrates. A review of the stomach content analyses of girellids and kyphosids help support this argument (Table 2.2). Moreover, Raubenheimer et al. (2005) postulate that *G. tricuspidata* has digestive physiology that is actually *specialized* for the processing of animal-derived proteins. Given the prominence of invertebrates and other animal components within the diets of other species (Clements & Choat 1997; Clements & Zemke-White 2008), it will be important to examine the validity of this hypothesis across all girellids. It is of particular interest that the other genus of family Girellidae, *Graus* (consisting of a single species, *Graus nigra)*, is commonly considered "strictly carnivorous", although there are limited citations used to verify this (e.g. Muñoz & Ojeda 1998). However, a full analysis of the dietary spectrum is still required, especially to consider the spatial and temporal variation often found in other girellids (e.g. Morrison 1990, Clements & Zemke-White 2008). *G. nigra*, however, do lack the apparent morphological adaptations of the other "herbivorous" girellids, namely increased relative gut length (Bell et al. 1980) and specialized tricuspid dentition (Yagishita & Nakabo 2000).
Research to date indicates that girellid young often consume prey across more trophic levels than adults, appearing omnivorous for the period before they leave nursery areas and move into the adjacent intertidal zones and/or migrate further to open coastline (Bell et al. 1980, Johnson & Fritzsche 1989, Kingsford 2002). In some species, an increased ingestion of macroalgae, and hence an increased trend towards herbivory, is accompanied by changes in dentition as well as somatic growth (Kanda & Yamaoka 1994; Yagishita & Nakabo 2000).

Interestingly, some girellids are known to be caught with animal material as bait (Kingsford 2002, and personal observations): an observation that has undoubtedly led to the reference of *G. cyanea* as a carnivore (Doak 1978, Ayling & Cox 1982), and further demonstrates the need for more quantified research into the family.

Table 2.2 Diets of adult *Girella* and *Kyphosus* species. Values are percentage composition expressed as volume. Adapted from Clements & Choat (1997)

Species	Main algal types	% algae	% animal	Source
Girella				
cyanea	Chlorophytes, rhodophytes	100	0	Clements & Choat (1997)
elevata	*Pterocladia, Ulva, Sargassum*	77	19.4	Bell et al. (1980)
	Phaeophytes, chlorophytes, rhodophytes	99.3	0.7	Clements & Choat (1997)
nigricans	Delesseriaceae, *Polysiphonia*, Ulva	85	14	Barry & Ehret (1993)
tricuspidata	Rhodophytes	98.9	0.2	Choat & Clements (1992)
	Enteromorpha, Ulva, Cystophora	22	1.1	Kilner & Akroyd (1978)
	Phaeophytes + rhodophytes	100	0	Russell (1983)
	Chlorophytes + rhodophytes (coastal)	66	33	Morrison (1990)
	Chlorophytes + rhodophytes (estuarine)	35	30	Morrison (1990)
	Chlorophytes, phaeophytes, rhodophytes	49.1	50.9	Clements & Choat (1997)
Kyphosus spp.	Chlorophytes, phaeophytes, rhodophytes	100	0	Clements & Choat (1997)
	Rhodophytes	> 99	< 0.25	Randall (1980), Rimmer & Wiebe (1987)
	Phaeophytes	100	0	Randall (1967), Rimmer & Wiebe (1987)

Reproduction

Few studies have investigated reproductive biology in girellids, and in some species there are no scientific data available. Indirect evidence suggests spawning activity throughout spring in both northern and southern hemispheres: local fishers note higher productivity as *G. elevata* move inshore during the Austral spring (Wilson 1992); gravid individuals of *G. cyanea* (Roughley 1917); larvae of *G. nigricans* found in nearshore plankton tows midsummer, and field collections of eggs in late spring (Stevens et al. 1989); probable pelagic larval durations of up to 40 days back-calculate to late winter/early spring in *G. elevata* (Gallahar & Kingsford 1992). Spawning activity in *G. tricuspidata* appears trans-seasonal, peaking later at higher latitudes along the east coast of Australia (Gray et al. 2000, Smith & Sinerchia 2004). Smith & Sinerchia (2004) propose that monthly recruitment pulses in this species may be due to spawning, possibly related to lunar or tidal cycles, or accumulation of larvae in estuarine plumes that can transport larvae during flood tides. Other species recruit to tide pools early summer (Limbaugh 1955, Norris 1963). Limited data exists for girellids in the northern hemisphere: *G. nigricans* is thought to have a 90-day pelagic larval duration (Waples 1987) following a spawning season through late spring/early summer (Love 1996).

Age and growth

Little is known of age and growth in girellids. Pollock (1981) ascertained a maximum age of 11 years in *G. tricuspidata*, albeit his methods used a now outdated aging technique utilising scales. More recent studies have assessed age structure of adult girellid populations using the more preferable otolith (ear bone) micro-examination. Preliminary estimates provided by Ferrell (2005) suggest that *G. cyanea* is considerably long-lived; 41 years at 520 mm L_F. Similarly Gray et al. (2010) found that *G tricuspidata* can reach in excess of 24 years at 560 mm L_F. These studies extend only to adult populations, however, as sampling has been restricted to commercial landings and/or supplementation with recreationally caught fish. For *G. nigricans*, Bredvik et al. (2011) concluded that this species is short-lived and fast growing, with a maximum age of 10 years; however, they also acknowledge that their largest fish ($L_T = 1.2221*310\ L_S = 378.51$ mm) was far from the maximum recorded L_T of 660 mm (Love 1996). Such disparate findings would suggest that sampling has not represented the overall demography of the species. Whether size and age are decoupled in girellids remains unquantified.

2.6 Fisheries and populations

A paucity of information on the relative importance of girellids within commercial and recreational fisheries highlights the need for species-specific research. A number of records for commercial landings are available *c.* 1970-1980s, though more recent reports are scarce. Our limited knowledge of population dynamics in combination with a lack of understanding in demographic characteristics (length, sex and age compositions) creates a difficult environment for managers.

The Americas

Historically, *G. nigricans* were harvested as part of the incidental catch of the Californian coastal purse seine fleet and sold as "perch" in fish markets (in Stevens et al. 1989). Annual landings were 2.5 t, with a max 12 t in 1973. Recreationally, *G. nigricans* has been popular amongst rocky-shore anglers (Pinkas et al. 1968) and was considered the second most important species in competitive spearfishing (Fitch & Lavenberg 1971). More recent figures, or information on current population stocks, seem limited (but see Stephens 2001) and Anon. (2005) state that *G. nigricans* (along with *Medialuna californiensis*) make up 32 % of the total catch taken from Californian rocky shores. It is possible this species has not been fully assessed in fisheries studies, perhaps due to the relatively small harvest and subsequent lack of commercial interest. Curiously *G. nigricans* falls into the "unlisted species" category of the California Department of Fish and Game, which implies a catch limit of 10 individuals of any size (DFG 2011). Moreover, it is named as a fish "likely to benefit from the establishment of MPAs" (Anon. 2005), despite its exclusion from the recreational no-take list of the Marine Life Protection Act (Ashcraft 2009).

G. laevifrons is the most abundant transitory intertidal fish along the Chilean coast (Varas & Ojeda 1990). However, no data on potential fish stocks were located for this review, thus it remains unclear whether this species forms part of a commercial or recreational fishery.

Australasia

G. tricuspidata occur predominantly along the east coast of the Australian mainland and Tasmania, and are subject to differing management strategies across state governments. In NSW, *G. tricuspidata* are harvested as part of the estuarine and ocean haul fisheries and are the predominant bycatch species of the dusky flathead, *Platycephalus fuscus*, gillnet fishery (Gray et al. 2004). Recorded estimates fluctuate between 350-500 t with a peak in 1980 of 800 t (Scandol et al. 2008). Huveneers et al. (2002) also mention the species' use as bait in the NSW wobbegong fishery. Current reported commercial catches total *c.* 400 t annually after the complete/partial commercial closure of thirty estuaries within NSW (Gray et al. 2010). Hook and line recreational fishing is still permitted within these areas, however, and an estimated annual recreational catch in NSW of 270-550 t is of a similar magnitude to the commercial fishery (Henry & Lyle 2003). A minimum legal length (MLL) is currently set at 270 mm total length, L_T (~ 240 mm fork length L_F) after having been revised in 2005 in order for greater protection of immature fish (Gray et al. 2010). Current management also extends to a bag/possession limit of 20 individuals (DPI 2007). Interestingly, the size limit for *G. tricuspidata* caught in Queensland (QLD) state waters is maintained at an MML of 300 L_T, though only 10 individuals may be caught. Whilst the total recreational catch in QLD is unclear, the QLD Fish Board (1979) recorded an annual commercial catch of 100 t within the Moreton Bay region. *G. tricuspidata* is also taken from Moreton Bay, QLD, with an annual commercial catch of 100 t (QLD Fish Board 1979). Towards the southern limits of its range, *G. tricuspidata* is considered 'commercially insignificant' with 0.6 t landed in Tasmania in 1999 (Smith & Heran 2001). Despite the unknown status of recreational fishing pressure and of stock populations, the potential of this species for increased recreational development has been suggested (DPIPWE). Tasmanian populations of *G. tricuspidata* are currently managed through a bag limit of 20 individuals, and a possession limit of 45; MLL of 250 mm L_T (I&I NSW 2010). In Victoria, recreational anglers are limited to a bag/possession limit of10 *G. tricuspidata*, with a MLL of 230 mm L_T (DPI 2010). Despite fishing restrictions in the 4 Australian states above, *G. tricuspidata* is completely unprotected by size or bag limits in South Australia, where it has been nominated as near-threatened due to lack of population information, intensive fishing pressure, and biological traits that make it susceptible to over-exploitation (Baker 2009).

Elsewhere in the region, Russell (1983) considered *G. tricuspidata* predominant members of the reefs in north-eastern New Zealand, contributing 33% of the total biomass , however their large size means numerically they may not be as dominant (max. L_F 710 mm, Kailola et al.1993). A daily bag limit of 20 *G. tricuspidata* (known locally as Parore) is imposed in the Auckland & Kermadec and Central Fishery Management Areas.

The Australian east coast endemic species, *G. elevata,* was the third most abundant species found in tide pools at Bass Point, south of Sydney (Griffiths et al. 2004). This species contributes significantly to the NSW recreational rocky reef fishery (Kingsford et al. 1991) and was considered one of five most commonly speared fishes in competitions off Sydney (Lincoln Smith et al. 1989). Findings by Last et al. (1983) indicated a restricted distribution in south-eastern Australia, including Tasmania, however recent work suggests *G. elevata* are more abundant with an expanded distribution, particularly in the Furneaux Group (Last et al. 2011). Current management of *G. elevata* restricts the bag limit to 10 individuals and MLL to 300 mm L_T (DPI 2007). This appears to be precautionary, as very little is known of the life history or population connectivity for the species (Curley et al. in prep.). Additional protection of this species is incidentally through MPAs in Sydney, although the no-take zones may not fully encompass the preferred spawning aggregation sites (Curley 2007).

Although protected elsewhere in its range (see next section for more detailed review) *G. cyanea* is the fourth most commonly caught species in the Lord Howe Island fishery, attributing 5 % to the total reported annual fish catch (MPA 2010). Despite a daily bag limit of 5 individuals, recent surveys show a decline in abundance within habitat protection zones where fishing is still permitted (Aquenal 2010). No size limit has been established for this species despite preliminary age and growth estimates suggesting a MLL of 300 mm L_F (Ferrell 2005).

Japanese archipelago

Figures for fisheries and populations of the three girellid species occurring in the waters surrounding Japan and Taiwan are difficult to locate. Yagashita & Nakabo (2000) state that *G. punctata, G. leonina*, and *G. mezina* are "quite common along the southern coasts" but give no data or citation to validate this observation. Likewise, Umino et al. (2009) mention the recreational and commercial importance of *G. punctata* in Japan and

Korea, but neglect validation of this. Governmental support of these statements is also elusive and appears somewhat non-transparent.

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Chapter 3 - Method Development

3.1 Preface

Estimates of abundance and population composition are critical components of ecological studies. Many procedures and problems involved in gaining these estimates have been reviewed, and it appears that not any one solution is best for the diverse habitats and behaviours of fishes. Two main objectives are common for all census techniques, however: 1) to estimate density and 2) to provide a confidence interval for the estimate. This chapter describes the pilot studies that assessed these two objectives. Initial *in situ* observations of *Girella cyanea* revealed habitats of high surge amongst high-relief rocks and highly mobile, patchy distributions; attributes that were less than conducive to laying standard transect tapes. A roaming transect survey method that utilised a tracking GPS-receiver was tested for consistency (Part A). In order to be able to compare surveys of *G. cyanea* in the future, it was important to ensure the precision of these estimates. Underwater size-based observations of models were tested for consistency to identify biases (Part B). These were important steps to take in order to be confident that the descriptions of density and distribution for Chapter 4 were representative of the real populations.

3.2 Introduction

Regardless of the field of study, ecologists are invariably confronted with the issue of quantifying density and abundance (Seber 1973, Caughley 1977, Andrew & Mapstone 1987, Buckland et al. 1993). Although determining absolute numbers within a population may be the ideal, it is widely accepted that a relative index can be adequate for comparative purposes, given the objective is often to understand variation in the population over time or space, or between species. However, for many studies, even relative abundances are not quantifiable due to pervasive biases, such as observer effects, observer-error, and subject detectability (Sale 1980, Lincoln-Smith 1989). Since the first attempts at quantifying fish stocks appeared in the mid-1950s (Brock 1954, Odum & Odum 1955), considerable effort has gone into providing recommendations on methods known to be most reliable (see reviews by Harmelin-Vivien et al. 1985, Thresher & Gunn 1986, Samoilys & Carlos 2000, Edgar et al. 2004). Underwater visual censuses (UVCs) are now the most common method employed in ecological surveys of shallow subtidal reefs (Edgar et al. 2004). They are generally preferred because they are cost-effective, minimally disruptive to organisms, and repeatable after short time intervals (Bortone et al. 2000). Two techniques are advocated in critical evaluations of UVCs: transects (Brock 1982) and point counts (Bohnsack & Bannerot 1986). A transect consists of the observer traversing a measured path while counting all individuals visible within a fixed width. During an instantaneous point count all individuals within a specified area are counted over a set period of time. For both of these methods density is quantified as number of individuals per unit area.

Evaluations and developments of the traditional UVC methods have been made mostly on small, site-attached, cryptic species (e.g. gobies, blennies, and damselfishes) as well as large common schooling species (e.g. parrotfishes and wrasses) of tropical coral reefs (Sale & Sharp 1983). More recent work has considered modifications for situations where environmental conditions and/or fish behaviour may be markedly different. For example, Meekan & Choat (1997) and Cole (2001) recognised the difficulties in laying transects in the high swash zones favoured by herbivorous fish in New Zealand and the Kermadec Islands, adapting their methods to include densities measured using three-minute timed counts. Similarly, Gillanders (1997) employed three-minute rapid visual counts (RVC; see Jones & Thompson 1978) of *Achoerodus viridis* in estuarine and rocky reef sites in Sydney, whereby abundances were recorded 5 m either side of an imaginary line continuously swum on SCUBA. Patchily-distributed fishes have also been recognised to benefit from a timed swim approach due to the potential requirement of larger-than-normal census areas (Colin 2006). Density estimates that measure abundances per unit effort (i.e. time), however, have one distinct pitfall: they can be only semi-quantitative (Colin et al. 2003). Few studies to date have addressed this shortcoming (but see Bellwood & Wainwright 2001).

If the UVC is the most preferred and utilised method of underwater surveying, then enhancements that can offer a quantitative approach should enrich the toolbox of methods available for fish ecologists. One possible solution is the roaming transect survey (herein referred to as *RTS*). Several versions of this technique have been reported (see Colin et al. 2005, Frisch & Hobbs 2009, Dickens et al. 2011). All versions utilise a handheld global positioning system (GPS) to georeference the location of a time-based UVC. In theory, this information allows a quantitative measure of density (individuals per unit area) by calculating the distance covered - providing that swathe width remains constant over sampling time. Moreover, a permanent record of the transect route may be archived for future repeat surveys.

This study aimed to test the efficacy of the RTS method by assessing its consistency over variable nearshore habitats, using bluefish, *Girella cyanea*, as a focal group. The main question asked was 'does the RTS method have a utility in multi-habitat studies of a patchily distributed fish?'

3.3 Materials and Methods

Field methods

This preliminary study took place in October 2005 within the North Bay Sanctuary Zone (31°33'S, 159°05'E) of the Lord Howe Island Marine Park (Fig.2.1).

Underwater visibility and 'angle of vision' limits showed a 3 m swathe to be optimal across depths. As the observer (M.L.) swam down the middle of this swathe on snorkel, individual fish were counted 2 m ahead, i.e. across an arc of 1.5 m either side of the observer (Fig. 3.1).

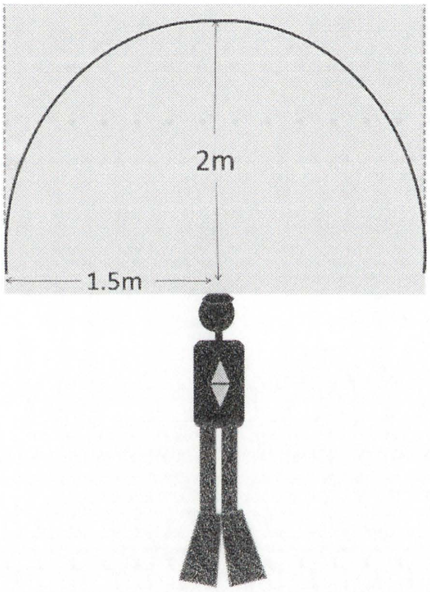

Figure 3.1 Schematic of the roaming transect survey (RTS) technique showing swathe dimensions and field of view of the observer.

Swims were timed to three minutes in order to fit within the visible boundaries of each habitat (Table 3.1).Start- and end- waypoints for each swim were taken using the "rocker" shortcut button on a GPS (Garmin eTrex Legend H) receiver towed on a float behind the observer. Swims commenced only when a minimum of four satellites were fixed by the GPS unit (i.e. 5-10 m accuracy). All surveys were conducted at high tide (HT ± 1 hr) in order to gain access to all habitats (Table 3.1). Weather was fine with minimal cloud cover and the sea state was calm. Twelve replicate swims per habitat were swum on three consecutive days. Fish observations were considered independent across days. The survey start points were haphazardly chosen to lie within a

Table 3.1 Defining characteristics of habitat categories used in RTS at North Bay, LHI.

Category	Description
Rocky Intertidal (RK)	Intertidal area of large basaltic boulders. Surge present. Turf algae covering some rock. *Ulva* spp.. often present. Depth < 1 m.
Sand (SA)	Homogenous white sandy substrate. Surge absent. Bare or minimal *Halophila ovalis* present. Depth 1 to 2 m.
Algal Zone (AZ)	Biological substrate adjacent to RK areas; relatively homogenous with small boulders often covered in brown algal spp. Surge absent. Depth 1.5 to 2 m.
Coral Dominant (CD)	Area of predominantly scleractinian coral species (especially Acropora spp.) and limited macroalgae. Depth 2 to 3 m.
Deep reef (DR)	Habitat furthest from shore consisting of mixed coral and macroalgal species. Wavelets present. Depth 4 to 7 m.

Howell test revealed that swims conducted over sand resulted in a significantly shorter distance covered over a three minute time frame. There was no significant difference found for distance covered in the more complex rocky intertidal when compared against all other habitats (Fig. 3.2).

Swimming speed was highly consistent with distance covered but displayed two tangents (Fig. 3.3). Greater speeds were experienced mainly in microhabitats that took the observer on an increased sinusoidal path in order to follow a depth contour or stay within a habitat boundary ($s_1 = 0.50d - 0.01$, $R^2 = 1$). Slower speeds occurred mainly in complex boulder habitats where higher abundances of fish were observed ($s_2 = 0.33d$, $R^2 = 1$), although this is not indicative of increased sampling effort; such habitats occur in very shallow water, at times requiring the observer to pull over rocks (i.e. not swimming *per se*). Lower speed for equivalent distances also occurred on swims conducted in high wave conditions, which induced 'floating' behaviour with next to no fin beats (i.e. swimming did not require any kicking action for motion).

Abundances in the shallower habitats (RK, AZ) yielded higher mean numbers of individual *G. cyanea* than when converted to densities. *T* tests indicated a statistically significant difference between numbers in the rocky intertidal habitat only ($t(11) = 4.48$, $p < 0.001$; Table 3.2). The average number of individuals extrapolated across 100 m^2 constituted less than 40 % of the mean number directly observed on RTS swims in RK habitat (Fig. 3.4).

3.5 Discussion

On Lord Howe Island, a mix of temperate and tropical waters offers a significant underwater architecture, from rocky landscapes, to macroalgal beds, to coral reefs (see Chapter 1). Highly variable habitats pose considerable challenges for assessing distribution and habitat-use of fishes. Methods that prove successful in one habitat may not be as effective in another. The rocky intertidal habitat is subject to high-surge and water is turbid and very shallow even at high tide (± 1 hr). The clear waters over coral

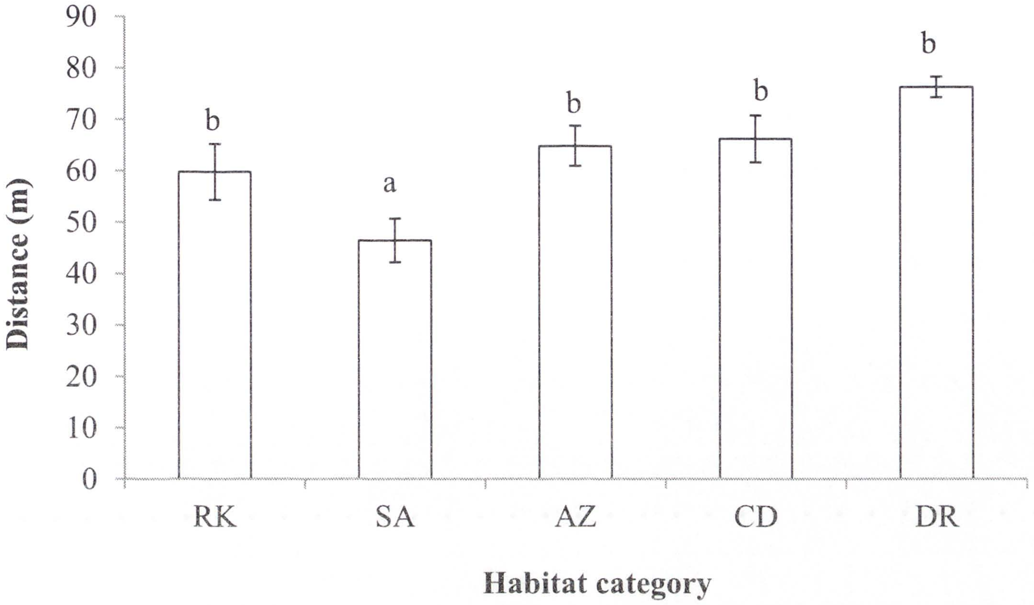

Figure 3.2 Distance covered during a three-minute RTS per habitat at North Bay, LHI. Data are mean numbers with standard errors of the mean ($n = 12$). Differing letters denote significance (Tukey's Test: $p < 0.01$). Refer to Table 3.1 for habitat descriptions.

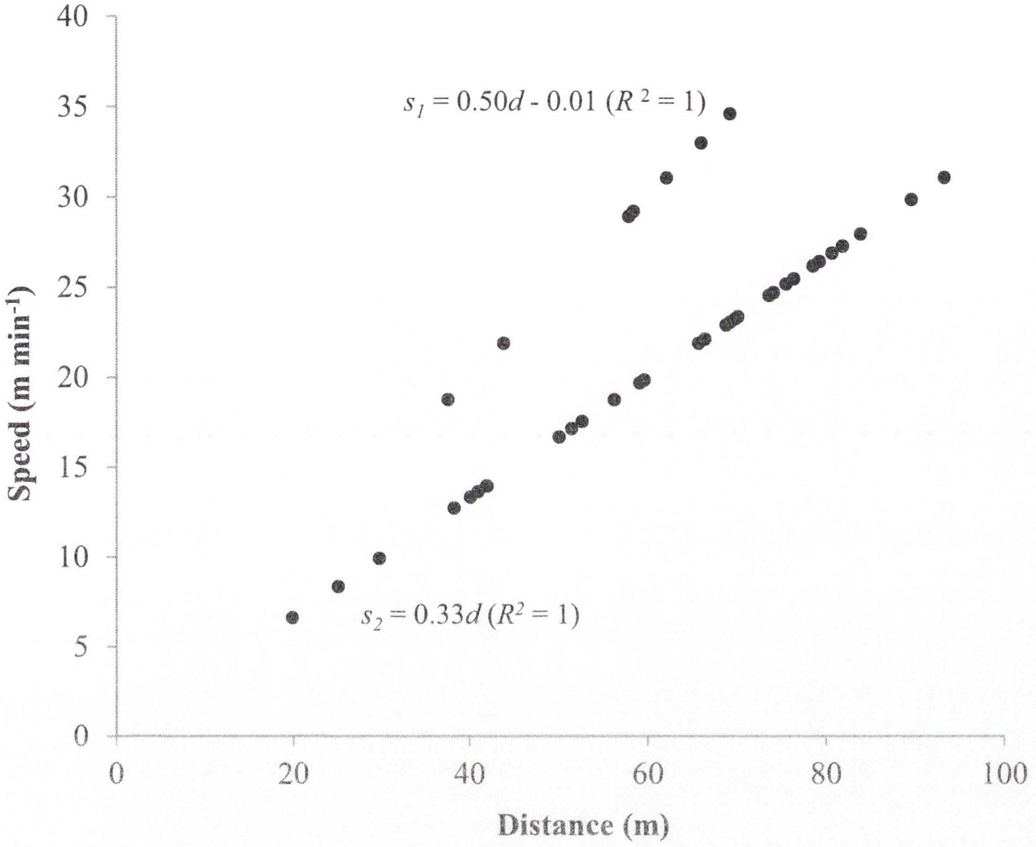

Figure 3.3 Distance (*d*) versus Speed (s) of each RTS conducted over a three minute interval ($n = 60$). Two slopes emerged, as denoted by subscripts. Regression equations and R^2 values are shown.

Table 3.2 Dependent samples *t* -test of density (number of fish calculated $100m^{-2}$) and abundance (number of fish counted per 3min RTS) in each habitat where fish were observed

Pair	M_D (S.E.)	M_A (S.E.)	*t*	df	*p*
RK (*D* x *A*)	5.32 (1.59)	13.40 (3.52)	4.48	11	0.00
AZ (*D* x *A*)	0.36 (0.16)	1.20 (0.57)	1.96	11	0.76
DR (*D* x *A*)	2.22 (0.14)	0.50 (0.50)	1.00	11	0.34

Abbreviations used: Density (*D*), Abundance (*A*), Mean (M), Standard Error of the mean (S.E.), *t*- value (*t*), degrees of freedom (df), significance of the *t* -value at $\alpha = 0.01$ (*p*).

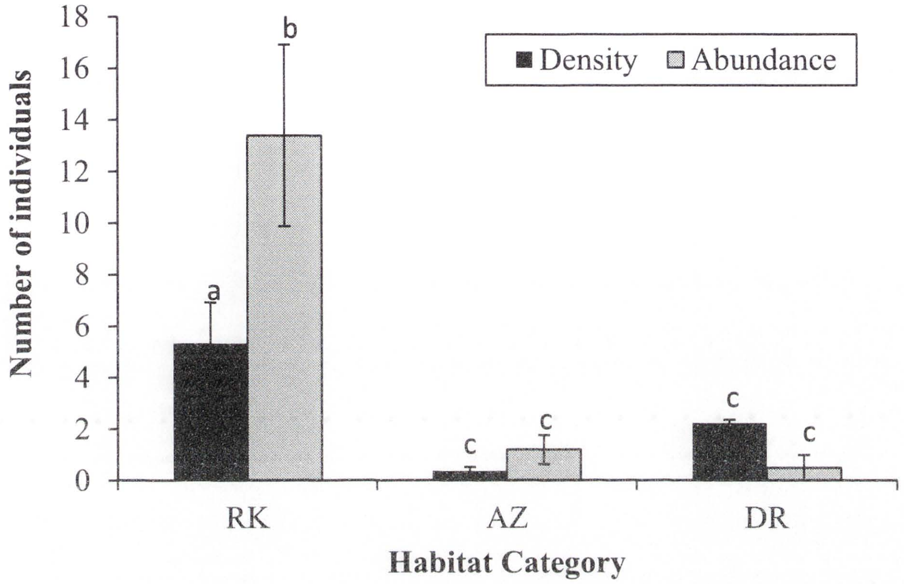

Figure 3.4 Density (number of fish calculated per 100m^2) and abundance (number of fish counted per three minute RTS) for each habitat that *G. cyanea* were observed. Data are mean numbers with standard errors of the mean ($n = 12$). Differing letters denote significance (Dependent-sample t test, $p<0.01$).

reefs are in stark contrast to this. The present study aimed to test an underwater survey method that could be utilised in a range of habitats. Limited options were provided in the literature despite the recognised difficulties in laying transect tapes in swash zones (Meekan & Choat 1997, Cole 2001). Results here showed no significant differences between mean distances covered in swims over diverse habitats (RK, AZ, CD, DR), except for sand where RTS covered less distance than other surveys (Fig. 3.2). This was surprising, given that topographically complex environments can result in increased search effort and thus less distance covered. As pointed out by Lincoln-Smith (1988) "if more time is required for searching [as in topographically complex or high-abundance situations] a time-based method will lead to shorter distances being covered in the time allocated; but a distance-based method may require more time to cover the distance". However, speed is hard to gauge without a visual reference, and it is probable that the lack of visual clues (boulders, algal tufts, etc.) on a homogenous sandy floor resulted in slower swims (i.e. less distance covered over three minutes). The effects of observer swimming speed have been previously demonstrated (Lincoln-Smith 1988, Watson et al. 1995) yet standardisation is not often taken into account (Samoilys & Carlos 2000). Several average speeds have been reported in the literature. Three-minute surveys of blue grouper, *Achoerodus viridis* covered 60.72 ± 2.02 m resulting in a mean swim speed of 20.24 m min^{-1} and within the range of those presented here (Fig. 3.3). Slightly faster swims were achieved by Samoilys & Carlos (2000) at 0.50m sec^{-1} (i.e. 30 m min^{-1}), to try to match the apparent 0.60 m sec^{-1} (i.e. 36 m min^{-1}) swimming speed of the blue trevally, *Caranx ferdau*, being observed. . Lincoln-Smith (1988) draws reference to reported speeds as 'unregulated', in that the researchers fix either distance or time, but not both. His presumptions that such speeds will reflect the observer's natural swimming speed, or be a result of environmental factors, are valid. The results of our 'regulated' RTS swims show that variable distances may be covered and that time is not reliable for density assessments. It would seem prudent in future surveys to conduct a distance/speed analysis if multiple observers were to perform underwater density surveys. The limited literature would suggest that swimming speed of the observer often goes unnoticed as a potential source of variation. Overlooking speed as a potential bias in underwater surveys may not be altogether surprising, however, with some concerns raised that standardising speed in multispecies UVCs may lead to over-counting more mobile species (Lincoln-Smith 1988, Samoilys

1992). In the present study, where fish abundance was relatively high (i.e. RK habitat), densities of fish per three minute survey were significantly higher than when distance was factored in (Table 3.2, Fig. 3.4). This suggests that in single-species studies, like this one, variable speed (distance) should be taken into account. This can be done by utilising the speedometer function on a GPS, although somewhat tricky when maintaining focus on fish counts. A better alternative is using the GPS tracking feature or waypoints to conduct underwater surveys as RTS presented here (rather than timed swims). This has the additional benefit of quantitative results that are more comparable with existing literature.

Further recommendations

The GPS may not be capable of picking up small changes in direction due to resolution by the satellite fix, especially in more remote places like Lord Howe Island where maximum number of satellites used in waypoint determinations was never more than 4 of the 12 available (pers. obs.). Therefore, the distances reported here may exclude the distance added by an RTS that follows a sinusoidal path, and may be the reason why some swims present at a faster speed. To combat this in future GPS surveys we suggest either: (i) a less sinusoidal path should be followed, where possible, to keep speed (and thus distance) as consistent as possible, or (ii) that the GPS tracking feature be utilised. The latter suggestion allows a series of waypoints to be automatically taken each predetermined time interval (eg. every 10 sec) thus allowing a more accurate distance to be calculated. It must be noted that this method would be affected more by any lack of resolution from the satellites received by the GPS. However, in areas where resolution is high (i.e. < 5 m), this method would be preferable, as it could allow the surveyor to follow delineations in habitat that may change fish abundance, such as depth contours (e.g. Morrisey & Gruber 1993) and habitat boundaries (Leum & Choat 1980). The higher resolution available in North America using the wide area augmentation system (WAAS) improves this situation dramatically and enables a waypoint to have accuracy to 5 m with a 95 % confidence (FAA 2008). In other parts of the world, land-based differential GPS (DGPS) reportedly improves location accuracy from a nominal 10m to up to 3 m (e.g. Bellwood & Wainwright 2001). Recently installed maritime stations of Australian Maritime Safety Authority indicate that accuracies of 2 to 4 m can be expected from DGPS receivers in nearby waters (AMSA 2007). Unfortunately DGPS was not available at the time of the present study, but we strongly advocate its use for future RTSs conducted in appropriate locations (see www.amsa.gov.au for a current list of operational stations). Where this is plausible, a DGPS antenna is required.

Conclusion

RTS swims should offer an improvement on the more traditional methods of UVCs because they require zero deployment or prior disturbance on fish communities. This is especially important for locations where tape laying is problematic, or species are rare and/or clumped and display negative/positive reactions to observers.

Preliminary Study B: Determining the accuracy and precision of underwater estimates of fish lengths

3.6 Introduction

A key objective of any animal census procedure is to provide reliable results (Thresher & Gunn 1986). Repeatable methods will facilitate sound statistical comparisons in order to track spatio-temporal changes in population size and structure (McClanahan et al. 2007). This is especially important for management decisions where quotas and multiple-use zoning schemes may be based upon such results.

A number of problems are inherent when conducting UVCs for mobile fish species: effects of fish behaviour (e.g. Watson et al. 1995, Edgar et al. 2004); diver-effects (e.g. Dickens et al. 2011); and, distance/size estimations (e.g. Thompson & Mapstone 1997). Without consideration of these sources of error, observations may be under- or over-estimated and subsequently lead to altered densities and/or calculated biomass contributions. Substantial analyses of the probable sources of bias inherent in the UVC method fail to supply a technique that is free from biases of some kind (Edgar et al. 2004, Dickens et al. 2011). Although biases are inevitable, a number of mitigations have been identified in order to keep error to a minimum: use of a single observer; use of a single method (i.e. standardisation), and observer-calibration. At the very least, use of a single observer will allow consistency of the bias throughout the data set, which is both measurable and correctable *post hoc*. Similarly, a decision can be made to allow only data subjected to a pre-determined level of acceptance (commonly 20 %).

The purpose of this pilot study was to examine the consistency of a single observer, single species UVC so as to ensure a level of confidence in subsequent data collection (Chapter 4). It was anticipated also that the exercise would calibrate the author (M.L.) across the expected size-range of *G. cyanea*, and aid in the assignment of size-classes for future diet and age analyses (Chapters 5 and 6).

3.7 Materials and Methods

Study area

This calibration study was carried out in the lagoon at Lord Howe Island (Fig. 2.1) during October 2005. Conditions inside the lagoon were calm, and cloud cover ranged from 2 to 5 octas.

Field methods

Eighteen laminated *G. cyanea* photos scaled to various sizes (50 to 400 mm L_T) were deployed over a sandy bottom in the LHI lagoon at an approximate depth of 1 m. The fish models were placed randomly and perpendicular along a line transect using clear line, a small spherical float, and a buried dive weight. During the survey, a single observer (M.L.) estimated fish model sizes whilst snorkelling slowly at a fixed distance of 1 m from the models. Size estimations of Total Length (L_T) were assigned to size classes (arbitrarily set to < 100, 100-149, 150-199, 200-249, 250-299, and ≥ 300 mm) as well as continuous measures (mm). Four replicate surveys were conducted using the same models, after the random rearrangement of the models along the transect line.

Data analysis

The potential for systematic sampling error associated with size estimations was determined by comparing the estimated lengths of model fish with direct length measurements of the same models after estimations were complete. Two components of visual error were measured:

(i) Relative Error was used to compare how accurate the size estimations (X_E) were to the true size ($X_{T,}$) using the formula:

$$R.E. = (X_T - X_E) / X_T *100$$

A systematic error in accuracy occurs when sizes are consistently over-estimated or consistently under-estimated.

(ii) The Coefficient of Variation (Seber 1973) was used to assess how precise the size estimations were:

$$C.V. = S.D.\ \bar{X}_E \ / \ X_T$$

The C.V. is a dimensionless number that reflects any variability in relation to the average size estimation, and should be achieved at levels 0.10 to 0.20 for acceptable levels of precision (Thresher & Gunn 1986). A systematic error in precision occurs when variability is increased only in fish of a particular size category.

3.8 Results

Overall, R.E. was 25 % or less, indicating that accuracy of all size estimations was reasonable (Fig. 3.5A). Of the 72 size estimations conducted, 25 % were exact to the true size across the entire L_T range. The *ad hoc* assignment of estimates to size-classes, improved this to more than 94 % (i.e. 68 of 72, Fig. 3.5B).

Although there was a slight bias towards overestimating body length in models greater than 250 mm, accuracy remained relatively high (R.E. $\leq$ 8 %, Fig. 3.5A). The increased variability of size estimations in models smaller than 150 mm L_T was not systematic, with single sizes being both over- and under- estimated on different occasions. This was not the case, however, in measurements of precision, where increased C.V. in fish models below 100mm L_T suggested a systematic error of precision in estimates of fish of smaller body sizes (Fig 3.6). Beyond 100 mm L_T, precision remained high (C.V. $\leq$ 8 %) and, in general, a high level of precision was obtained, with 89 % of C.V. values at the lowest end of the desirable range (Fig. 3.6).

3.9 Discussion

By using a single observer, this study tested accuracy and precision of size estimation skills in the field. It is acknowledged that these UVCs were conducted in ideal conditions (sandy floor with low relief, in still water of high underwater visibility, and with sedentary model fish oriented across the observer's path). As a consequence, one may expect less-desirable conditions experienced under real field-conditions to slightly impact the results presented here. However, since these levels of R.E. and C.V. were achieved well-within expectations set in the literature (*sensu* R.E. = 30 %, Gillanders

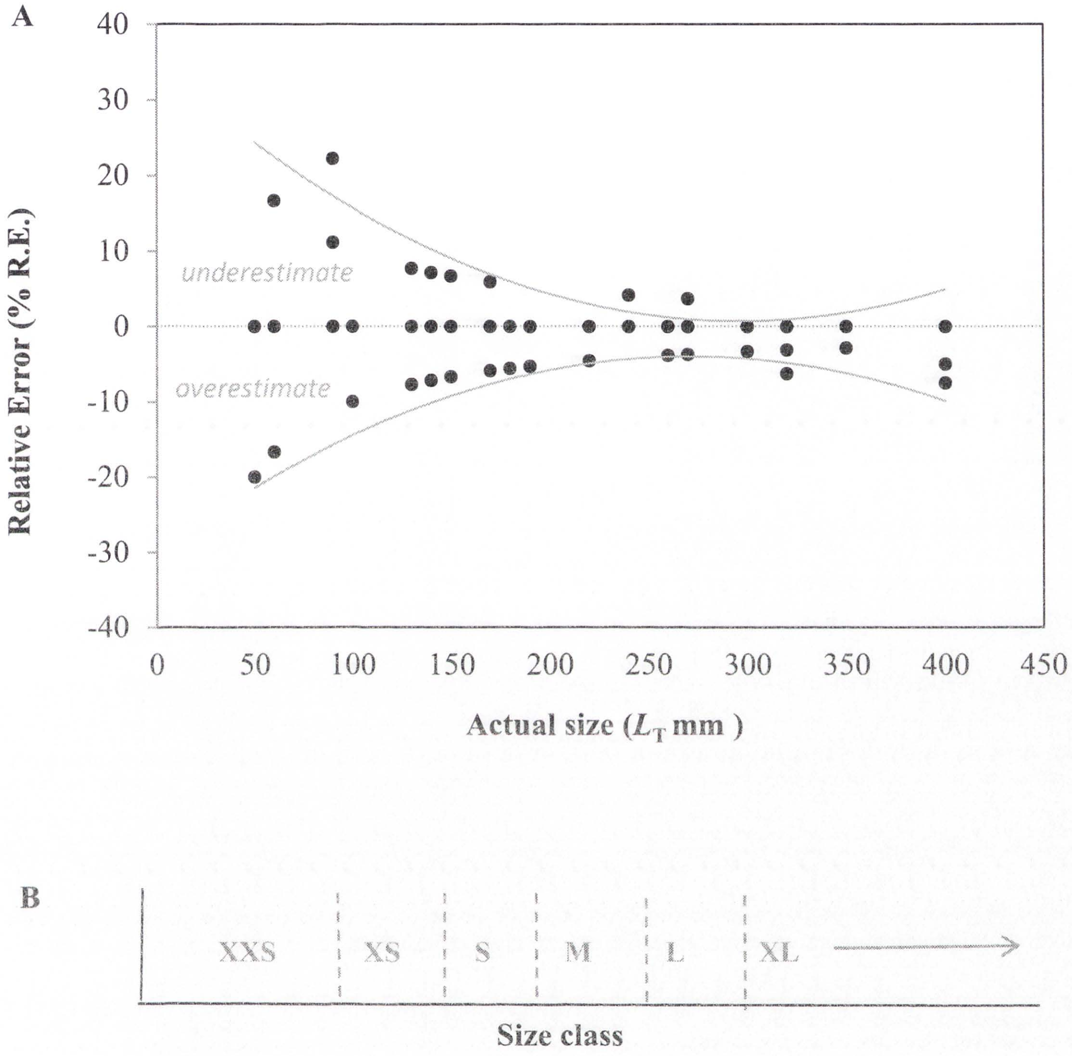

Figure 3.5 A: Accuracy of model fish size estimations in the field. Each model was visually estimated four times. Solid lines are 95% Confidence Intervals. The horizontal line at R.E. = 0 represents exact agreement between the estimated and actual size. R.E. = (true L_T - estimated L_T) / true L_T * 100 (n = 72). **B:** Size class categories used to assign fish length estimates ad hoc. Dotted lines indicate category borders and use the x-axis in Fig 2A. Arrows indicate continuation across 50 mm intervals.

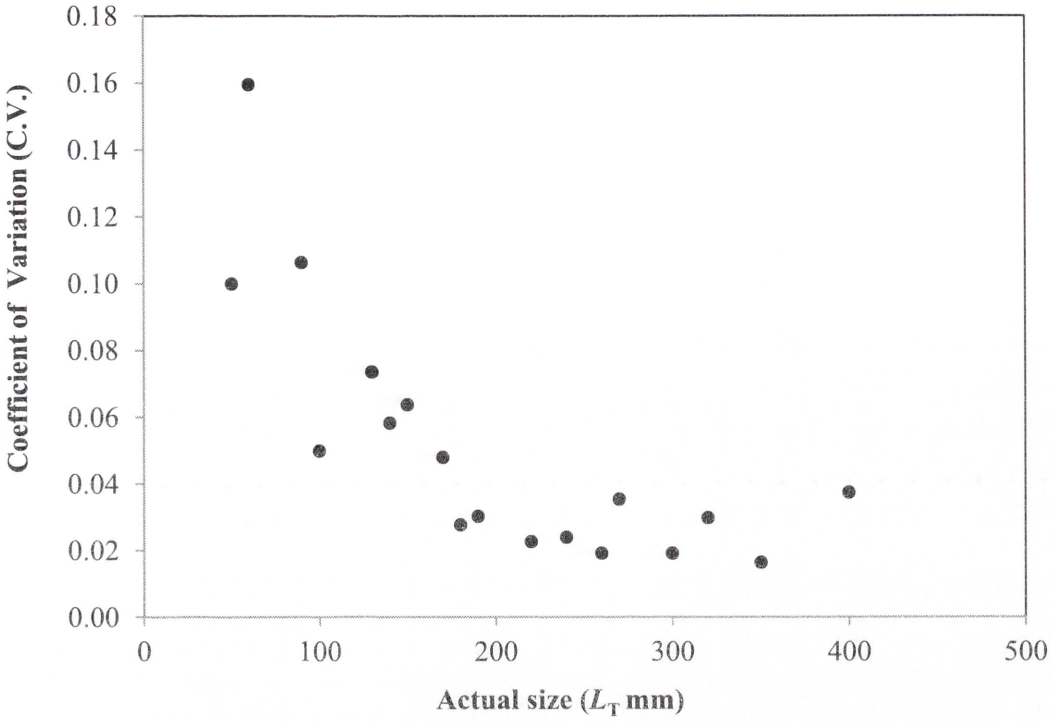

Figure 3.6 Precision of model size estimations in the field. C.V. = S.D. X_E / X_T

1995; C.V. = 0.1 to 0.2, Seber 1973, Thresher & Gunn 1986; Fig. 3.5A and 3.6)) confidence is high that subsequent data collected on *G. cyanea* using such methods are suitably representative of the real population. Additionally, in order to achieve the highest levels of accuracy and precision, it seems reasonable to conduct future surveys of *G. cyanea* using the following size-classes: < 100, 100-149, 150-199, 200-249, 250-299, ≥ 300 mm L_T (Fig. 3.5B).

Chapter 4 - Putting Bluefish (Girellidae: *Girella cyanea*) on the map: Patterns of abundance and population size structure using the roaming transect survey method

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Abstract. The present study is the first to investigate ontogenetic distributional patterns in *Girella cyanea*. Roaming transect surveys (RTS) were conducted in nearshore rocky intertidal, algal, coral and rocky reef zones to compare size distributions of *G. cyanea* amongst habitats. Additional sightings were recorded offshore on opportunistic SCUBA surveys. Horizontal partitioning was evident, with mean densities highest in complex rocky intertidal areas. Vertical partitioning was also indicated by significantly different depth distributions between size classes. Fish < 200 mm standard length were not observed beyond 2 m depths. Reasons and implications for these distributions are discussed.

4.1 Introduction

Uneven distribution of individuals among habitats is not uncommon; some species are closely associated with certain habitats and others with wider distributions. Varied needs in food and shelter requirements may characterise these patterns (Williams 1991), with correlations found between fish population numbers and specific habitat features, such as wave exposure (Williams 1982, Russ 1984) and structural complexity (Hixon 1980, Kingett & Choat 1981, Choat & Ayling 1987). An understanding of densities in various habitats can reveal patterns of resource overlap or separation amongst size classes of the same species (ie. intraspecific variation and competition). Such ontogenetic shifts are common in reef fish (Williams 1991, Mumby 2006, Lecchini 2006, Pratchett et al. 2008) and can be manifest on two axes. Horizontally, it has been shown that fish partition by substratum type (Nakamura 1976a, Mayr & Berger 1992, Zander 1995) and colour (Burgess 1978). In vertical space, depth stratification and zonation of the rocky intertidal has been shown to structure populations (Gibson 1972, Nakamura 1976b, Yoshiyama 1981, Bennett & Griffiths 1984).

The present study is the first to investigate ontogenetic distributional patterns in *Girella cyanea*. Very little is known about the habitat associations of this species and, despite the prevalence of congenerics, patterns of abundance along depth gradients are largely unknown for girellids (Cole 2001). Here, size-based observations of *G. cyanea* were collected with the aim of identifying the dominant size-classes within each habitat and depth. This was a necessary prerequisite for further studies which aimed to make sample collections for diet analyses (Chapter 5) and life history models (Chapter 6).

4.2 Materials and methods

Study site

The heritage-listed Lord Howe Island lies approximately 600 km off eastern Australia (31°33'S 159°05'E) and is considered to be the southern-most coral reef in the world. Often described as subtropical, it is influenced by the warmer waters following the East

Australian Current and the cooler waters of the Tasman Front (Fig. 1.3). Consequently it harbours a mix of tropical and temperate coral and fish species and a diverse range of habitats (see Chapter 1).

This study was conducted over four sampling periods: November-December 2005, March 2006, November-December 2006, and March 2007. Local monthly mean sea surface temperatures vary between 21.46 ± 0.16 °C for Nov. /Dec. ($n = 44$) and 23.86 ± 0.11 °C in March ($n = 23$; NOAA Pathfinder data, 1985-2007).

The use of a single diver (M.L.) for all surveys eliminated any bias introduced between size estimates and depth or width perception (see Chapter 3, Parts A and B). From the pilot study it was known that estimations of size were within the given 50mm size-class 95 % of the time (see Chapter 3, Part B).

Nearshore sampling

Six locations, separated by a minimum of 1 km were sampled (Fig. 4.1). These included North Bay, Ned's Beach, Signal Point, Middle Beach, Little Island, and Boat Harbour. These sites were chosen based on their distribution on the island (east-west) and accessibility (SZ no-take reserve, HPZ regularly fished by locals and tourists, and relatively isolated HPZ). One extra site, Old Gulch, was sampled also for densities, but data were omitted from marine park zone comparisons.

Habitats were delineated by various biological and architectural descriptors and were depth-stratified (Table 4.1). At some sites, small seagrass meadows and bare sand were sampled; however these habitats were excluded from analyses in order to balance the experimental design across all sites. To gain access to the shallow (< 1 m) intertidal areas, all swims were conducted within an hour either side of mean high tide (as predicted by tidal charts). Accessibility in these areas was not only limited by tidal activity, but also by high levels of surge and subsequent turbidity. No swims were conducted on days with less than 15 m horizontal visibility, as estimated at an arbitrary

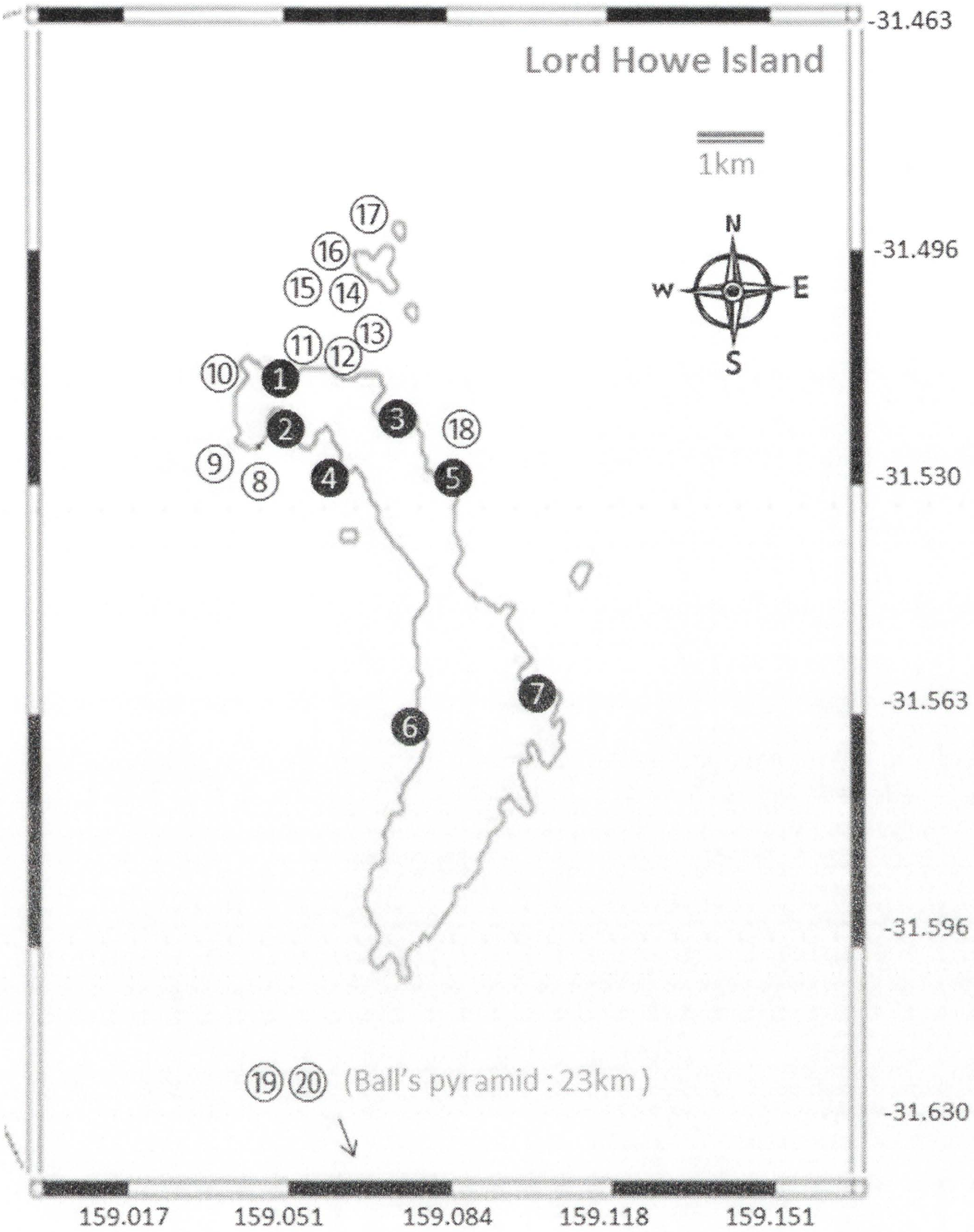

Figure 4.1 Sampling locations within the LHI archipelago: nearshore RTS swims (black) and *G. cyanea* sightings recorded on SCUBA dives (white). LHIMP zone comparisons were SZ (2 & 3), HPZ (4 & 5) and isolated-HPZ areas (6 & 7). [1: Old Gulch, 2: North Bay, 3: Ned's Beach, 4: Signal Point, 5: Middle Beach, 6: Little Island, 7: Boat Harbour, 8: Yellow Rock, 9: North Gutters, 10: New Gulch, 11: Landslide, 12: Malabar, 13: Soldiers Cap, 14: Noddys Rock, 15: Ruperts Reef, 16: No Name Reef, 17: Tenth of June, 18: Middle Beach Reef, 19: Whitesheath, 20: The Aquarium].

3 m depth outside the swash zones. Swims were conducted according to the RTS technique (see Chapter 3, Part A). Each fish observed within the transect swathe (see Fig. 3.1) was assigned to the pre-determined size-classes based on standard length estimates (Fig. 3.5B): < 100 mm = XXS; 100-149 mm = XS; 150-199 mm = S; 200-249 mm = M; 250-299 mm = L; and ≥ 300 mm = XL. The presence of adjacent shelter (suitable rocky overhang or crevice within 2 m) was recorded for each *G. cyanea* sighting, regardless of whether the individual/s were utilising it at the time. The presence of any species of kyphosid was also noted, as were observations of active feeding (midwater or substrate-based bites). Depth at the beginning and end of each swim (in metres) was recorded and generally differed by no more than 1 or 2 m; thus the average depth was used for analyses. Cloud cover (in octas) and sea-state (glassy, calm, surge, rough) were also recorded for each sampling session (i.e. a new location or day).

Offshore sampling

Only a limited number of SCUBA dives were undertaken due to time, cost and University diving safety regulations. These were opportunistic in nature, taking place where and when the local dive operator had availability (Fig. 4.1, see caption for site names). Dives were conducted under the auspices of PADI limitations (including bottom time and depth limits) and required no additional equipment for surveys. Each sighting of *G. cyanea* was supplemented with further observations of active feeding behaviour (bites on substratum), potential shelter in 2 m vicinity, shoaling with *Kyphosus* spp., and schooling behaviour with conspecifics. Densities were not recorded, thus data are presented as presence/absence only. Depths used in analyses were the actual depths of the observed individuals.

Data analyses

Repetitions of RTS swims amongst each habitat were limited to the habitat boundaries within each of the nearshore locations; therefore, data was pooled to describe *G. cyanea* patterns of abundance across habitats rather than locations. Whilst this added additional variability into the dataset, power of the subsequent analyses was increased by substantially increasing the sample size, and hence decreasing the probability of a Type II error (Zar 1984).

Table 4.1 Description of habitats assessed for *G. cyanea* distributions at locations nearshore on the main island of LHI (RK, AZ, CD, DR, SA, SG), and at offshore islets and dive sites (DI).

Category (code)	Defining characteristics
Complex intertidal rock (RK)	Areas characterised by stacked basaltic boulders >30cm diameter or weathered calcarenite, with > 1 m relief, exposed at low tide. Potential shelter is a feature. Average estimated depth at high tide is < 1 m
Algal zone (AZ)	Areas dominated by mixed macro-algal species, and often with rocks variable in size but < 1 m in relief. Few, if any, shelter holes provided. Average estimated depth at high tide is 1.5 to 2 m.
Coral-dominated shallow reefs (CD)	Areas dominated by scleractinian coral species. Very few sizeable shelter possibilities, some overhangs. Average estimated depth at high tide is 3 to 5m.
Deep reef (DR)	Deeper rocky reef with mixed corals and macro-algal species. Overhangs and small caves sometimes present. Average estimated depth at high tide is > 5 m
Offshore (DI)	Areas accessed by boat only; beyond DR zones. Includes sites attached to islets of the greater archipelago. Often adjacent to subtidal rock features with macro-algal stands. Overhangs and small caves sometimes observed. Average estimated depth > 10 m.
Seagrass (SG)	Subtidal areas dominated by *Zostera* beds; sometimes with sparse *Halophila ovalis* present also. Epiphytic growth is a characteristic. Average estimated depth 1 to 1.5 m.
Sand (SA)	Homogenous areas with predominately sand and little algae or plant growth. Average estimated depth 1.5 to 2 m.

Initial exploration of the data revealed that patterns of abundance were similar across the four sampling periods ($p = 0.37$), therefore sampling period factor was removed and data was pooled to give more power across habitat comparisons – the main focus of the study (Quinn & Keough 2002).

Habitat partitioning was assessed by examining data obtained from quantitative RTS in nearshore habitats using a general linear model (GLM) ANOVA. Size frequency analysis allowed patterns to be evaluated across size-classes and included observations acquired for DI habitat. Depth distributions of different-sized fish were compared using a one-way ANOVA, fixed for size class. Significant differences were located using the *post hoc* Student-Newman-Keuls test (SNK, $\alpha = 0.01$). Where assumptions of homogeneity could not be met, even after data transformations (Levene's; Sokal & Rolf 1995), significance was measured against an alpha value of 0.01 to compensate for the increased likelihood of a Type I error (Underwood 1997).

All statistical analyses were performed using the software package SPSS Statistics 17.0.

4.3 Results

A total of 282 RTS (on snorkel) and 29 SCUBA dives were used for analyses. Of these, 55% resulted in a *G. cyanea* sighting (Table 4.2). A further 28 surveys conducted in SA and SG habitats were excluded, contributing < 3 % of total *G. cyanea* sightings.

Habitat partitioning

Abundances (Table 4.2) and densities (Fig. 4.2) of *G. cyanea* varied across nearshore habitats, with populations more than 80 % higher in the RK zone than all other habitats (ANOVA: $F_{3,1688} = 49.20, p = 0.00$; SNK, $p < 0.01$). Size frequency analysis revealed that habitat partitioning occurred amongst the smallest and largest size classes observed (Fig. 4.3). Smaller individuals were consistently observed in the complex rocky intertidal habitats, and no sightings of fish below 200 mm L_S (i.e. size classes XXS, XS and S) in habitats at depths greater than 5 m. Larger size classes, on the other hand, were occasionally seen in the algal zone at 2 m depth; however, fish over

Table 4.2 Details of total sampling effort and *G. cyanea* abundance across habitat categories surveyed at locations across the LHI archipelago. See Table 4.1 for comprehensive descriptions of each habitat.

	Map	Depth (m)		Bluefish present		N	*n*	
HABITAT	Location$^{\#}$	Mean (± S.E.)	Spread	Yes (%)	No	surveys	fish	% total
Rocky Intertidal (RK)	1 to 7	0.79 (0.03)	0.5 - 1.7	98	2	80	1430	66
Algal Zone (AZ)	1 to 7	1.65 (0.03)	1.0 - 2.5	29	71	74	167	8
Coral Dominant (CD)	1 to 6	2.96 (0.10)	2.0 - 4.5	14	86	56	87	4
Deep reef (DR)	1 to 7	5.02 (0.07)	4.0 - 6.2	46	54	72	253	12
Offshore^ (DI)	8 to 20	15.21 (0.71)	7.7 - 20.1	89	11	29	222	10
			TOTAL:	**55**	**45**	**311**	**2159**	**100**

^ denotes boatdives conducted on SCUBA; includes sites attached to islets. Note: All other surveys were roaming transects conducted on snorkel. $^{\#}$ As per Fig. 4.1

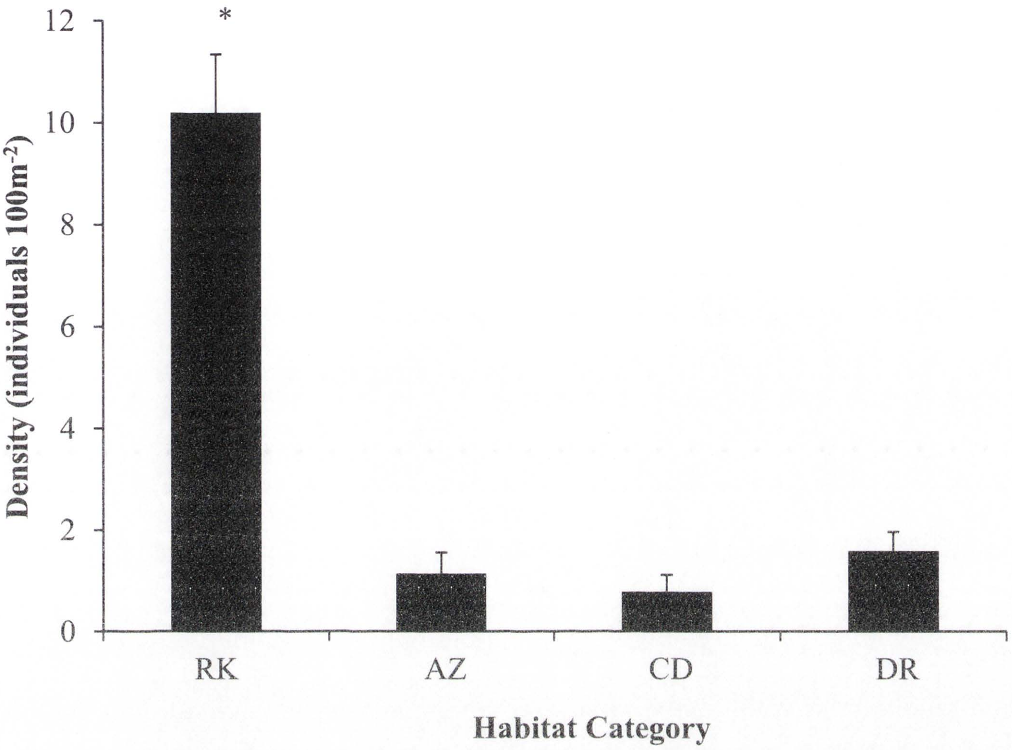

Figure 4.2 Mean densities (± S.E.M) of *G. cyanea* in nearshore habitats, recorded from RTS swims pooled across locations (see Table 4.2 for sample sizes). Asterisk denotes significance ($p < 0.01$).

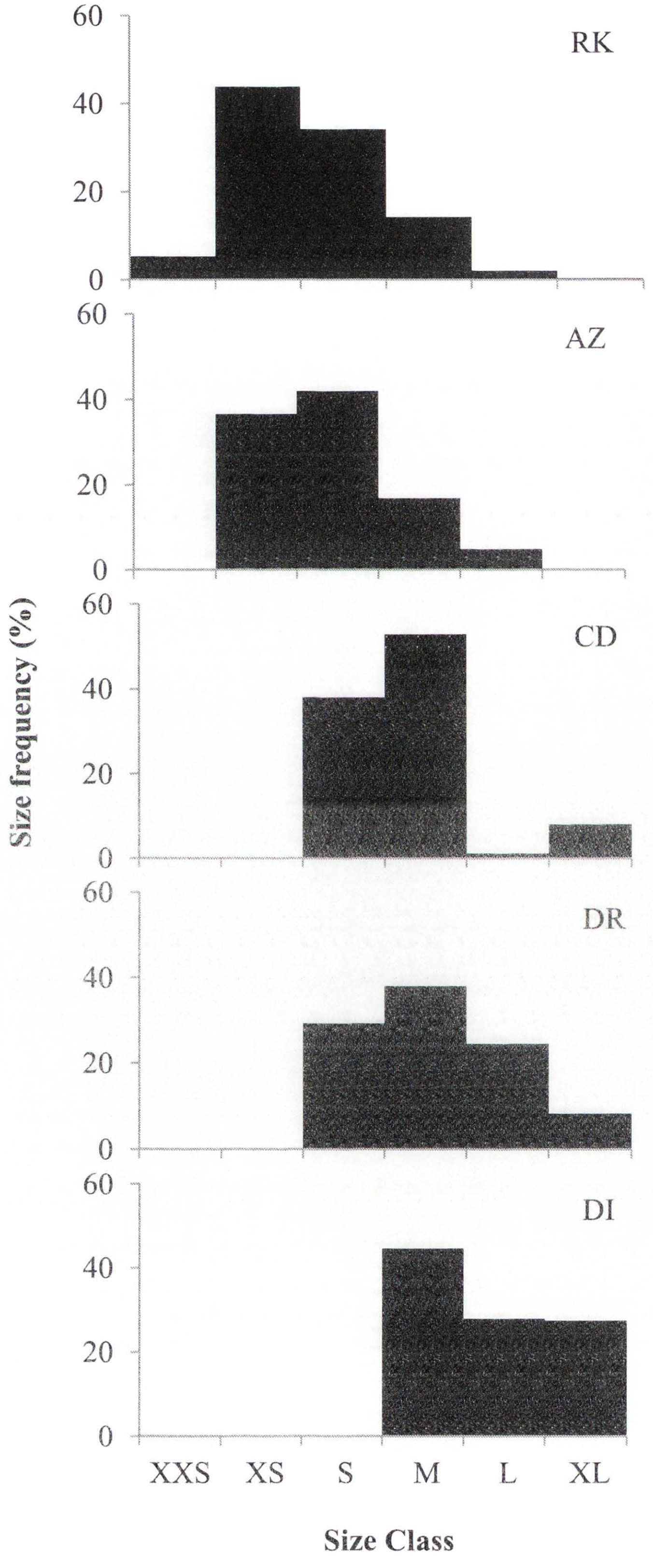

Figure 4.3 Size compositions of *G. cyanea* within habitat zones: RK - Rocky intertidal, AZ - Algal, CD - Coral-dominated, DR - Deep reef, DI - offshore (see Table 4.1 for habitat descriptions). Data for nearshore RTS swims (RK, AZ, CD, DR) combines *G. cyanea* sightings across locations.

300 mm L_S were not sighted in any habitat shallower than 4m, with almost 64 % of XL individuals observed on offshore dives (Fig. 4.3: DI).

Depth stratification

When data was pooled for habitat, depth distributions of *G. cyanea* were significantly stratified (ANOVA: $F_{5,2164} = 199.08$, $p = 0.00$). Fish observed below 200 mm L_S showed a strong relationship with intertidal depths whilst fish of increasing size classes were associated with greater depths (SNK, $p = 0.01$, Fig. 4.4). Increased variability in M, L and XL size classes suggested a greater range of depths utilised by fish > 200 mm L_S (Fig. 4.4: SEM).

Environmental factors

Nearby shelter (67 %) and the presence of other bluefish (91 %) appear to be important factors in *G. cyanea* distributions (Fig. 4.5). Closely related kyphosid spp. (*K. pacificus*, *K. vaigiensis*) were observed within *G. cyanea* schools in 37 % the sightings. Although, L_S were not recorded for heterospecifics, body sizes observed were consistently similar to those of *G. cyanea* within the same school (pers. obs.). Observations of *G. cyanea* actively feeding on benthic substrate (turf / *Ulva* sp.) or in midwater (*Ulva* sp. / unidentified material) were limited (22%; Fig. 4.5).

LHIMP zones

Comparisons of LHI Marine Park management zones revealed similar patterns of abundance across habitats, although the total number of fish observed differed amongst the zones: 24 % more fish were observed within the SZ than in the HPZ, and 37 % more than in the isolated HPZ (Fig. 4.6). Slightly more *G. cyanea* were observed in DR habitat where fishing pressure was presumably low (isolated HPZ) or absent (SZ). The AZ, where shelter is absent and complexity is low, exhibited a higher proportion of fish within the isolated HPZ compared to the HPZ and SZ (17 %, 6 %, 7 % respectively), which may reflect naivety to diver/observer presence. An opposite affect is possibly reflected in the surprisingly higher proportion of fish in RK habitat within the HPZ (82 % vs. 77 % in SZ, 62 % in isolated HPZ), where complexity and shelter may provide refuge from regular exposure to angling.

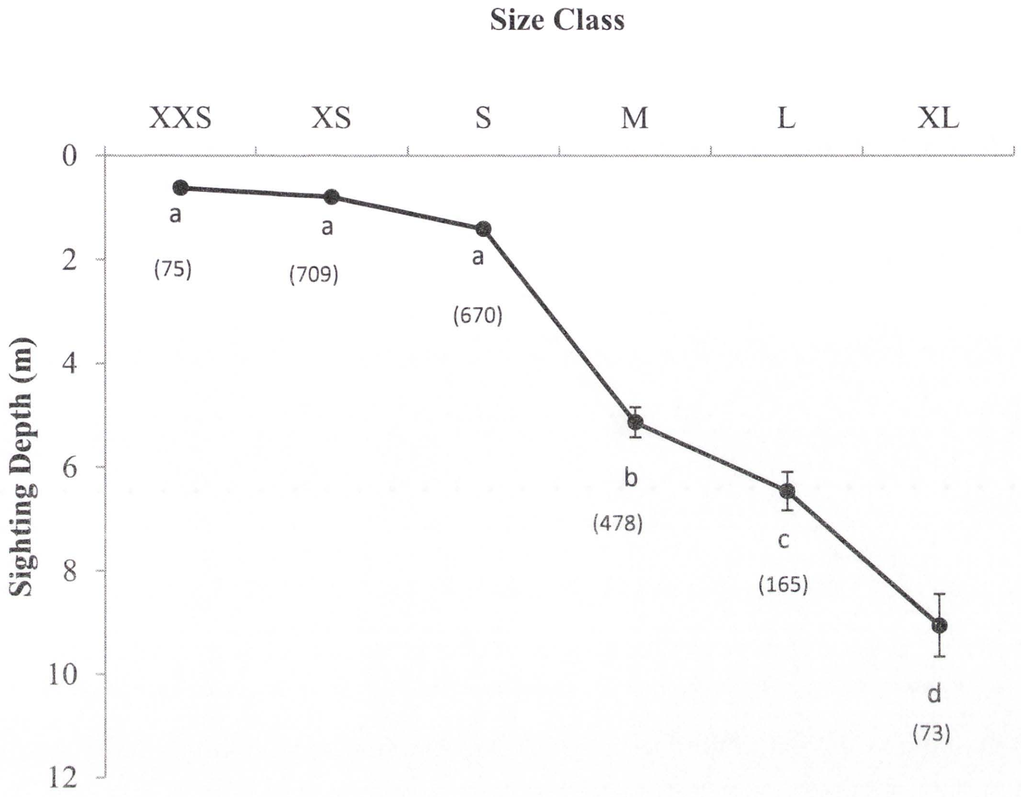

Figure 4.4 Depth distributions of *G. cyanea* (Mean ± S.E.M.). Data represents all sightings (nearshore + offshore), pooled for habitats. Differing letters denote significance (SNK: $p < 0.01$). Sample sizes for each size-class are given in parentheses.

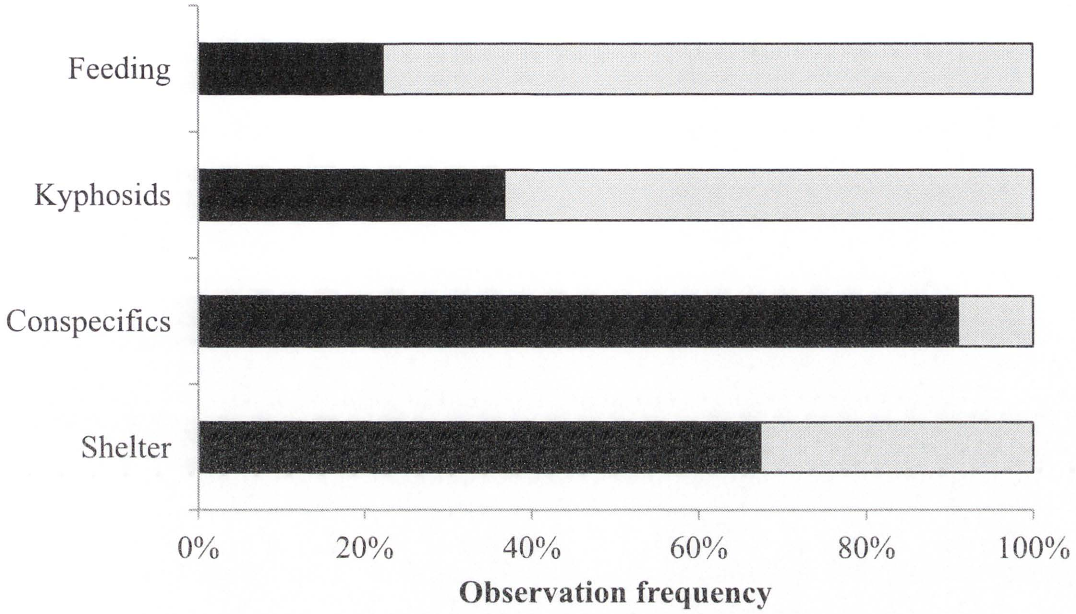

Figure 4.5 Occurrence of four environmental factors associated with *G. cyanea* sightings. Data is presence (black)/absence (grey).

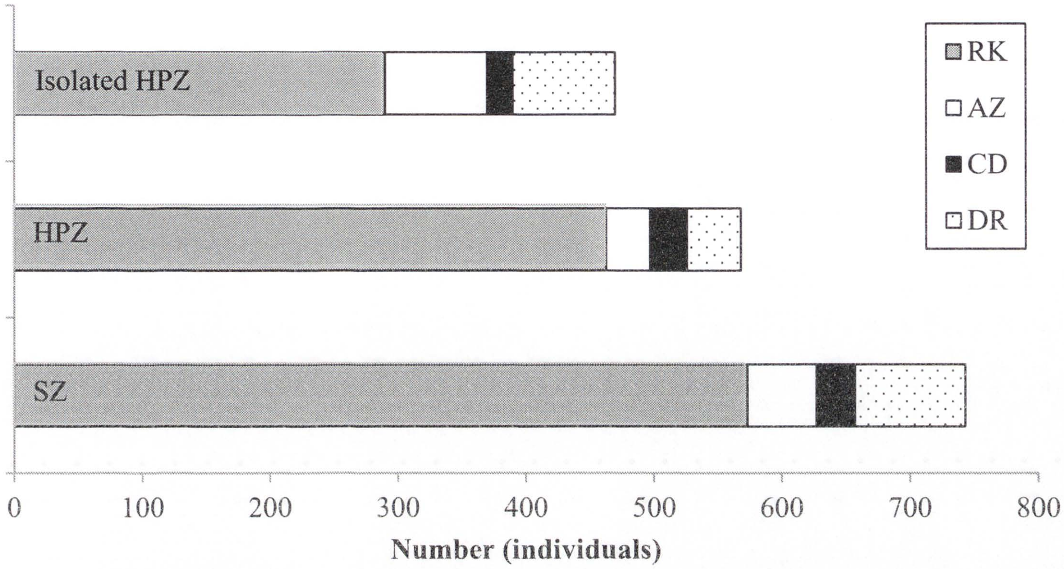

Figure 4.6 Segregation of RTS-observed *G. cyanea* across LHI Marine Park zones. Data are pooled for nearshore habitats and size-classes within zones (i.e. two locations per zone; see Fig. 4.1 for further detail).

4.4 Discussion

This study took place over four sampling periods, five habitat types, and twenty locations around the LHI archipelago. This considerable sampling effort revealed relatively low densities of *G. cyanea* in all areas surveyed (Fig. 4.2). Speare et al. (2004) raised similar concerns when deep baited video surveys failed to record any reservoir stocks that may replenish nearshore populations of *G. cyanea*.

Distribution of juveniles to adults, from complex intertidal to rocky-reef

Mean densities were highest in complex rocky intertidal areas, a finding consistent for many herbivorous species (e.g. Choat & Ayling 1987), including congenerics (Thomson & Lehner 1976, Stevens et al. 1989, Cole 2001). This was not surprising, given the evidence that tide pools in adjacent high intertidal areas are important in the early life histories of girellids. *Girella nigricans* settles in to its post-planktonic life as an abundant transitory species in tidepools along the Chilean coast (Pulgar et al. 1999). At approximately 2 yrs of age it migrates to subtidal areas, where it completes its life cycle (Norris 1963, Stepien 1990, Varas & Ojeda 1990). Body sizes of 28-191 mm L_T have been reported in tide pools in Chile (*G. laevifrons:* Munoz & Ojeda 1997, Aldana et al. 2002) and 17-90mm L_S at LHI (*G. cyanea:* Chapter 6). The relatively high abundance of *G. cyanea* in the rocky intertidal (Table 4.2) is most likely indicative of this habitat selection by settling larvae. No studies have looked at pre-settlement behaviour in *G. cyanea*, but many larval fish exhibit high mobility and can sample habitats as they move across them (Sale et al. 1984, Levin 1991, Kingsford et al. 2002).

An ontogenetic shift in habitat was evident beyond the S size-class (i.e. fish > 200 mm L_S). Pooled for habitats, all observations of fish < 200 mm L_S were made in depths shallower than 2 metres. At this size, *G. cyanea* are likely in transition to sexual maturity (Chapter 6). Utilising shallower habitats, especially of high complexity, would reduce predation risk until sexual maturation is achieved. Larger fish utilised a greater range of habitats (Fig. 4.3) but significant vertical partitioning occurred with increased body size (Fig. 4.4). Nearby shelter and the presence of conspecifics appeared to be important factors in *G. cyanea* distributions (Fig. 4.5). Feeding was observed only some of the time (22%), and these observations were recorded across all habitats, thus the conclusions of distribution made here are not biased towards foraging behaviour. This does, however, raise the question as to why large feeding aggregations were not observed in the present study. Subtropical areas, like LHI, harbour browsing herbivores often observed feeding on subtidal algae in large numbers (Schiel et al. 1986, Choat 1991, Cole et al. 1992). Anecdotal reports suggest feeding aggregations of adult *G. cyanea* at common dive sites around LHI, especially at Yellow Rock (Busteed pers. comm.) – a site surveyed in the present study. Some work has suggested feeding peaks (Choat & Clements 1993 Ferreira et al. 1998) corresponding to photosynthate accumulation in algae (Polunin & Klumpp 1989). Sampling in the present study took place only at high tide (± 1 hr) so it is plausible that many RTS were conducted outside of the preferred foraging window. Very little is known of the diet of *G. cyanea* to help explain the distributions observed here, but given their association with high relief rocky-reef habitat, it seems likely that a dietary analysis might reveal the importance of macro-algal species found in these habitats (Chapter 5). The depth stratification shown here may indeed correlate to the vertical gradient in abundance and quality of algal foods, from shallow chlorophytes (e.g. *Ulva* spp.) to deeper phaeophytes and rhodophytes (Metataxa & Scheibling 1993).

Shortcomings of this study are acknowledged. Due to relatively small areas of contiguous habitat within the four nearshore habitats used here (RK, AZ, CD and DR), localities were not able to be tested for local-scale differences in patterns of abundance and size structure. This isn't considered a major issue, however; the results nevertheless concur with findings in other girellid studies (Thomson & Lehner 1976, Stevens et al. 1989, Yagishita & Nakabo 2000, Francis 2001), and confirm that *G. cyanea*, typically occur in shallow rocky reefs (< 30 m) where they are associated with resources such as food (i.e. macroalgal spp.) and refuge from predators (i.e. complex rock/shelter). For the purpose of effective management however, future data should consider a resolution of several spatial- and temporal- scales. This will provide a means of assessing if/when changes in populations are occurring and prioritise adjustments to current management regimes.

Small-scale changes in habitat (e.g. shallow intertidal to deeper reef zones) and/or complimentary behavioural shifts (e.g. shoaling to solitary) are likely to accompany size-related shifts in diet (Jones 1984, Brodeur 1991). This study confirms that *Girella cyanea* have similar requirements (i.e. complexity) but occupy different areas throughout their ontogeny. Fish that recruit to shallow intertidal rocky habitat yet occur in deeper waters as adults may encounter a wider range of prey and availabilities of prey than fish which remain in one habitat throughout their lives. Patterns of *G. cyanea* distribution observed in the present study would likely be complimented by an increased understanding of their dietary resource-use.

Chapter 5 - Herbivory, pseudo-herbivory or omnivory? The highly variable diet of the Bluefish (Girellidae: *Girella cyanea*) at Lord Howe Island

Abstract. In this study, the stomach contents and gut morphology of 88 *Girella cyanea*, collected from Lord Howe Island, were analysed. Size-specific relationships among diet, relative gastro-intestinal length, and body mass were assessed. An ontogenetic dietary shift was evident in fish < 40 mm standard length (L_S). Individuals at that size exhibited a predominantly carnivorous diet, with an observation of a pyloric caeca a novel finding for species of the Girellidae Family. High levels of omnivory were exhibited by all size classes > 40 mm L_S, despite some large adult individuals consuming no animal-derived food items at all. Our results suggest that diet, at least in some nominally herbivorous fishes, is highly variable. *G. cyanea* should be considered an omnivore, as has been suggested for other congenerics.

5.1 Introduction

Food is a fundamental resource for life and plays a major role in the distribution, abundance and growth rate of a species. At suboptimal levels, variability in growth will influence the size structure of a population, and has been found to alter size at sexual maturity as well as reproductive output (Jones 1991).

Gastro-intestinal length as an indicator of diet has been reported in terrestrial (e.g. Jackson 1992, Korn 1992, Yang & Joern 1994) and aquatic (e.g. Al-Hussaini 1947, Kapoor et al. 1975, Ribble & Smith 1983, Horn 1989, Kramer & Bryant 1995b) trophic studies. Generally, species that eat mainly algae and higher plant material ("herbivores") exhibit longer digestive tracts than those with a mixed plant and animal diet ("omnivores") and also than those consuming mainly animals ("carnivores"). This widely recognized anatomical feature was first observed in the ruminants which require longer retention times and increased exposure of ingesta to the gauntlet of digestive processes (Sibley & Calow 1986), since target food items are not easily digestible and considered nutrient poor (Horn 1989). The nutrients of the morphologically and chemically-defended food items often ingested by herbivores are shown to be more efficiently extracted with such an increase in exposure (Savory & Gentle 1976, Sibly 1981, Yang & Joern 1994, Starck 2005).

Herbivorous marine fish commonly display a shorter relative gut length as juveniles. This observation corresponds to an early carnivorous diet and, at some point in the ontogeny, a shift in diet to herbivory is accompanied by a lengthening of the digestive tract (Montgomery 1977, Horn *et al.* 1982, Rimmer 1986, Bellwood, 1988). Consistency in this observation has led to the Optimal Foraging Theory (OFT) that is based on the assumption that energy should be maximised by organisms that select their diet, and thus that consumers will concentrate their foraging efforts on achieving the best possible diet (see review by Pyke et al. 1977). Two predictive models are prevalent in the OFT: 'optimal digestion' (Sibly 1981) – when organisms consume nutritionally low-quality food they will ingest larger amounts and therefore exhibit larger digestive chambers; and, 'optimal diet' (Schluter 1981) – under conditions of high food density, a forager will concentrate its feeding in the energetically most valuable prey type. Additionally, changes in dietary profiles will likely occur along growth trajectories, especially in long-lived species. The rapid growth of individuals, for example, may be facilitated by high quality (protein) diets. Often, large species will have passed through several magnitudes in size throughout their ontogeny, with each life stage modifying the availabilities of prey.

Existing information on the diet of *G. cyanea* is limited. Gut analyses in previous work (Clements & Choat 1997 and Clements & Zemke-White 2008) have provided snapshots (i.e. specimens are from a single sampling event and/or constitute a limited size-class), but the generality of these patterns is unknown. The present study analyses diet data on *G. cyanea* collected over a two year period. Although seasonal, spatial and microhabitat differences in diet selection have been reported elsewhere (Clements & Choat 1993, Raubenheimer et al. 2005,Caceres et al.1994), the opportunistic sampling strategy and ensuing unbalanced design here prohibited testing of these sources of variation. This limitation often provides for an incomplete picture of the variable of concern. In the present study however, the descriptions of diet are less about microhabitat differences than the importance of ontogeny. They provide the first information on diet of *G. cyanea* across size classes. A particularly important objective was to assess whether a dietary shift occurred in this species because post-settlement habitat use varied over the growth of the species (Chapter 4). The hypothesis was that gut contents of small size-classes (juveniles) would exhibit predominantly animal-derived food items and that this would change to predominately plant/algal -based foods with increases in body size (adults). An attempt to assign *G. cyanea* to a feeding guild is also made by assessing dietary items alongside two standard indices for gut length.

5.2 Materials and methods

Sample collections

Fish were collected at different locations of the Lord Howe Island (LHI) archipelago (Fig. 5.1) over four fieldtrips: Oct-Dec 2005, Mar-Apr 2006, Nov-Dec 2006, Feb-Mar 2007. Sites were chosen opportunistically on the day of sampling based on accessibility and areas known by locals to have *G. cyanea* present at that time. Because of very low abundance or absence at some sites, it was not possible to replicate sampling by location or season. Further specimens were obtained from local recreational fishers on an opportunistic basis at periods from May to October 2006. All specimens were collected between 0900 and 1800 hours. Adults and large juveniles were caught using a barbless small-gauge hook and 3-4 kg line fitted with a single split-shot weight and prawn bait. Capture methods and locations were restricted due to constraints imposed by the scientific research permit, the Marine Park Management Plan, and community acceptance. Small juveniles (< 90 mm) and settlers (< 17 mm) were collected from intertidal rockpools at low tide using a handnet and administering a 40 mg/L eugenol solution (1 part clove-oil: 9 parts 95 % ethanol) dispensed through a spray-bottle. Once captured, all fish were immediately placed in a tub of seawater and euthanised by anaesthesia-overdose using the eugenol solution (Bordski & Hodson 2003), which caused fish to rapidly lose consciousness and induced hypoxia. Fish were left in the solution until all evidence of gill movements had ceased.

An insulin needle was inserted ventrally into the gut cavity to dispense 70% ETOH for preservation of the digestive tract. This was repeated for larger fish and was also dispensed both orally and anally. Fish were then frozen for transport from LHI to the UTS Fish Ecology Laboratory, Sydney.

Fish dissection and measurements

At dissection, fish were weighed (Wo, +/- 0.0001g) and measured (L_S, +/- 1mm). The relationship between length and weight was calculated by fitting a nonlinear regression model using least squares (Ricker 1973) and described in the form:

$$Wo = \mathrm{a}\, L^{\mathrm{b}}$$

where Wo is total wet weight (g), L is standard length (mm), and a and b are constants.

The gastro-intestinal tract was then excised, uncoiled and measured at a relaxed state (L_G, +/- 1mm), and separated into segments: oesophagus and stomach (I), then four equal segments (intestinal II, III, IV and V) after Clements & Choat (1997). The length of the entire tract was standardised for body length by using the common formula for relative gut length (also called *gut length ratio, GLR*):

$$\mathrm{RGL} = L_G / L_S$$

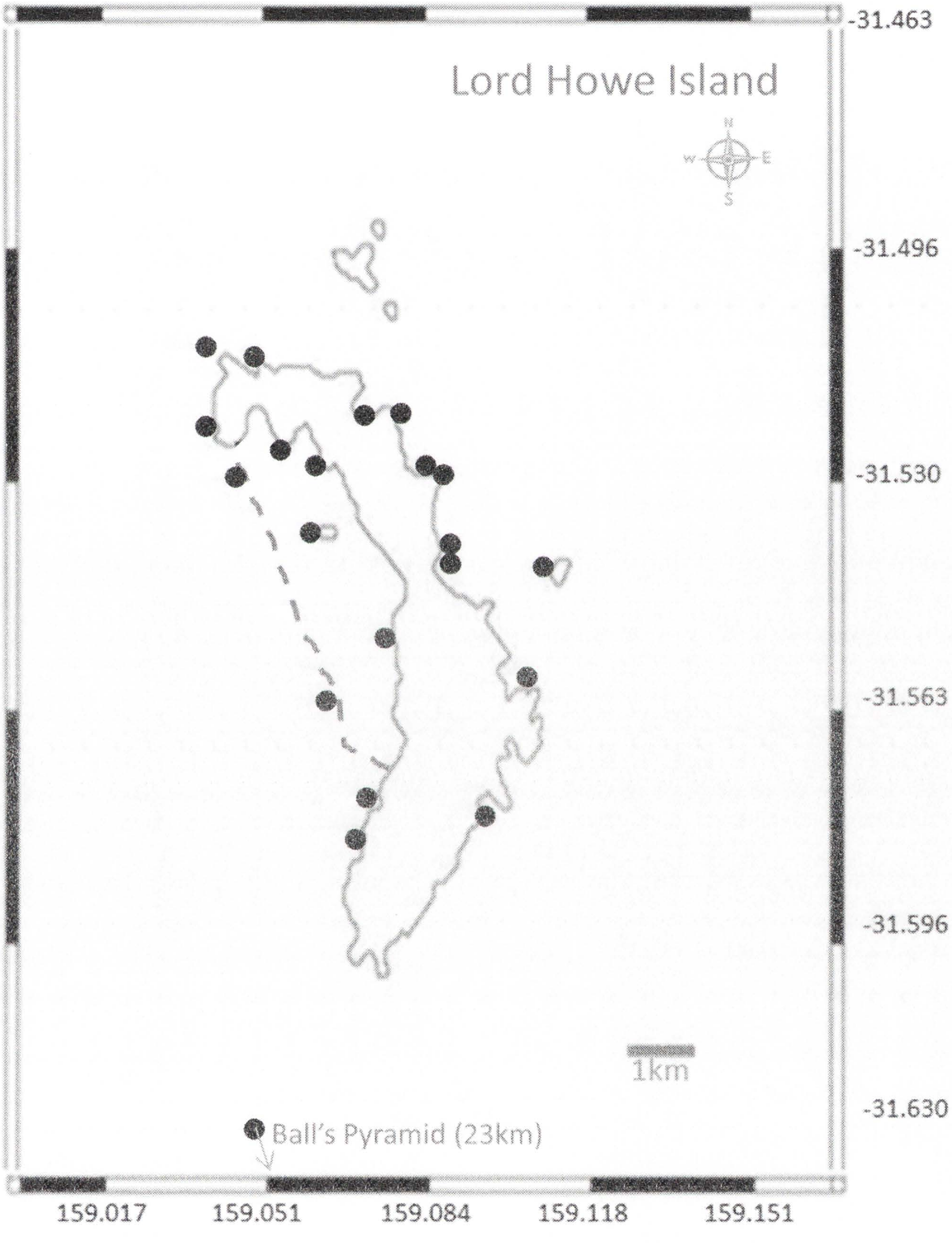

Figure 5.1 Sampling locations of *G. cyanea* at Lord Howe Island. Black dots represent fish collections (see Methods for details).

Additionally, since intraspecific variation in intestinal length is sometimes assumed to be the result of size-dependent dietary changes (e.g. Montgomery 1977, Rimmer 1986), we used the Zihler Index (ZI) which is based on body mass (Wo):

$$ZI = L_G / 10 \times Wo^{1/3} \qquad \text{(Zihler 1982)}$$

To examine the size-specific relationships among diet, relative gastro-intestinal length, and body size, four arbitary size classes were selected (<100mm, 100-199 mm, 200-299mm, ≥300mm L_S) based on previous work on related species to aid in interspecific comparisons. Boundaries of these size classes also corresponded with those developed in Chapter 3 and used in Chapter 4 (i.e. XXS, XS+S, M+L, XXL respectively). Internal gut morphology, however, indicated a marked reduction or absence of pyloric caeca in recruits, so the juvenile <100 mm L_S (i.e. XXS) size class was separated further into two (<40 mm and 40-99 mm). Interestingly, individuals of the smallest size class were collected within weeks of recruiting to tidepools (pers. obs.) and subsequent otolith analysis have dated them to be less than 50 days old (unpublished data). Absence or decreased size of pyloric caeca, to the best of our knowledge, has not yet been reported in the literature for girellids or kyphosids.

Dietary examination

For individuals obtained by angling methods, bait found within the pharyngeal cavity (bread burley and prawns) was discarded and not included in estimates of gut volume and mass, nor recorded as dietary items. It should be noted however, that some of the indiscernible animal content in some individuals may have been from previous angling effort on that individual, although in this study the same sites were only visited once per fieldtrip.

Visual sampling of gastro-intestinal contents was carried out at x10 magnification using a dissecting microscope and a white background. Unidentified matter was further visually examined under higher power using x40 magnification. Contents were recorded from within one of the five gut sections to allow for differing rates of digestion along the digestive tract. Contents were grouped into 15 categories (see Table 5.2) based on classification or algal functional group where specific identification was not possible due to the small fragments or part-digestion.

The literature provides no standardised method for quantitative analysis of dietary components, thus several methods were included to ensure accurate description (Hyslop, 1980). For each category in each individual, contents were volumetrically measured using a 220 x 50 x 1 mm Sedwick-Rafter cell, resulting in a cubic millimetre measurement that was later converted to cubic centimetres. In some individuals, the cell was filled up to 20 times so transfer loss was measured. This was found to be negligible (0.06 %, $n = 32$). Although time-consuming, this method was chosen over others (e.g. Choat and Clements 1992) to omit ambiguity with depth of 'spread' which could affect volumetric calculations and result in comparisons of a more relative nature. In cases where the cell was not completely filled (i.e. $< 1\text{cm}^3$) the grid was viewed under x6 magnification on a black background for enumeration. The entire tract was examined because initial observations suggested episodic feeding, that led to pooling of contents that may be missed if only a portion was assessed. Enumerated contents were pooled by item per fish and wet weighed (+/- 0.0001g) using a Sartorius balance.

Diet composition and data analyses

For each dietary category the following were calculated:

1. the frequency of occurrence (FO): the proportion of sampled fish that contain that dietary item.
2. mean percentage volume (% V): the sample average of the percentage of the volume of that dietary item with respect to the total volume of the gut contents.

For the quantification of herbivory, food categories 1-7 (algae and seagrass) and 8-14 (animal derived) were summed to give the proportional amount of 'plant' versus 'animal' content. Trophic diversity was assessed using the Shannon-Wiener Index (H):

$$H = -\sum_{i=1}^{R} p_i \ln p_i \qquad \text{(Shannon 1948)}$$

where p_i is the proportional occurrence of food category i. This index is particularly appropriate because it accounts for the total number of food categories (dietary richness, R) used by each size class and the frequency that different foods are ingested. Thus, an opportunistic feeder will display a tendency to euriphagy, expressed as a higher H'. Within-group variability was then described using the Evenness Index (J):

$$J = H / \ln R \qquad \text{(Pielou 1966)}$$

where J is constrained between 0 and 1. Hence, less variation in diet amongst individuals of a particular size-class will be expressed in a J-value that nears 1.
To examine whether the degree of herbivory changed with size, all analyses were partitioned into the previously defined size classes. Morphometric relationships were assessed using regression analyses. Differences between size class means for relative gut length, Zihler's Index, and major food groups were assessed using one and two factor GLM analysis of variance where appropriate, with all factors fixed. Significance levels were set at an alpha level of 0.01 to decrease the probability of Type I errors associated with heteroscedastic data (refer to Chapter 4: Methods). ANOVA tests were performed using IBM SPSS Statistics 19. Volumetric quantities of dietary components were assessed for each size class using Primer (v6). Food items that contributed most to the differences between diets of each size class (i.e. between-group variability) were extracted by pairwise comparisons of Bray-Curtis dissimilarities (SIMPER). Running food items as variables and size class as a factor, a one-way analysis of similarity (ANOSIM) tested the null hypothesis that diets among size classes did not differ (Global R = 0); rejected at $\alpha < 0.05$. Only SIMPER results from adjacent size classes are presented because these were also the minimum average dissimilarities of all ten pairwise comparisons.

5.3 Results

Length-weight relationship and morphology

Body length and mass were determined for a total of 258 *G. cyanea*, from newly settled recruits to spawning females. The standard length and wet weight of specimens ranged from 17 to 446 mm and 0.05 to 2220 g, respectively. The length-weight function was calculated as $W = 0.00001L^{3.18}$ (Fig. 5.2), indicating that growth is positively allometric for this species.

Small juvenile fishes that lacked pyloric caeca (<40 mm L_S, $n = 11$) also exhibited less demarcated stomach chambers, as opposed to the well-defined muscular stomachs observed in larger specimens ($n = 216$; Fig. 5.3). Ratios of stomach (inclusive of oesophagus) to intestinal segments were 0.50 (± 0.06) for fish <40 mm L_S and 0.24 (±

0.02) for > 40 mm L_S. The entire length of the intestine was thin and coiled (Fig 5.3: inset), and no hindgut chamber was present at any size. Digestive tract as a function of body length was considerably shorter in specimens smaller than 40 mm than all other sizes combined ($L_G = 1.42\ L_S$ vs. $3.77\ L_S$; Fig. 5.3). Regression analysis showed that this relationship was significant ($R^2 = 0.89$, $\beta = 0.944$, $p < 0.0001$), and best expressed for the species as $L_G = 3.69\ L_S + 31.96$ (Fig. 5.4: left). Plots of gut length on body length and gut length on body mass were far from isometric, with both relationships exhibiting a high level of allometric scaling (Fig. 5.4). A rapid increase in gut length in the early juvenile stages (fish < 80 mm L_s) was evident. At 80 mm L_S the rate of increase in gut length slowed. Although the sum of least squares line of best fit explained the L_G to Wo curve as a power function ($R^2 = 0.96$), a single data point exerts considerable pressure on the end of the curve. This data point was not necessarily an outlier; more data collected from larger specimens could show the L_G to Wo relationship as asymptotic, and further explain the slowing of growth of the digestive tract.

Diet composition

Each of the 88 specimens analysed for diet had full guts except one that had an empty intestinal segment II. In all sizes, algal colour and integrity remained relatively intact in the stomach, and was only slightly altered in colour and consistency by segment V. However, when animal material was present and mixed with algae (n = 34), the algae appeared well digested by the time it reached the posterior end of the gut and often not separable from the animal tissue. Additionally, the animal source was indiscernible by segment V. This problem increased with each size class (see 'Mixed' group: Table 5.1).

No one dietary item was present in all fish sampled for gut contents, with all size classes displaying highly variable diets (Table 5.1). Green algal species (chlorophytes) were consumed more commonly than red (rhodophytes) and brown (phaeophytes) algae, with *Ulva* spp. found in over half the guts of specimens (Table 5.1). All size classes exhibited high levels of omnivory, but newly settled juveniles (< 40 mm L_S) consumed predominately animal-derived items as opposed to algae (87.5 % vs. 12.5 %; Table 5.1). In fact, only one of these fish consumed any algae at all (50 % sheet chlorophytes), and that individual was the single contributory factor behind the relatively low evenness index, J, for that size class (Table 5.2). Interestingly, this was the largest specimen of that size class assessed in dietary analyses ($L_S = 35$ mm). The digestive tract in this fish

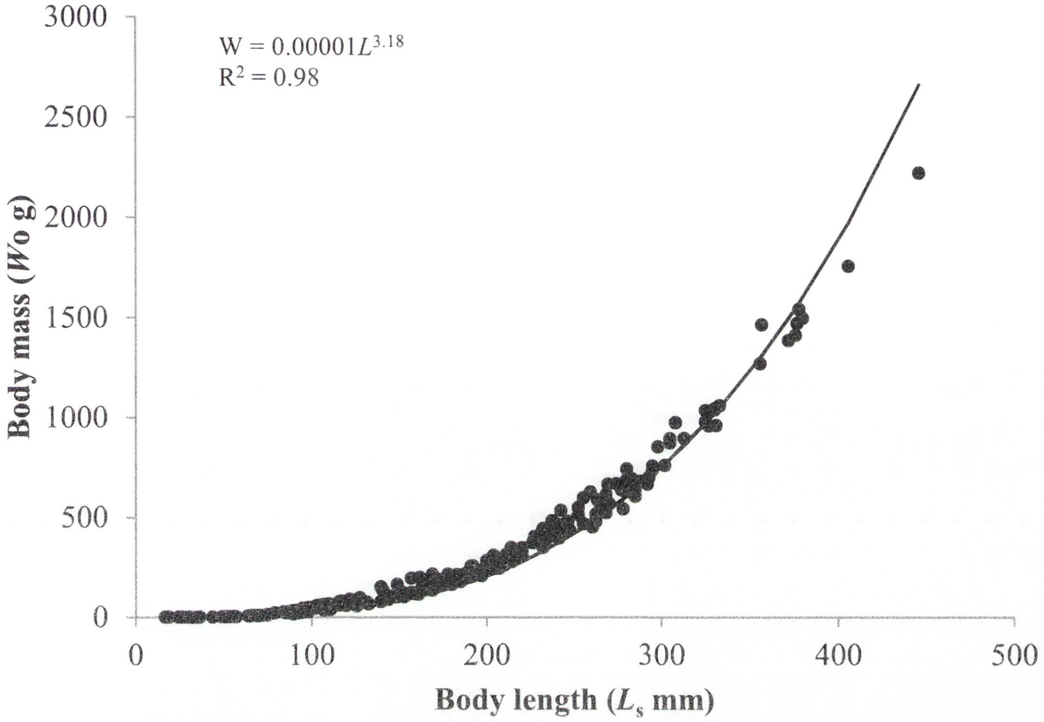

Figure 5.2 The relationship of length and weight in *G. cyanea* (n = 258).

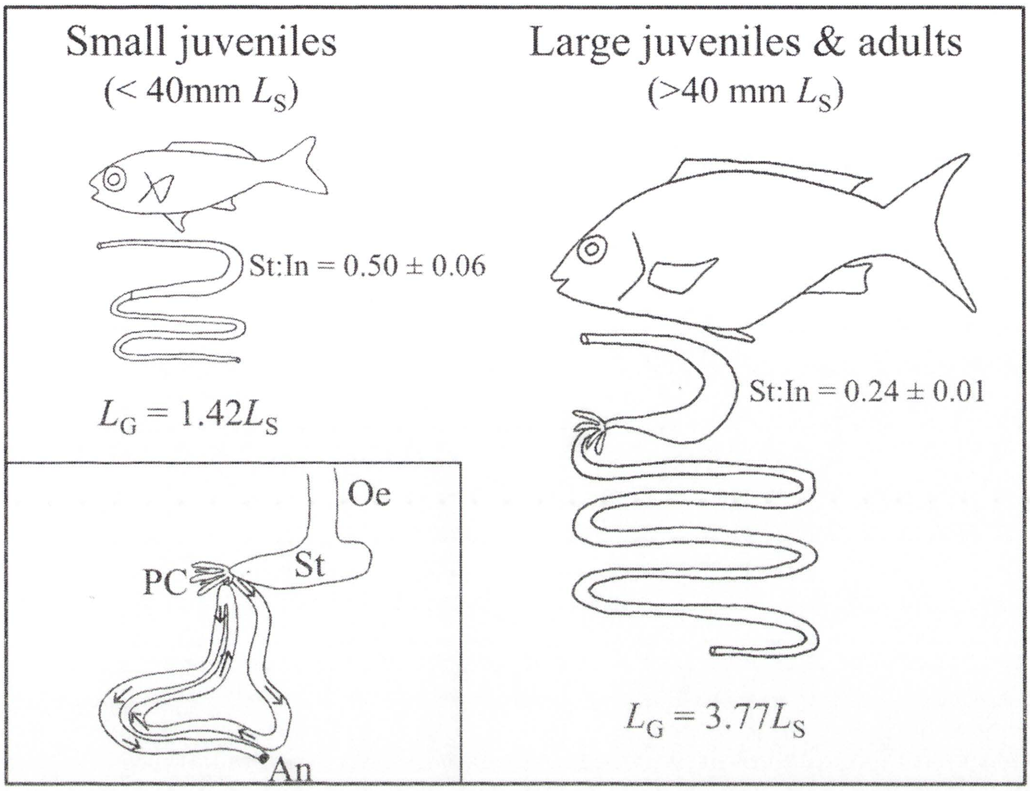

Figure 5.3 Schematic drawings of the digestive tract of *G. cyanea*. Gut length is to scale with body lengths with equations displayed (small juveniles, $n = 22$; juveniles to adults, $n = 216$). Inset shows the general coiling pattern of the intestine, with direction of movement shown by arrows (Oe = oesophagus, St = stomach, PC = pyloric caeca, An = anus).

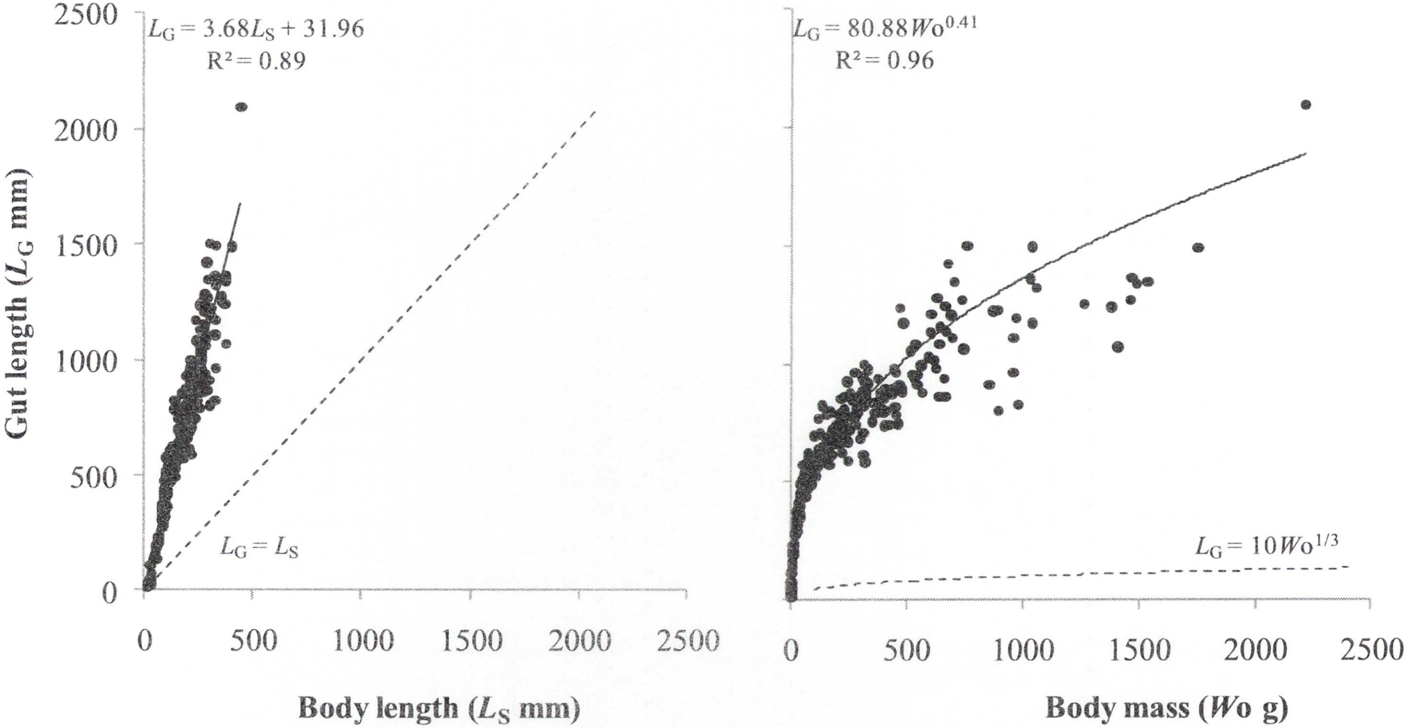

Figure 5.4 The relationship between the length of digestive tract and two measures of body size (n = 258). Data points represent individual specimens. Solid lines express regression slopes. Dotted lines indicate isometric growth ,with gut length equal to standard length (left) and gut length equal to 10(body mass)$^{1/3}$ (right).

Table 5.1 Food items in the diet of sampled *G. cyanea*. Shown is the percentage of individuals in which the dietary item occurred for each size class (n = 8, 8, 27, 34, 11) and for all sizes combined (n = 88). The total number of guts containing the food item is also shown. (— indicates item was absent from gut contents).

Major Food Group			**FO (%) per size class**					**FO (all sizes)**	
	Category	**Description**	**<40**	**40-99**	**100-199**	**200-299**	**≥300**	**%**	***n***
PLANT	Chlorophytes:								
	—Sheet	*Ulva lactuca, U. rigida, U. laetevirens, U. compressa*	12.5	62.5	66.7	79.4	63.6	65.9	58
	—Branching	*Enteropmorpha howensis* - endemic to LHI, occasional *Caulerpa cuppressoides*	—	87.5	59.3	55.9	72.7	56.8	50
	—Filamentous	Turf: *Cladophora* spp.	—	25.0	44.4	23.5	63.6	33.0	29
	—Spongey	*Codium bulbopilum, C. Spongiosum*	—	—	—	2.9	27.3	4.5	4
	Rhodophytes:								
	—Branching	Delesseriasaeae, *Plocamium hamatum*, very occasional *Liagora howensis*	—	12.5	3.7	2.9	9.1	4.5	4
	Unidentified algae	Inseparable algae often with like-forms. Mostly chlorophytes, some rhodophytes.	—	12.5	22.2	38.2	54.5	29.5	26
	Phaeophytes:	*Ecklonia radiata, Glossophora kunthi* (kelplike)	—	—	3.7	—	36.4	5.7	5
	Seagrass	Exclusively *Zostera capricorni*	—	—	11.1	11.8	—	8.0	7

....continued overleaf

Table 5.1 ctd.

Major Food Group	Category	Description	FO (%) per size class					FO (all sizes)	
			<40	40-99	100-199	200-299	≥300	%	n
ANIMAL	Krill	Exclusively *Euphausid* sp. Comparitively large black eyes; pink often fleshy; approximate length 6± mm L_T	—	—	18.5	23.5	54.5	21.6	19
	Planktonic	Plankton-derived animals such as copepods (~3mm), barnacle cyprids and nauplius, megalopa, salps	12.5	25.0	—	8.8	9.1	8.0	7
	Benthic	Benthic-derived animals such as gastropods, polychaetes, isopods, chironomids, nemerteans	—	12.5	—	5.9	9.1	4.5	4
	Hydroid	A number of species of epiphytic and free floating forms, including *Velella* sp.	12.5	—	3.7	—	18.2	4.5	4
	Foraminifera	Two species: *Baculogypsina sphaerulata* (Calcarinidae) and *Marginopora vertebralis* (Soritidae)	—	—	7.4	11.8	—	6.8	6
	Fragments	Molluscan and crustacean exoskeletons that could not be identified further. Fish scales. Occasional urchin spine.	—	25.0	11.1	5.9	—	8.0	7
	Unidentified	Tissue of animal origin with no distinguishable parts; often occurring within gut segments also containing krill	87.5	62.5	3.7	20.6	27.3	26.1	23
MIXED		Inseparable algae (often *Ulva* spp.) and unknown animal tissue	—	—	3.7	11.8	18.2	8.0	7

was 50 % longer than the next smallest fish (L_S = 30mm), despite an increase in body length of only 16.6 %. Moreover, the stomach to intestine ratio (St:In = 34.2) was considerably lower than that for the average for newly settled fish (St:In = 50.0; Fig. 5.3). Whether this is an expression of gut plasticity, whereby the gut changes in response to diet over a short time or of the ontogenetic dietary shift in progress, cannot be explained by our limited data.

Differing levels of dietary specialisation between size classes were evident (Table 5.2). The Shannon-Wiener Index, H, increased with body size from 0.94 for fish < 40 mm L_S to 2.16 in fish > 200 mm L_S. The number of different food items (R) consumed also increased with body size, levelling after a L_S of 100 mm, which is most likely a reflection of the increased areas accessible for foraging in larger sized fish. Despite increased feeding areas available to roaming *G. cyanea*, variability of the diets between fish of the same size class (J) remained relatively constant after 100 mm L_S, suggesting that *G. cyanea* have target food items that may be supplemented by opportunistic consumption of other items as they occur. Indeed this theory would explain the high consumption of chlorophytes and apparent episodic feeding bouts on euphausids, megalopa and hydroids.

The most common algal species (i.e. sheet and branching chlorophytes) and euphausids and other unidentified animal matter were the key contributors to dissimilarity in the diets between size classes (Table 5.2). Sheet chlorophytes accounted for between 20-29 % of the variability, branching chlorophytes for 13-19 %, euphausids for 5-14 %, and unidentified animal tissue for 12-37 %. Diets between size classes were found to be significantly different for all but the S-M/L pairwise tests (ANOSIM: $p < 0.05$ vs. $p = 0.46$; Table 5.3), albeit the Global R was weak (R = 0.33, $p = 0.001$). The high (i.e. > 1) dissimilarity/SD function for unidentified animal tissue in XXS-XS comparisons indicates that this food category was a strong and consistent contributor to the difference between sizes and further supports the occurrence of an ontogenetic shift at a body length < 40 mm *LS*.

The separation of newly settled fish (< 40 mm L_S) from the other specimens under 100 mm L_S allowed an ontogenetic dietary shift to become apparent when assessing mean relative gut lengths across size classes (Fig. 5.5). RGL rose sharply from 1.3 in the

Table 5.2 Degree of dietary specialization within size classes.

Size class (L_S mm)	*n*	Dietary richness (R)	Trophic diversity (H)	Dietary evenness (J)
<40	8	4	0.94	0.68
40-99	8	8	1.84	0.88
100-199	25	12	1.99	0.80
200-299	29	13	2.16	0.84
≥300	9	12	2.16	0.84

Table 5.3 Discriminatory food items contributing to dissimilarity in pairwise comparisons of size classes (XXS is <40, XS is 40-99, S/M is 100-199, L is 200-299, and XL is ≥ 300 mm LS). Data is percentage dissimilarity.

Pairwise comparison:	XXS-XS	XS-S/M	S/M-L	L-XL
ANOSIM:	$\neq$ *	$\neq$ **	=	$\neq$ *
Chlorophytes				
— sheet	20.2	25.0	#28.4	#24.2
— branching	15.5	13.3	18.6	#17.5
Animal				
— *Euphausid* sp.	5.6	10.1	13.6	13.1
— Unidentifiable	#37.1	18.3	12.5	12.6

Levels of significance are * $p < 0.05$, ** $p < 0.001$; # indicates diss/SD > 1

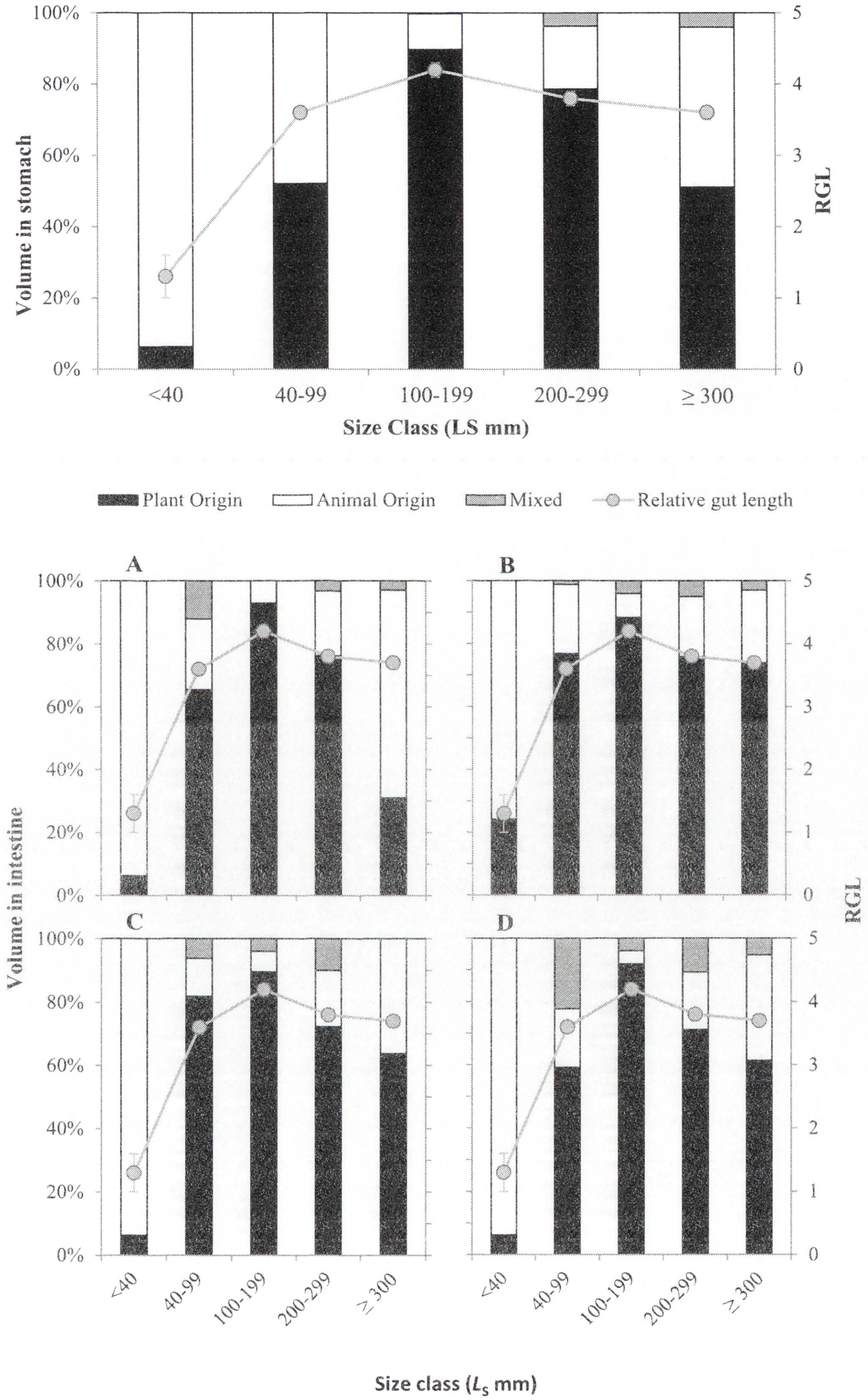

Figure 5.5 Volume of major food groups in digestive tract and relative gut length per size class. Stomach is section I (top) and intestinal segments are II (A), III (B), IV (C), and V (D). RGL errors are ± SEM. Standard errors for each major food group were <17 % of the sample means but are not shown to keep visual clarity.

smallest size class to over 3.6 in all other sizes and was concurrent with increased mean consumption of algae (Fig. 5.5). This pattern was consistent for proportions of algal material in all gut segments (Fig. 5.5 A-D). The increased algal consumption in specimens sized 100-199 mm L_S, combined with the corresponding lower proportions of non-algal components, was reflected in a spike of RGL for this size class at 4.2 (Fig. 5.5). Likewise, the ingestion of increased amounts of animal-derived food items in fish of the largest size class (i.e. $\geq$ 300 mm L_S) was reflected in a slightly lowered RGL of 3.6).

Zihler's Index expressed a similar relationship to RGL (Fig. 5.6). When considered alongside the levels of herbivory shown above, ZI corresponded well with its proposed trophic categories, with the newly settled fish (ZI = 5.4) fitting into the range for omnivores (ZI = 2.4-5.8), and the largest three size classes (ZI = 12.0-12.7) inside the range proposed for herbivores (ZI = 11.6-55.0). The 40-99 mm L_S size class fell just below the range for herbivores at ZI = 11.4 (Fig. 5.6).

Partitioned by seasons, the frequency of intake of both plant and animal based food items was highest for autumn and spring (Fig. 5.7). *Ulva* was the main driver of high algal frequencies in summer (64 %), autumn (67 %) and spring (76 %) compared with lower consumption exhibited for winter (36 %). Such high frequencies of occurrence, especially when combined with corresponding high levels of animal tissue in autumn (56 %) and spring (69 %), are indicative of a highly varied diet for *G. cyanea*.

5.4 Discussion

Intertidal algal spp. are an important dietary component for *G. cyanea*

The stomach-intestine contents of *Girella cyanea* analysed in the present study were composed mainly of algal species, supporting earlier findings for *Girella* spp. (refer Table 2.1: Chapter 2). Sheet and branching chlorophytes appear to be the most preferred of the algal types, occurring in > 55 % of guts in fish over 40 mm L_S (Table 5.1). Below this size, diets appeared more restricted (Table 5.2). Of all the algal types identified in larger size classes, fishes < 40 mm L_S ingested only sheet chlorophytes (i.e.

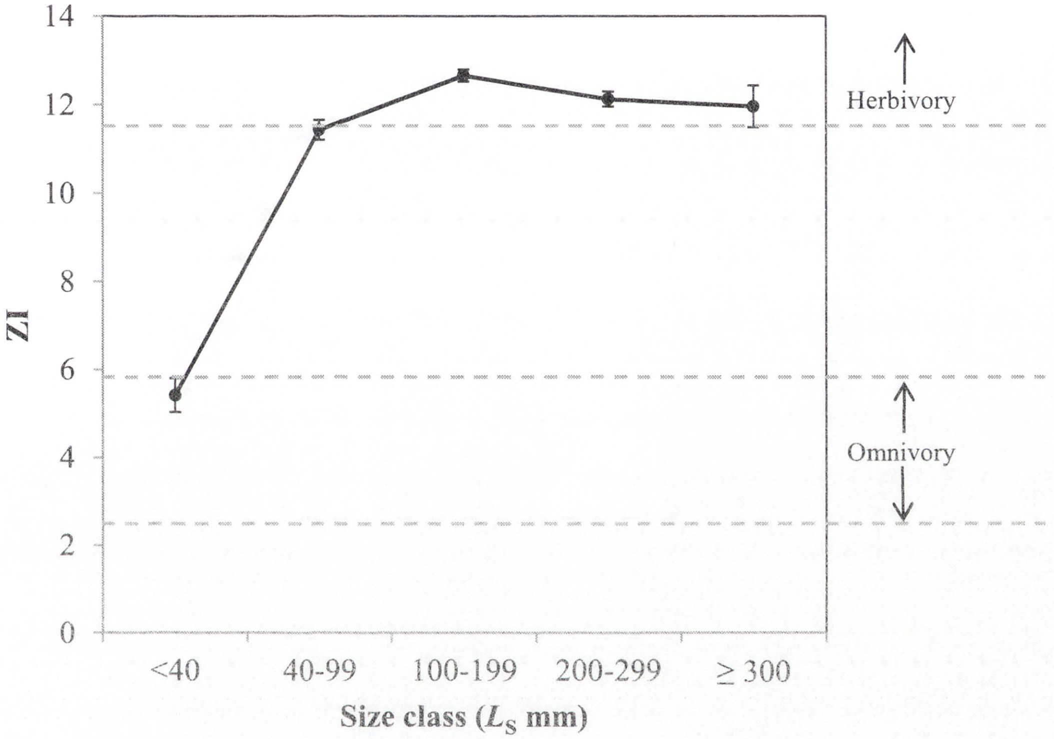

Figure 5.6 Gut length standardised for body mass, expressed as Zihler's Index (ZI). Dotted lines delineate ZI size classes as omnivorous (ZI = 2.4-5.8) and herbivorous (ZI = 11.6-55.0), from Kramer & Bryant (1995).

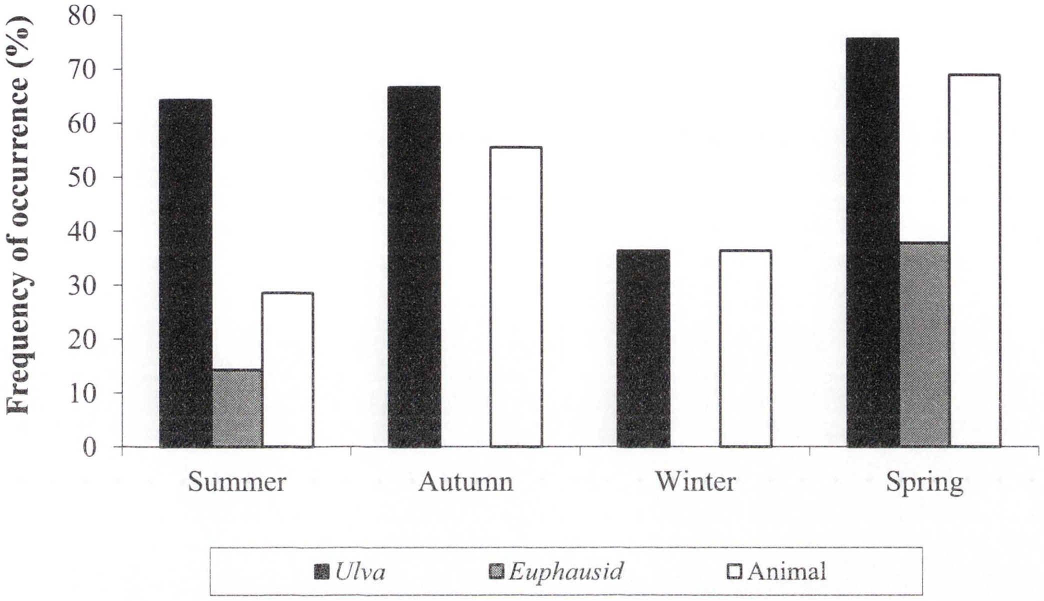

Figure 5.7 Seasonal frequency of the most common dietary items in plant (*Ulva* spp.) and animal (*Euphausid* sp.) categories found in gut contents. Total animal tissue is also displayed.

Ulva spp.). Whether this is representative of the relative availabilities of various algae was not quantified in this study. Fish diets often reflect the availabilities of prey species (e.g. Morrison 1990, Gillanders 1995, Zemke-White & Clements 2004), but not always (e.g. Sturm & Horn 1998). *Ulva* is a known intertidal algae, and lacks the herbivore deterrants (e.g. chemical defences) of some other chlorophytes (Nelson et al. 2008) and typical of phaeophytes (Hay & Fenical 1988, Steinberg 1989). The dominance of this and other green algae over red or brown is not surprising given their susceptibility to fish digestion (Montgomery & Gerking 1980, Zemke-White & Clements 1999, Zemke-White et al. 1999) and that girellid species lack the exogenous microbial hindgut digestion of the closely related *Kyphosus* spp. (Clements & Choat 1997, Mountfort et al. 2002, Skea et al. 2005, and ML pers. obs). Clements & Choat (1997) note that algal selectivity should rank chlorophytes > rhodophytes > phaeophytes in terms of digestibility when relying on the endogenous mechanisms exhibited by girellids. Results of the present study support this pattern of consumption for large juvenile (> 40 mm L_S) to adult individuals ingesting algal material. Clements & Zemke-White (2008) found two rhodophyte species to be important in their study of *G. cyanea* and infer that because these algaes are not located at Lord Howe, they may be replaced with the locally abundant family Delesseriacaea. Whilst this was found in the stomachs of some specimens of the present study, the relative importance of it to *G. cyanea* at Lord Howe Island appears low for all size classes (Table 5.1), including those in the similar range for their study (i.e. 355-485 mm L_S). Stomachs of six *G. cyanea* > 150 mm L_S caught at Middleton Reef (220 km north of LHI) contained mainly (> 95 %) chlorophytes: predominantly the spongey *Codium fragile* (Clements & Choat 1997), rare in the diets of *G. cyanea* at LHI. It is evident that the diet of *G. cyanea* is variable across populations: a problem encountered also in dietary descriptions of *G. tricuspidata* at various sites around New Zealand (Morrison 1990).

An ontogentic dietary shift occurs in *G. cyanea* at < 40 mm L_S

The higher dietary specialization (Table 5.2), greater stomach-intestine ratios (Fig. 5.3) and reduced RGL and Zihlers indices (Fig. 5.5 & 5.6) provide ample evidence for an ontogenetic dietary shift in juvenile *G. cyanea* at Lord Howe Island. Consumption of animal-derived food items was high (~90 %) in fish < 40 mm L_S compared to other size-classes (> 50 %), with the exclusion of segment II in fish $\geq$ 300 mm L_S (Fig. 5.5).

A shift from carnivory and omnivory in juveniles to a herbivorous adult diet is well documented for marine fish (see Muñoz & Ojeda 2000 and refs therein). High proportions of animal prey for other juvenile girellids have been reported at body lengths of 13-55mm L_S (Bell et al. 1980), and 63-107 mm (Thomson & Lehner 1976[2]) ; both studies also observed predominantly herbivorous diets in larger sized fish.

Pyloric caeca (finger like projections found just below the sphincter posterior to the stomach) were observed for all fishes > 40 mm L_S. Histological analyses of their structure has revealed their similarity to the intestine and suggests that one of their roles is to increase the absorption zone (Houssain & Dutta 1998). The absence of pyloric caeca in juvenile fishes appears to be a novel finding for girellids and kyphosids. These fish were sized between 17 and 40 mm L_S and observed as a settlement pulse into tidepools of the rocky intertidal zone. The smallest (c. 17 mm L_S) were first observed as silvery-sided prejuveniles (Norris 1959), followed by the development of juvenile/adult morphology over only a few days (M.L. pers. obs). There appears to be limited studies examining the gut morphology in pre-settlement and at-settlement fishes. It appears that characters associated with the capture and digestion of food develop during metamorphosis (Tanaka 1971, Balon 1975) alongside the development of fins and vertebrae that increase movement ability (Balon 1979). Formation of the stomach and pyloric caeca is known to occur during this transitional phase from larvae to juvenile (Tanaka 1971, Govoni et al. 1986). In cod (*Gadus morhua*), stomach development takes place from 15 mm to 45 mm L_S (Pedersen & Falk-Petersen 1992) at ages corresponding to 25-30 and 60 days post-hatching (Otterlei et al. 1999). Formation of the pyloric caeca occurs in parallel with the stomach, and after what is considered metamorphosis from larval to juvenile form.

In the more closely related *Kyphosus cornelii*, digestive strategies are considered to be unusual in that digestion of algae can occur at settlement size, believed to be at 30 mm L_F (Rimmer 1986). The percentages of algae in small juvenile *K. cornelii* (30-92 mm L_F) were higher than in *G. cyanea* of similar size (34-116 mm L_F converted using length regressions, Chapter 6; Fig 5.5).

It is therefore likely the gut morphology in *G. cyanea* observed in the present study reflects the early stages of digestive development during the transition from larvae to

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[2] The reference does not specify whether this body length is standard (L_S), fork (L_F) or total (L_T).

juvenile. Williams & Williams (1955) correlated this period of transformation of *G. nigricans* with a marked change in diet, whereby stomachs of fish < 32 mm L_S contained 55 % animal material compared to 14 % in larger juveniles.
Pre-settlement *G. cyanea* (i.e. < 17 mm L_S) were not available but are presumed to be pelagic like other girellids (see Chapter 2). The development of pyloric caeca appears to occur as the diet settles into a post-settlement pattern away from the planktivorous diet described for larvae of most reef-fishes (Thresher 1984). As herbivory increases in *Girella cyanea*, development of the pyloric caeca appears to accompany gut elongation (Fig. 5.3, Fig. 5.6) and increased RGL (Fig. 5.5). The dietary shift in the kyphosid, *K. syneyanu,* appears to be associated with size-related but different changes in digestive mechanisms (Moran & Clements 2002).

Omnivory across adult sizes makes *G. cyanea* a pseudo-herbivore

Food selection by plant-eating animals is of considerable interest in understanding ecological processes (Jones & Flynn 2005). The feeding guild of a species has traditionally been inferred from morphological traits, including observations of tooth shape and length of gut. The eco-morphology of *G. cyanea* suggests they are geared towards an herbivorous diet, with incisor-like teeth and a terminal mouth: useful adaptations for browsing algae (Kanda & Yamaoka 1994). Moreover, the adult gut morphometrics measured in this study were within the parameters known for primary consumers (Al-husseini 1947, Kramer & Bryant 1995). A similar ratio (5.0) was reported for the Japanese *G. mezina* sized 269-368 mm L_S (Kanda & Yamaoka 1997). There is increasing evidence, however, that fishes appearing as herbivores, but lacking highly specialized digestive features, exhibit varying levels of omnivory and widespread diet mixing (Stergiou & Karpouzi 2001, Choat et al. 2002). In the present study, animal material accounted for no less than 10 % of total gut contents in all size classes of *G. cyanea*, consistent with earlier findings for *G. tricuspidata* (Raubenheimer et al. 2005).

Nutritional needs may vary through ontogeny and at different life stages, not just juvenile periods of rapid growth (e.g. Capinera 2010), but perhaps also in periods of gamete production and post-spawning events. von Bertalanffy parameters place fish of 300 mm L_S at ~5 years of age, at which growth starts to slow and gonad activity begins (Chapter 6). *G. cyanea* at this size had a higher mean animal-based component than all but the smallest size class. Moreover consumption of animal material was more frequent in fish captured in spring (Fig. 5.7) when gonadosomatic indices were highest (Chapter 6). A nutritionally rich diet allows greater energy allocation to reproductive structures (e.g. egg production) and influences the length of the reproductive season in temperate herbivorous *Aplodactylus punctatus* (Caceres et al. 1994). The increased consumption of animal material observed in the present study may allow a large investment in gonadal production and gametogenesis. Dietary shifts associated with gonadal production have been described in other herbivorous fish (Fishelson et al 1987, Montgomery et al 1989).

Clements & Choat (1997) suggest that girellids 'complement protein from invertebrates with readily-available energy from algae'. Traditionally it has been thought that omnivory is primarily a strategy that allows animals to supplement a nitrogen-poor diet (typically made up largely of plant-based foods) with nitrogen rich animal foods (Denno & Fagan 2003). Are these *Girella cyanea* demonstrating the complementarity hypothesis put forward for *G. tricuspidata*: plant and non-plant components are complementary rather than substitutable (Raubenheimer et al. 2005)? Or is increased ingestion of animal-derived food occurring when local abundances of preferred algal species are seasonally low? Data for winter (Fig. 5.7), when *Ulva* densities are lowest (ML pers. obs.) show both *Ulva* and animal tissue frequencies at their lowest (36 % each). Individual consumption showed less overlap of the two food groups, in that 36.4 % (4 of 11) of fish assessed for diet composition over winter had almost exclusively (>99 %) consumed animal derived food items .Whilst the small sample size did not permit statistical analysis, there appeared to be limited patterns associated with this consumption. These specimens were sized between 140 and 208 mm L_S, all with minimal GSI values (see Chapter 6). Other fish assessed for this season included specimens of body lengths smaller, larger and of equivalent size, from the same location, consuming from 37 to 70 % algae. This would suggest that: (1) these fish had 'preferred' the animal components over the algae available (e.g. Optimal Foraging Theory: Sibly 1981, Schluter 1981), or (2) these fish exhibit higher competitive advantage in order to capture the prey (i.e. intraspecific competition), or (3) these fish are competitively excluded from the algal foraging arena (e.g. territorial damselfishes: Reinthal & Lewis 1986).

Conclusion

This study appears to be the first to describe an absence of pyloric caeca in juvenile girellids. This observation was consistent with a predominantly carnivorous diet in *G. cyanea*. Gut length ratio increased with increased ingestion of macroalgae, but varying levels of omnivory were exhibited across sizes. It remains unclear as to whether the omnivory displayed by *G. cyanea* is simply opportunistic or selective around certain life history events. Further work on the seasonal and temporal patterns of consumption alongside life history stages where increased nutrient supply is advantageous (e.g. juvenile growth, gamete production) will be informative. Nonetheless, data here provides good evidence that *G. cyanea*, like other girellids, is a broad-spectrum omnivore, despite their morphology. Clements & Choat (1997) concluded from their comparative study of kyphosid and girellid species that girellids should be considered omnivores, despite no animal material present in the stomachs of the six *G. cyanea* analysed. Our results, like Clements & Zemke-White (2008), confirm that *G. cyanea* consume animal-derived food items also at adult sizes.

Chapter 6 - Long live the Bluefish: Size-at-age, growth and longevity of *Girella cyanea* (Girellidae) and information for the management of the recreational fishery at Lord Howe Island Marine Park

Abstract. *Girella cyanea* is a protected marine fish on the eastern (New South Wales) coast of Australia yet maintains a recreational fishery on the small island of Lord Howe Island (South Pacific). Here, size-at-age data collected from specimens caught using common hook and line methods confirm that *G. cyanea* is long-lived with determinate growth. This decoupling of age and body growth is in contrast to the relationship of age and otolith growth. Otolith weight appears to be a significant predictor of age and could be utilised for rapid and cost-effective age determination for LHIMP managers. The growth curve determined from von Bertalanffy growth coefficients indicated rapid growth through the first 5 years of life, corresponding to the presence of gonadosomatic activity. Ongoing data collection is required to assess the applicability of the empirical equations for mortality, maturity and fishing-related estimates presented. Management strategies should encompass precautionary measures that limit exploitation, especially of sizes below 300 mm L_S (standard length) that may be below reproductive age.

6.1 Introduction

Interest in understanding the impacts of fishing and associated harvest strategies is increasing as management agencies and local governments invest more into the promotion of sustainable fishing practises (Green et al. 2009). In order to protect harvested stocks and their key habitats, parameterisation of life history characteristics, population structure, and small- and large- scale migration patterns is required.

Body size is one of the most obvious of the biological characteristics of a species or individual, and measurements are relatively easy to obtain and generally non-destructive. Thus, the causes and consequences of body size have been frequently studied for terrestrial and aquatic environments, and show observed patterns core to our understanding of biology and ecology. For example, patterns of body size across taxa show predictable scales of metabolic rate (Peters 1983, Clarke & Johnston 1999) and biogeographic distributions (Gaston & Lawton 1988, Blackburn & Gaston 1994, Gaston & Blackburn 1996, Warwick & Clarke 1996, Loder 1997, Hodkinson & Casson 2000). Hence, population considerations, such as geographic distribution (Gaston 1990), habitat use (Ziv 2000), and local density (Damuth 1981, Johnson 1999, Polishchuck & Tseitlen 1999) all appear to be directly or indirectly related to body size (Munday & Jones 1998).

Maximum body size and related growth is one of the most useful attributes because it has a direct bearing on patterns and processes at all levels of biological organisation (Peters 1983, Calder 1984, Schmidt- Neilsen 1984). Important life history traits, such as size and age at maturity, reproductive output and life expectancy often covary with body size and may be measured by assessing the growth trajectory of a species.

Growth is often determined by sampling a broad size range of individuals from a population and estimating their age in years (Fowler 2009). Measurements of body size coupled with an estimate of age have been used to describe growth trajectories in terms of several standard equations. Such a uniform approach has allowed for comparisons of growth and life history within and between taxa, populations and species. Terrestrial animals are known to exhibit distinct life history traits that are categorised as *r* and *K* strategies (Cody 1966, MacArthur & Wilson 1967, Pianka 1970). Typically, *r*-strategists are small-bodied, and short-lived, achieving early maturation. *K*-strategists, on the other hand, are considered large-bodied and long-lived, with delayed maturation. Research has shown that the varied life histories of many fishes cannot be adequately described by this dichotomy. In particular, some fish have been characterised as large-bodied and long-lived, with *early* maturation (Kawasaki 1983, Choat & Robertson 2002). Several studies have extended this work to include continuum models of life history strategies at endpoints such as *opportunistic*, *periodic*, and *equilibrium* strategies (Winemiller & Rose 1992), *salmonic* strategies (McCann & Shuter 1997), and *intermediate* strategies (King & McFarlane 2003). All groupings are based upon parameters such as maximum size, growth rate, size at maturity, fecundity, egg size and parental investment; all of which are the underlying determinants for population responses to environmental conditions and are fundamental for best practice management (King & McFarlane 2003). Simpler descriptions of life history patterns in fish refer to the shape of a growth curve generated from known longevity and age at size. Many of the great temperate water fish stocks (Beverton & Holt 1957) exhibit *indeterminate* growth characterised by the strong correlation of size and age (i.e. a life-long continuous increase in size). More recent data on coral reef-fishes, however, reveal a *determinate* pattern of growth where an initial period of rapid growth is followed by a relatively long period of little or no growth (Choat & Robertson 2002). A comparative analysis of fish life histories led Beverton (1992) to postulate that:

> "If a species is long-lived, and especially if it approaches its asymptotic growth limit fairly rapidly, it would seem a justifiable risk to delay maturation until a relatively large proportion of the growth span is completed".

Growth models of fishes in the past have been based upon length-frequencies of populations or age estimates attained by examination of rings formed on the scales. Unfortunately, many of these age classes have been found more recently to underestimate the age of the fish and thus lead to inaccurate calculations of growth parameters (Beamish & McFarlane 1983, Campana 2001, Berkeley et al. 2004). Assessment of age rings in the ear bones (otoliths) is the most reliable indicator of age in most fishes (Secor et al. 1995, Campana 2001, Begg et al. 2005). The acellular, mineralisation (Campana & Neilson 1985) that occurs in otoliths continually from birth to death forms a permanent record of life history events of the fish (Campana 1999).

Confidence is high that the structures (rings) observed in otoliths represent annual increments (see Choat et al. 2009 for a review on validation), thus allowing estimates of age from direct counts. Such widespread acceptance of the chronological properties of otoliths is unparalleled in the animal kingdom (Parkinson 2004). Despite the success and frequency of ageing fishes over the past 25 years (e.g. 1 million otoliths were aged in 1999 alone: Campana & Thorrold 2001), knowledge of age, growth and life history traits of many fish species and families is lacking (Pogonoski et al. 2002, Choat & Robertson 2002). Moreover, age-based demography remains biased towards temperate, boreal and deep sea fishes (Choat et al. 2009).

Little is known of the life history of the subtropical bluefish, *Girella cyanea*, despite it being a conspicuous member of the reef fish assemblage at Lord Howe Island (LHI). Although its distribution is thought to include the east coast of Australia (see Chapter 1), the lack of observations of the species in recent times has warranted a fishing ban by the New South Wales Department of Primary Industries (DPI 2006) which prohibits harvest in all state waters, except for Lord Howe Island. Information, with regards to the LHI population, is therefore of crucial importance for the sustainable exploitation and conservation management of the species. Preliminary findings of LHI-caught samples suggest *G. cyanea* are long-lived (> 40 yrs; Ferrell 2005) and further highlights the importance of more research into age-based demography of the species. The current study builds upon these preliminary findings, more than doubling the dataset, and providing more confidence in the description of growth in *G. cyanea* at Lord Howe Island. The main aim was to estimate life history parameters from length-at-age data to best describe the life history strategy representing the *G. cyanea* population at LHI. Due to the opportunistic nature of sample collection, data on maturation size/age and mortality levels are presented only as preliminary descriptions for management suggestions that aim to protect the species across its natural life span.

6.2 Materials and Methods

Samples

Specimens used in dietary analyses (Chapter 5) were also utilised in this study. Before dissection, measurements of fish length (total length = L_T, fork length length = L_F, standard length = L_S) were used to derive length conversion equations using the following linear regression models:

$$L_T = a + bL_F;\ L_F = a + bL_T;\ L_F = a + bL_S;\ \text{and } L_S = a + bL_F.$$

To increase the accuracy of age and growth estimates, field-collected samples were supplemented with data acquired with permission through the NSW Department of Primary Industries Fisheries Research Centre (Ferrell 2005). These additional data reported body size in the form of fork length (L_F) and was therefore converted to L_S using the equation calculated from the linear L_S-L_F regression. Whether samples from the additional dataset are included in calculations is reported within the text or captions.

Otolith preparation

Sagittae and lapilli were extracted from each fish, rinsed in distilled water, and stored dry in micro-assay trays until sectioning. Preliminary examinations showed that zones (banding) of whole otoliths were difficult to interpret. Each sagitta was weighed (± 0.0001g) prior to sectioning using an analytical balance. The left sagittal otolith was used for all otolith morphometrics and age, unless it was damaged or could not be located (8 cases). The nucleus was marked manually using a fine point permanent marker under a dissecting microscope (20-40 x magnification). Each sagitta was then embedded in Polyplex Clear Cast 20' resin catalysed with methyl ethyl ketone peroxide (30 g:1mL) and allowed to set for a minimum of 24 hrs. Otoliths were later sectioned through the focus (see F: Fig. 6.1) using a Buehler-Isomet Series 15HC diamond saw fitted with two 0.3 mm diamond wafering blades separated with an acetate spacer. The resulting transverse section of each otolith was approximately 0.35 mm thick. Sections were ground wet on each side using 0.09 mm lapping film and further polished with 0.06 mm lapping film. Each section was then mounted on an individual standard glass slide using adhesive and stored for later microscopic viewing.

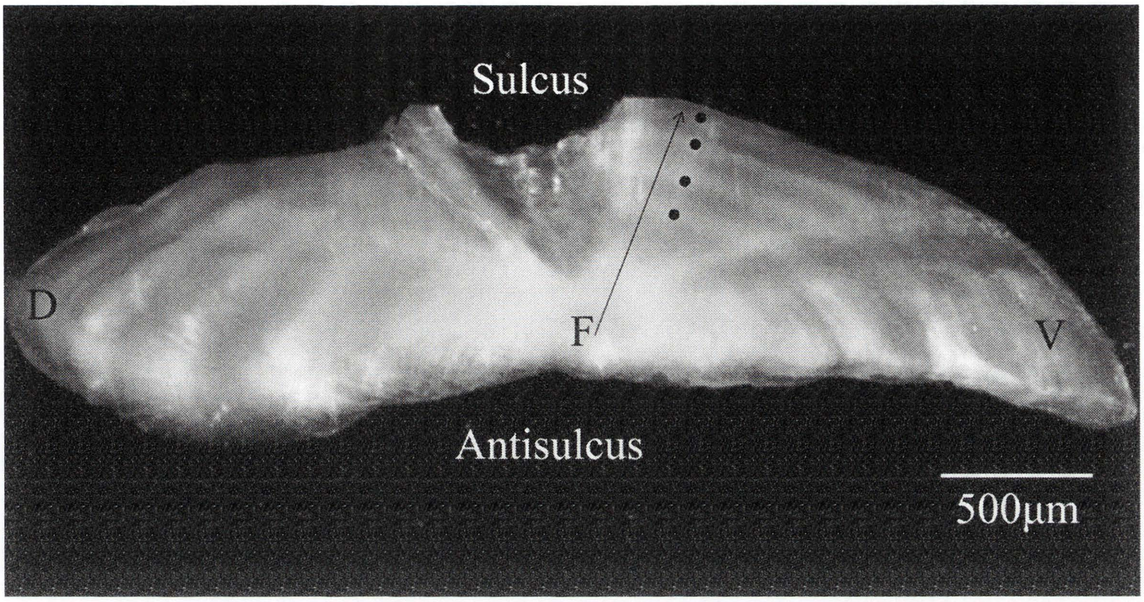

Figure 6.1 Transversely sectioned sagittal otolith of a four year old *G. cyanea*, showing a dense central opaque region (F) and a subsequent alternating sequence of opaque and translucent banding (D = dorsal, V = ventral. Scale bar = 500µm). Dots indicate presumed yearly increments. The counting axis is shown as the black line.

Age determination

Transverse otolith sections were examined under a binocular microscope (6- 25 x magnifications) with reflected light against a black background. Otolith sections displayed patterns of translucent (dark) and opaque (light) banding: each complete pair was presumed an annuli (i.e. a yearly growth ring, Fig. 6.1). Age (in years) was expressed as the sum of all opaque bands running a transect from the focus to the outer margin, along the sulcus (Fig. 6.1). Readings were conducted twice for each otolith section without prior knowledge of body length or sampling locality. The first count was made 'live' under the microscope, and the second followed one fortnight later by viewing an image captured on an Olympus BX40 Pixelink image analysis system using Image Pro® Plus and Image J software. On all but 4 occasions these readings were in agreement. Upon the third inspection, counts for these four otoliths remained unresolved and they were consequently omitted from the analyses.

Growth and development

The relationship between length and weight was best described by the equation:

$$W = 0.00001L^{3.18} \qquad \text{(refer to Chapter 5)}$$

where W is total wet weight (g), L is standard length (mm), and indicated that growth in *G. cyanea* was positively allometric (i.e. $b > 3$).

The gonadosomatic index (GSI) was calculated in order to provide a baseline seasonal analysis of gonad development and spawning activity:

$$\mathrm{GSI} = W_G / W \times 100$$

where W_G is the wet weight of the gonad tissue (g) and W is the wet weight of the whole fish (g).

Growth and mortality approximations

Growth was investigated by fitting length-at-age data to the von Bertalanffy Growth Model (VBGM): a non-linear expression of individual growth of an 'average' fish in the population. Several parameterizations of this model have evolved to make the parameters less correlated with one another (see Galucci & Quinn II 1979, Schnute 1981, Francis 1988, Mooij et al. 1999), subsequently making comparisons with data in the literature difficult. Moreover, the strict definitions of the parameters have sometimes been misunderstood (Francis 1988). The current study follows the Beverton& Holt (1957) equation and adheres to parameters defined in the literature:

$$L(t) = L_{\text{inf}}\,(1 - e^{-K(t - t0)})$$

where $L(t)$ is the average L_S at age t, L_{inf} is the asymptotic average length, K is the Brody growth coefficient (units are yr^{-1}; Ricker 1975), and t_0 is a modelling artefact of age when average L_S was zero (Schnute & Fournier 1980). The curve was fitted by minimizing the residual sum of squares (Chen et al. 1992, Haddon 2001) using the solver function in Microsoft Excel (MS Office 2007). The difference between each observed data point and that calculated from the VBGM (i.e. residuals) were squared and summed (SSQ). The line of best fit for the model was then determined by minimizing the SSQ through manipulation of the parameters L_{inf}, K and t_0. The empirical equations of Froese & Binohlan (2000) were then used for best estimates of mean length at first maturity (L_m) and mean length at maximum possible yield per recruit (L_{opt}), where:

$$\log L_m = 0.8979\,(\log L_{\text{inf}}) - 0.0782 \qquad (R^2 = 0.89,\ n = 467)$$

$$\log L_{\text{opt}} = 1.0421\,(\log L_{\text{inf}}) - 0.2742 \qquad (R^2 = 0.97,\ n = 206)$$

The age-based catch curve method was used to calculate the instantaneous rate of total mortality (Z): the natural logarithm of the number of individuals at age t (N_t) was regressed against age (t), thus resulting in an estimation of Z from the descending slope (Beverton & Holt, 1957, Ricker 1975). Construction of the catch curve was based on age-length data from this study combined with that from Ferrell (2005) to provide the age distribution of the total catch. The estimate of Z was then converted to estimates of the percentage survival (S) and percentage mortality (M) using the method of Ricker (1975) where:

$$S = 100\,e^{-Z}$$

$$M = 100\,(1 - e^{-Z})$$

Calculations of the instantaneous rate of natural mortality (M_n) were determined using two separate equations:

(i) $\log M_n = 0.0066 - 0.2790 * \log L_{\text{inf}} + 0.6543 * \log K + 0.4634 * \log T$ (Pauly 1980)

(ii) $M_n = 1.5K$ (Jensen 1996)

where L_{inf} and K are VBGM parameters, and T is the mean annual sea surface temperature (i.e. 21.5°C; n = 272, NOAA Pathfinder data, 1985-2007). Both values of M were then subtracted from Z to provide the range of fishing mortality (F):

$$F = Z - M_n$$

and corresponding estimated ranges of exploitation (E):

$$E = F/(F + M) \qquad \text{(Sparre \& Venema 1992)}$$

The optimum fishing mortality rate (F_{opt}) was described using the harvest strategy of:

$$F_{opt} = 0.5\ M \qquad \text{(Walters 2000)}$$

This strives to ensure that the current exploitation rate is not detrimental to the maintenance of recruitment nor that it compromises the ability to harvest the resource in the future (Newman & Dunk 2002). The limit reference point for fishing mortality (F_{limit}: Newman & Dunk 2002) was determined as:

$$F_{limit} = 2/3\ M \qquad \text{(Patterson 1992)}$$

since mortality rates above this have been associated with stock declines (Patterson 1992) and hence this level represents an undesirable state for the resource (Newman & Dunk 2000).

Data analyses

A one –way GLM analysis of variance (ANOVA) tested whether mean ages varied amongst size classes defined previously (Chapter 2, 3 and 4). Two aged individuals that were below 150 mm L_S were excluded from this analysis; hence comparisons were of S, M, L, XL_1 and XL_2. Due to unequal sample sizes and heteroscedastic data, the *post hoc* Games-Howell test was used to locate differences between means (see Field 2005, p 341).

6.3 Results

A total of 235 specimens of *G. cyanea* were examined for body size measurements. A broad size range was represented (i.e. 17 to 475 mm L_S), resulting in robust length conversion equations:

$L_T = 1.12\ L_F - 5.97\ (R^2 > 0.999, p < 0.001)$,

$L_F = 0.89\ L_T + 6.30\ (R^2 > 0.999, p < 0.001)$

$L_F = 1.06\ L_S + 16.33\ (R^2 = 0.99, p < 0.01)$

$L_S = 0.93\ L_F - 13.98\ (R^2 = 0.99, p < 0.01)$

Otolith and somatic growth morphometry

A sub-sample of 236 specimens was used for age analyses. These included otoliths removed from fish caught in the present study (63 %) as well as age data acquired from Ferrell (2005) and utilising the same ageing techniques. The oldest estimates of age for fish collections were 29 and 41 years, respectively, with corresponding body lengths of 446 and 475 mm L_S.

Sagittal weight was a significant predictor of age ($R^2 = 0.90$, $p < 0.001$, $n = 206$), with the relationship best described as:

$$A = 358.13\ W_S - 2.15$$

where A is presumed annuli (i.e. number of opaque bands) and W_S is the weight of the sagittal otolith (Fig. 6.2).

Body sizes of between 150 to 392 mm L_S were well represented amongst the *G. cyanea* samples, with size classes from S to XL having significant differences in mean representative ages (ANOVA: $F_{4,\,228} = 195.18$, $p < 0.001$). Mean ages (± S.E.) were suggestive of cohorts for S, M and L size classes, at 1.44 (0.15) yrs, 2.56 (0.09) yrs, 3.39 (0.09) yrs respectively. Large deviations from the mean for fish in the XL category (i.e. $\geq$ 300 mm L_S) were considerably improved by splitting this size class into two: XL_1 for fish 302 to 392 mm L_S, and XL_2 for fish 405 to 475 mm L_S. This resulted in a mean age of 4.97 (0.36) yrs for XL_1 that was in line with the preceding size classes. A mean age of 24 yrs for the small sample of specimens at body lengths within the XL_2 size class (i.e. $n = 9$) was accompanied by a relatively large standard error (Table 6.1), as ages showed considerable variability (i.e. 9 yrs to 41 yrs).

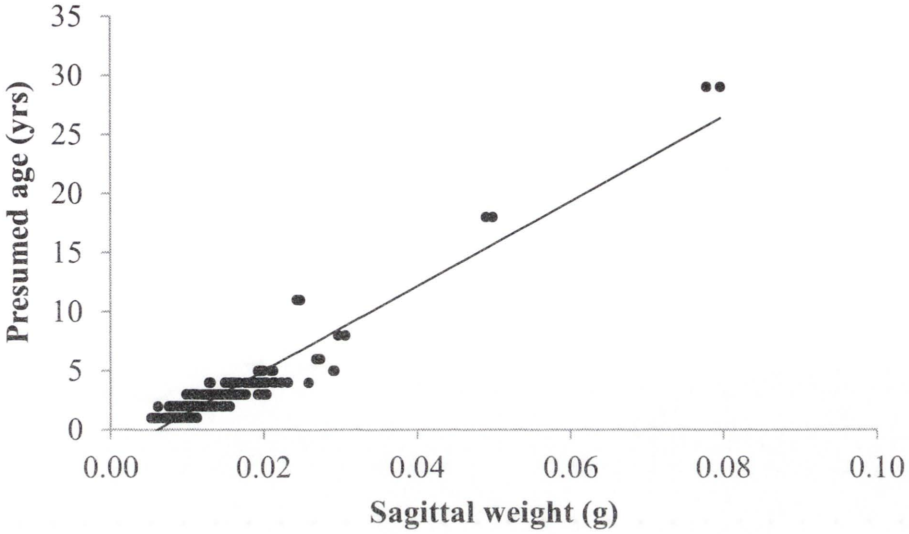

Figure 6.2 Linear growth of otoliths in relation to opaque bands (presumed age in yrs) in *Girella cyanea*. The line is a least-squares regression, $y = 358.13x - 2.15$ ($R^2 = 0.90$, $p < 0.0001$, $n = 206$).

Table 6.1 Mean age of size classes. All ages were significant (ANOVA: $F_{4,228}$ = 195.18, $p = 0.00$, $n = 232$; Games-Howell: $p < 0.005$).

Size class	Age (yrs ± S.E.)	L_S range (mm)	*n*
S	1.44 (0.15)	150 - 199	25
M	2.56 (0.09)	200 – 248	85
L	3.39 (0.09)	250 – 299	75
XL_1	4.97 (0.36)	302 - 392	39
XL_2	24.00 (3.48)	405 – 475	9

XL fish were separated into two L_S categories due to large age differences: [1] 300-399 mm, and [2] 400-499 mm

Gonad weights were measured in 135 specimens ranging from 103 to 2220 g *Wo* and 149 to 446 mm L_S, respectively. Standardised for each individual's body mass, gonadosomatic indices suggested a base-line index of $GSI \leq 0.12$, with 10 % (i.e. 12 individuals) separating from the base-line and peaking at $GSI = 1.5$ in the XL size class (Fig. 6.3A). Limited or no expression of sexual activity was apparent before the age of five yrs (Fig. 6.3 B). Monthly variation also divided into a base-line level of $GSI \leq 0.12$ for 90 % (i.e. 107 individuals), with spawning activity potentially occurring between the months of August to November (Fig. 6.3 C).

Life history traits and mortality
A total of 369 specimens were used for the development of growth models. Hook and line methods successfully captured 306 (i.e. 83 %) of these and suggested that fish susceptible to this method were ≥ 90 mm L_S. Thus, only juveniles caught in intertidal rockpools were excluded from the calculations for mortality and exploitation coefficients. All other fish were assumed to be fully recruited to the recreational fishery.

Growth was highly asymptotic and well described by the von Bertalanffy growth model. Estimates of the model parameters (Table. 6.2) indicated the best curve was achieved with the equation:

$$L(t) = 427 \text{ mm } L_S \, (1 - e^{-0.29(t + 0.25)}).$$

The majority of growth was achieved relatively early in the life span, with 78 % of the asymptotic average length (L_{inf}) reached by age five. Growth beyond this age substantially slowed with, 95 % L_{inf} being reached by 10 years of age. Given the oldest specimen was aged at 41 years, individuals may experience no further growth in length for over 50 % of their lifespan (Fig. 6.4).

For an asymptotic length of $L_{inf} = 427$ mm L_S, empirical estimations suggested a mean body length at first maturity as $L_m = 201$ mm and maximum possible yield per recruit at size $L_{opt} = 293$ mm. Within this framework, length frequencies of all fish caught by hook and line methods suggested that 24 % (i.e. 74 individuals) were below the mean body length at first maturity (Fig. 6.5). The largest modal peak indicated that almost 60 % (i.e. 183 individuals) were caught above the size at first maturity and within the range

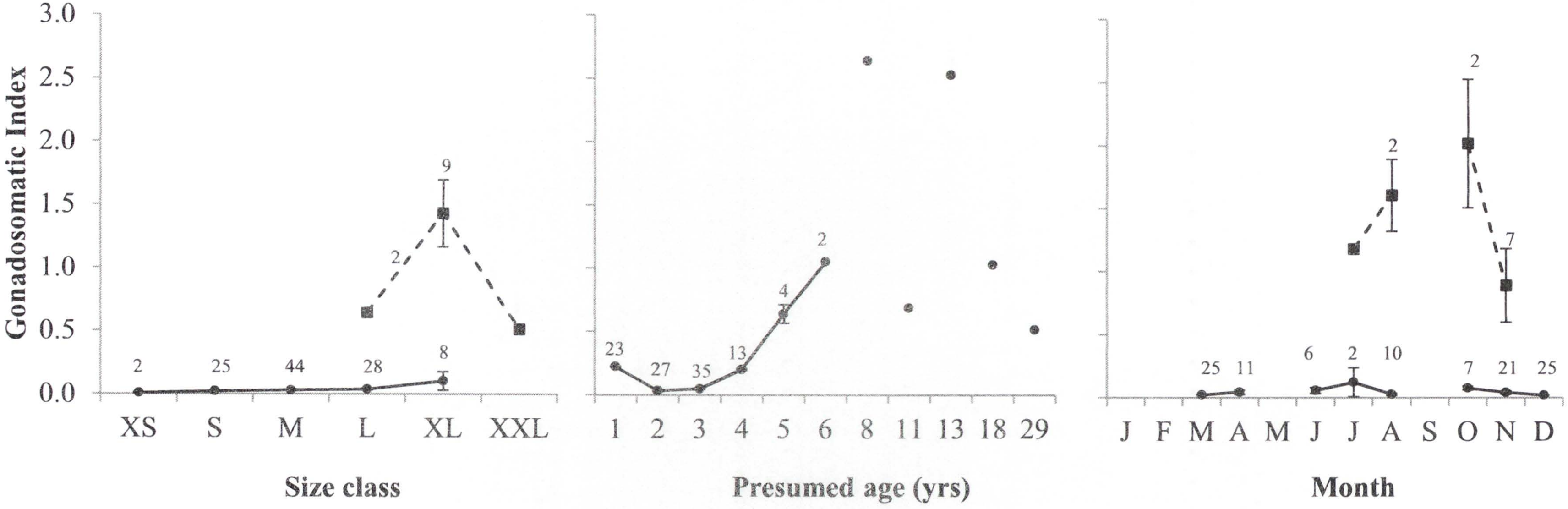

Figure 6.3 Temporal patterns of reproductive development across size classes (A), ages (B) and months (C). Pooled for sexes. Sample sizes are displayed. Baseline levels are indicated by sold line; individuals expressing a separate pastern are delineated by dashed lines (refer to text).

Table 6.2 Growth parameters derived from the von Bertalanffy growth model and population characteristics (n = sample size, L_S is in mm, and age (t) is in years).

Parameters	Present study	Ferrell (2005)	Combined
n	149	87	236
L_{inf}	429	415	427
K	0.28	0.28	0.29
t_0	-0.25	-0.25	-0.25
L_{Smean}	245	281	260
L_{Smin}	17	192	17
L_{Smax}	446	475	475
t_{mean}	3	5	3.9
t_{min}	0.12	2	0.12
t_{max}	29	41	41

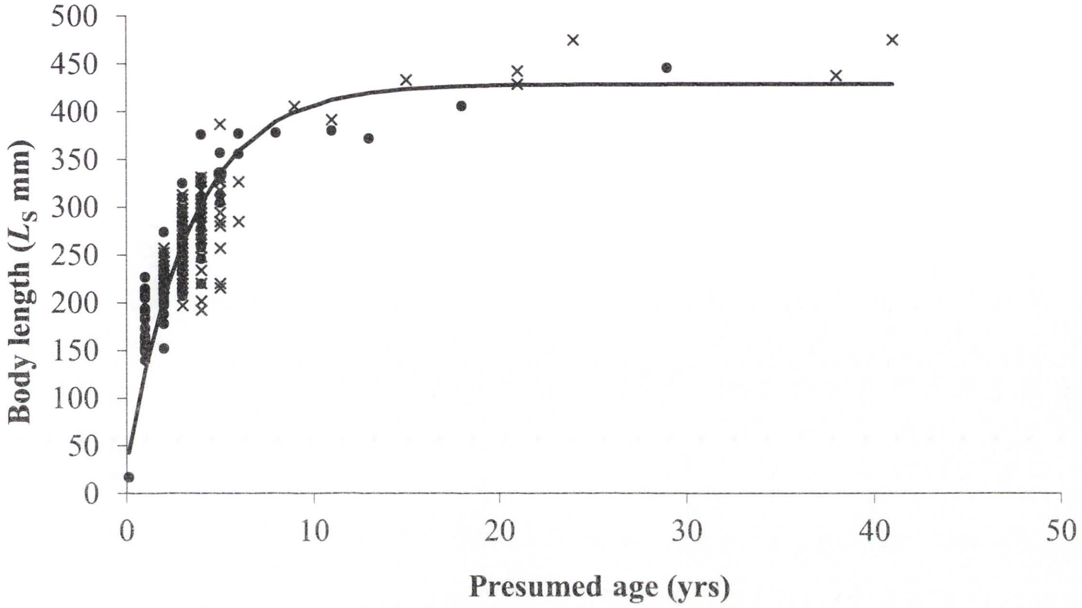

Fig. 6.4 Size and age of *Girella cyanea* from Lord Howe Island, with the von Bertalanffy Growth Model fitted (shown as black line). Data are sourced from the present study (•) and Ferrell (2005) (x). Parameters of this growth model, fitted for all data, are: L_{inf} = 427 mm L_S, K = 0.29 and t_0 = -0.25.

of maximum possible yield per recruit. Specimens above the L_{opt} range accounted for almost 19 % (i.e. 58 individuals) of the total sample (Fig. 6.5).

A value for the instantaneous total mortality rate of $Z = 0.18$ yr^{-1} was estimated from the catch curve, where the linear regression was $y = -0.18x + 3.81$ ($R^2 = 0.63$, $p = 0.02$). At that estimate of mortality, the percentage survival was calculated as $S = 83.53$ with a corresponding percentage mortality of $M = 16.47$. Pauly's (1980) empirical equation and a mean surface temperature of 21.5 °C produced an estimate of natural mortality of $M_n = 0.35$ yr^{-1}. This estimate was selected over that derived from Jensen's (1996) method where $M_n = 0.44$ yr^{-1}. The estimate of fishing mortality rate was thus calculated by subtraction as $F = 0.17$ yr^{-1}, giving a range of 0.17 to 0.26 yr^{-1} and subsequent estimates of the exploitation range as $E = 0.33$ to 0.44 at $M_n = 0.35$ yr^{-1} and $E = 0.28$ to 0.37 at $M_n = 0.44$ yr^{-1}. The optimum fishing mortality was calculated to be $F_{opt} = 0.18$ to 0.22, with a limit reference point of $F_{limit} = 0.23$ to 0.29.

6.4 Discussion

This study aimed to estimate life history parameters from length-at-age data to best describe the life history strategy of the *Girella cyanea* population at Lord Howe Island.

Otoliths as a utility for ageing *G. cyanea*

Ages were determined from the presumed annual deposition of opaque banding, and although this pattern of increment formation has not been validated for this species, the significant positive relationship between sagittal weight and fish age (Fig. 6.2) indicates that *G. cyanea* otoliths continually increase in weight over the life span of the fish. This continuous growth of the otoliths is noticeably independent of somatic growth (Fig. 6.2 vs Fig. 6.5). According to Fowler & Doherty (1992) this is one of the main conditions for these structures to be

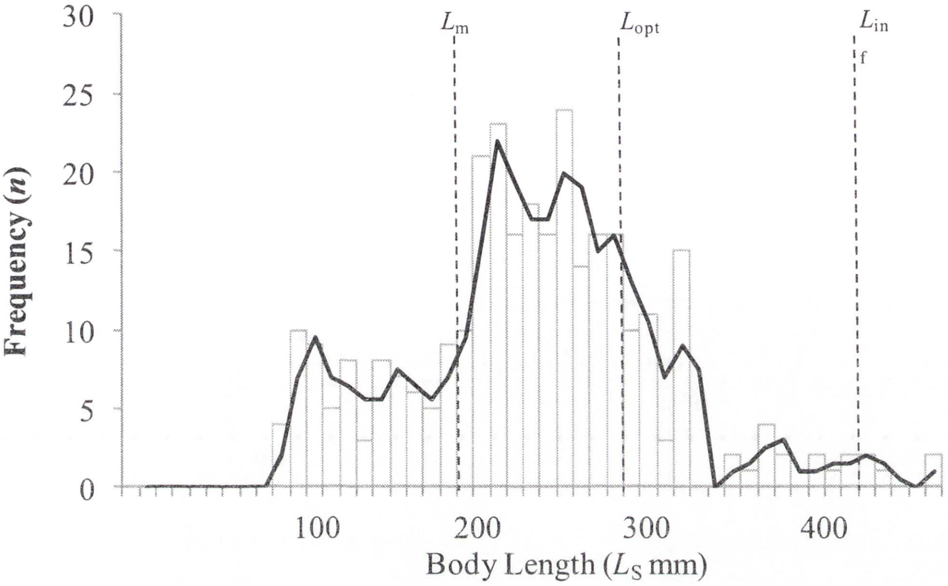

Fig. 6.5 Length-frequency distribution of *Girella cyanea*, with ranges for asymptotic average length (L_{inf}), length at first maturity (L_m) and maximum possible yield per recruit (L_{opt}) estimates. Frequencies are presented in percentage of total number captured by hook-and-line methods. The running average was used to emphasize modal peaks (shown as black line).

adequate for age determination, and is especially important in species that are long-lived (Sparre et al. 1989, Pawson 1990). Since 90 % of the variation was explained by this otolith-weight-age relationship, it may serve as a good proxy for the accurate estimation of age (Worthington et al. 1995, Newman 2002, Green et al. 2009) and indicates that opaque banding is probably deposited annually in *G. cyanea* (Choat & Axe 1996, Newman & Dunk 2002, Choat et al. 2009). Sample sizes across months were not large enough for marginal increment analyses here, but have demonstrated the annual deposition of one opaque and one translucent zone in *G. tricuspidata* at similar latitudes on the Australian east coast. Mark-recapture of that species also confirms annual deposition after fish were marked with oxytetracycline (Ferrell 2000). The estimates of age presented here for *G. cyanea* should therefore be reasonably accurate, especially given the readability of the increments in transverse sections.

***G. cyanea* are long-lived with determinate growth**

This study confirms that *G. cyanea* are long-lived. The oldest individual aged at 29 years old at a body length of 446 mm L_S, along with the oldest two specimens from Ferrell (2005) at ages 38 and 41 years at 438 and 475 mm L_S respectively, are the key determinants that suggest *G. cyanea* at LHI exhibit determinate growth. The asymptotic shape of the von Bertalanffy curve (Fig.6.4) is typical of many herbivorous reef fishes (Choat & Robertson 2002). Growth is relatively consistent through the first 2 to 5 years of life with asymptotic length reached on average at 10 years, a pattern consistent with similar sized herbivorous species in the literature. For example, growth curves exhibited by acanthurids (surgeonfish), of which appear at LHI in similar habitats to adult bluefish (M.L. pers. obs.), are characterised by rapid growth in the first 3 to 5 years (Choat & Axe 1996) achieving approximately 85 % of their growth by the time they reach sexual maturity (Choat & Robertson 2002). Comparisons of growth in other girellid species is scarce, with only two studies appearing to model von Bertalanffy curves on ages derived from otolith microstructures. Bredvik et al. (2011) concluded that *G. nigricans* of California is short-lived, and fast growing to a maximum age of 10 years, even though they acknowledged a sampling bias whereby the scientific gillnets used selected for individuals only up to 54 % of the maximum recorded size (Eschmeyer et al. 1983). Moreover, the pressure exerted on the VBGM asymptote clearly comes from the 10 specimens aged at ≥ 7 years, which constitute < 4 % of the total sample size. Gray et al. (2010) presents several VBGM curves of populations of *G. tricuspidata* from estuaries of eastern Australia. Their curves were truncated at 220 mm L_F and at a maximum of 11 years, as samples were based on commercial landings above the MLL, and where age classes had > 5 data points. The resultant curves are much shallower than those obtained in the present study (reflecting a lower K parameter) and fail to show the asymptotic (table-top) shape characteristic of determinate growth. The oldest age estimates mentioned in the study, but not included in the VBGM, were 21 and 24 years at 480 mm and 560 mm L_F. It is likely that increased numbers of old and large individuals would alter the growth curves for *G. nigricans* and *G. tricuspidata*, but it is not clear if they would or could incorporate the longevity exhibited by *G. cyanea,* given both species are exploited at reasonable levels (see Sommer 1995, Gray et al. 2010).

The determinate growth displayed by *G. cyanea* has implications for size-based estimates. The plateau in body length means that many age classes will fall into the largest size class (Table 6.1). This is a pattern consistent in many long-lived fishes (Choat & Robertson 2002) including *G. tricuspidata* (Gray et al. 2010), and indicates the decoupling of body size (i.e. somatic growth) and age (Hart & Russ 1996, Newman et al. 2000). In fish > 300 mm L_S, and presumably after sexual maturation (Fig. 6.3A), the large variation in size-at-age suggests that length data alone are of limited value for estimating life history parameters and assessing the population status and potential effects of harvest (Stewart & Hughes 2009, Gray et al. 2010). Despite this, age cohorts significantly described body lengths when placed into size-classes (Table 6.1). These findings suggest that size-based population assessments (like visual surveys) continue to be valid for *in situ* estimates of relative densities and/or habitat associations in *G. cyanea*.

Sexual maturity occurs between 2 and 5 years of age

Length at first maturity was estimated in *G. cyanea* to be early into the life history (i.e. approx. 6 % of maximum age) when using the empirical regressions (~2.3 yrs), but evidence of sexual activity from GSI (Fig. 6.3B) may indicate that L_m occurs at approximately 12 % of maximum age (~5 yrs). The former scenario is indicative of a life history pattern with an extended reproductive span similar to acanthurids (surgeonfish), whilst the latter may be more similar to the 15 % estimated for scarids (parrotfish) (Choat & Robertson 2002). When fish redirect energy into reproduction the slowing of somatic growth is common (Siems & Sikes 1998). Hence, the slower growth shown in our growth model after age 5 combined with the fact that 78 % of growth is achieved by this age (Fig. 6.4) suggests that the L_m may be more towards the 300 mm L_S size range suggested for a MLL by Ferrell (2005). The postulation of Beverton (1992) that long-lived species delay maturation until a large proportion of maximum somatic growth has occurred seems plausible in the life history strategy of *G. cyanea*. The empirical equations of Froese & Binohlan (2000) were conceived from estimates derived mainly from perciform fishes. It is becoming increasingly clear that life histories of fishes, even within this order, are extremely varied and complex. It is possible that *G. cyanea* life history events fall outside the range presented by the regression models and cannot be adequately estimated from the equations.

Mortality and harvest of *G. cyanea*

Natural mortality was estimated at moderately high levels for *G. cyanea* (M_n = 0.35). This is unusual in that long-lived species are generally expected to exhibit low levels of natural mortality (Choat & Axe 1996). Extensive sampling from commercial catches of the congeneric *G. tricuspidata* estimated M_n within the range of 0.21 and 0.30 (Gray et al. 2010), using the same equation for the estimates as the present study (i.e. Pauly 1980). Their values of $M_n > 0.27$ were applied to the four upper NSW study sites, at latitudes corresponding closer with LHI than all other sites (i.e. 29°29'S to 32°59'S). Conclusions based on the estimates of mortality here should thus be viewed with caution. That a heavily exploited, and now regulated, commercial fishery for *G. tricuspidata* displays similar natural mortality rates is a worry. Estimates of M_n used in the present study may be over-estimated when compared to an untouched population. If M_n is much lower than 0.35 yr^{-1}, estimates of fishing mortality (F) may increase beyond the range presented here. It is emphasized that the catch curve used to determine F in the present study constituted small samples per age class. Furthermore, levels of naturally occurring predation on *G.* cyanea have not been quantified. The literature presents no evidence of *G. cyanea* inclusion in the diets of any predatory species, but dolphins are known to feed on large numbers of the congeneric *G. tricuspidata* (Neumann & Orams 2003, Consantine & Baker 1997). Seabirds are presumably a predation threat given the large seabird population at LHI. The Great Cormorant in particular, may exert a considerable risk, since its diet has been shown to include large numbers of *G. tricuspidata* (Reside & Coutin 2001).

Additionally, it is possible that M or F do not operate uniformly during all ages. It is likely that one or more years of life may be susceptible to lower natural mortalities than are accounted for in the present model. The 'seasonal' occurrence of larger and older fish in this sampling regime (discussed below) is a case in point. It would be prudent to apply a higher estimate of Z and lower estimate of M_n to the LHI population of *G. cyanea* as a precautionary measure, at least until these results are verified with a more extensive databank of age observations for harvested *G. cyanea*.

The length composition was dominated by fish < 330 mm L_S (predominantly between 200 and 300 mm L_S; Fig 6.5) displaying similar characteristics to commercial (Gray et al. 2010) and recreational (Steffe et al. 2005) catches of the Australian congeneric *G. tricuspidata*. The majority of samples were obtained using the exact methodology of bluefish harvest by local fishers at Lord Howe Island and demonstrated that fish as small as 90mm L_S were able to be captured using a hook and line. The von Bertalanffy curve (Fig. 6.4) estimates these smaller specimens at < 1 year old. Other species of girellids have been shown to frequent tidal pools at similar ages (Stevens et al. 1989) where it has been postulated they use the increased temperatures to maximise their rate of growth (Norris 1963) before entering the adult population. The limited gonad analyses in the present study suggest that fish of this size are juveniles with an estimated 3 to 4 years or 190 mm of growth to achieve before recruiting to the sub-adult/adult population (Fig. 6.3). That these juvenile fish can be caught off the rocky shores at LHI is worrisome, since there is currently no data to determine morbidity and mortality of catch and release effects on this species.

The occurrence of only a few individuals (i.e. $n < 5$ %) aged over 10 years old, despite a maximum age of 41 years, is noteworthy. Seasoned fishers at LHI have noted declines of larger *G. cyanea* in nearshore locations in recent years (G. Kelly pers. comm.). This may be indicative of a heavily fished population, predominately based on the young fish entering the fishery. Several fish species in eastern Australia exhibit this population response to exploitation (Silbershchneider et al. 2009, Stewart & Hughes 2009). However, the estimates of fishing mortality presented here were less than that for natural mortality. Further to this, most specimens caught on hook and line were between L_{m} and L_{opt}, a distribution often exhibited by healthy, relatively lightly fished populations (Froese & Binohlan 2000). It is plausible that the present study reflects a gear selectivity issue. Although opportunistic in nature, the sampling strategy did include offshore areas as far as Ball's Pyramid (see Fig. 1.2 & 1.3) in habitats where larger individuals have been observed (Chapter 4). Whilst the exact localities of fish collected by Ferrell (2005) were not available, the largest fishes in the present study (estimated to be 8, 11, and 29 years old) were observed with enlarged gonads (GSI > 0.5) and were captured in late November preceding presumed spawning periods (Roughley 1916). It is a reasonable suggestion that larger specimens of *G. cyanea* may be more susceptible to seasonal/temporal hook and line captures because prawn bait offers an opportunistic high-protein prey (Chapter 5).

With the blanket ban of spearfishing as part of the Marine Park Zoning Scheme, it seems unlikely that an unbiased sample of *G. cyanea* will be obtained in the future. It should be noted that lower abundances of larger and/or older individuals in populations of reef fishes is not unusual (Blackburn & Gaston 1994, Warwick & Clarke 1996, Loder 1997) and so the range for size and age in the present study may accurately portray the true population composition of *G. cyanea* at LHI. Continued monitoring over many years will allow the estimation of temporal changes in age cohorts and may facilitate more thorough estimates of mortality (Ricker 1975) than those obtained here.

Conclusion

Notwithstanding the caveats discussed above, this study provides important baseline information on the bluefish, *Girella cyanea,* at Lord Howe Island. The objective was to determine age, longevity, and growth patterns of the species.

The von Bertalanffy estimates obtained from the length-at-age data show that growth in *G. cyanea* is determinate and that individuals may spend much of their adult lives without further somatic growth. This decoupling of age and body growth is in contrast to the strong relationship of age and otolith growth which helps to verify age estimates here should be robust. The disparate estimates of length at first maturity have implications for determining whether the catch composition represented here characterises a population experiencing light or heavy fishing pressure. Moreover, mortality estimates seem high for a species exhibiting such longevity. Until reproductive age and natural mortality levels have been more thoroughly researched, care should be taken to keep fishing mortality low to prevent overexploitation.

Chapter 7 – Final Discussion

Knowledge of the life history of a species is essential for conservation and management. Certain traits may render a species more vulnerable to exploitation and influence the effectiveness of different management strategies. The aim of this study was to provide crucial baseline information on the life history and ecology of *Girella cyanea* to assist in management decision-making for the Lord Howe Island population. Prior to this project, existing information on this species was sparse. Preliminary results suggested longevity (Ferrell 2005), but few data had assessed additional life history traits. Overfishing was recognised as likely in mainland Australian populations (Pogonoski et al. 2002), but little was known about resource-requirements and habitat-use. The primary stimulus for this project was the increased concern for the persistence of the species (Pogonoski et al. 2002) and that insufficient information was available for sound management. This discussion uses new data and known life histories of congenerics to construct a life history model for *G. cyanea*.

A life history model for *Girella cyanea*

Fishes of the family Girellidae are known to inhabit shallow coastal waters in parts of Australia, New Zealand, Japan, North and South America, and in the eastern Atlantic (Fig. 2.1). Of the little known about size-at-age, truncated growth models have shown asymptotic age-at-size to 10-24 yrs and relatively rapid growth preceding asymptotic maximum size (Gray et al. 2010, Bredvik et al. 2011). Data presented in this study has shown that *G. cyanea* live to at least 41 yrs and achieve their asymptotic maximum body size at approximately 10yrs. It seems reasonable to assume that Girellidae, at low exploitation rates at least, achieve considerable longevity, large asymptotic size and relatively rapid growth to sexual maturity. Fast growth to maturity has several documented advantages. Predation is considered a key mechanism of high mortality rates experienced by juvenile fishes (e.g. Cushing 1974, Houde 1987, Brunton & Booth 2003). A wide variety of piscivores exhibit size-selective predation on smaller fish (e.g. Healey 1982, Werner et al. 1983, Post & Evans 1989). Rapid growth enables juveniles to pass through the most vulnerable size classes (*sensu* the "bigger-is-better" hypothesis, but see Litvak & Leggett 1992). Furthermore, growth rate directly affects predation mortality (Takasuka et al. 2003). Since, growth rates vary as a function of habitat (e.g. Werner & Gilliam 1984, McNamara & Houston 1986), individuals should select habitats that provide the maximum potential for growth. Gut morphologies of the smallest juveniles (< 40 mm L_S) in the current study provided indirect evidence of settlement in *G. cyanea*, with these individuals settling into tidepools and ingesting predominantly carnivorous diets. A high quality diet, shallow settlement-habitat and warm temperatures within the tidepools collectively facilitate the rapid growth exhibited in the growth model determined here for *G. cyanea*. The curve demonstrated rapid growth in the first 5 years of life. Previous work has shown that girellids are up to 2 years old before they leave the shallow intertidal (Norris 1963, Stevens et al. 1989, Stepien 1990, Varas & Ojeda 1990). Results here on age-at-length of first maturity, similar also to congenerics (Gray et al. 2000), show that this recruitment likely corresponds with a transition to sexual maturity. Juvenile *G. cyanea* > 40 mm L_S were shown to undergo an ontogenetic shift to towards herbivory. Intertidal algae (*Ulva* spp.) dominated gut contents and supported the observed distribution, with large densities of fish at this size observed in rocky intertidal habitat. The high relief and complexity of this habitat on Lord Howe Island likely provides a refuge from predators for larger juveniles still progressing through the fast growth period preceding sexual maturity. At the beginning of the range for sexual maturation presented here (i.e. 200 mm L_S), *G. cyanea* displayed an ontogenetic habitat shift that involved moving to deeper water (> 2 m), presumably to recruit to the adult population. Again, dietary analyses supported this habitat shift, displaying greater variability and pelagic animal prey. A model of distribution patterns and resource-partitioning of *G. cyanea* is presented in Figure 7.1.

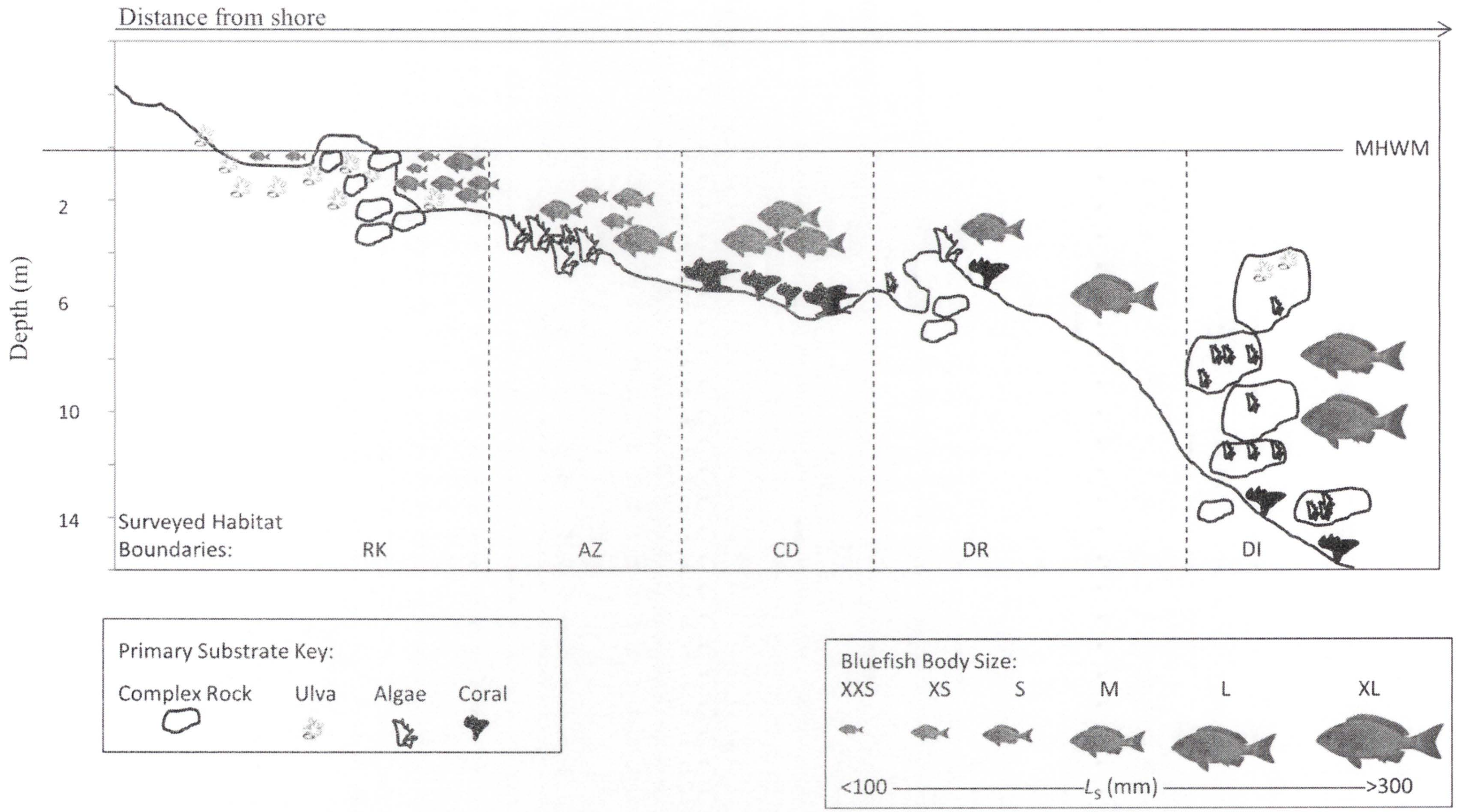

Figure 7.1 Diagrammatic representation of horizontal (habitat) and vertical (depth) partitioning in *G. cyanea* through ontogeny

(1) What resources do *G. cyanea* require/use?

Horizontal (habitat) and vertical (depth) partitioning was evident from densities of *G. cyanea* observed on roaming transect surveys (Chapter 4). An ontogenetic habitat shift occurred at 200 mm L_S, with smaller fish restricted to depths shallower than 2 m. Larger fish utilised a greater range of habitats, but size-distributions were stratified with increasing depth. All sizes appeared to stay close to shelter provided by high relief rocky-reef, and the presence of conspecifics was important.

An ontogenetic dietary shift occurred at 40 mm L_S, with smaller fish ingesting predominantly animal-based foods and an absence of pyloric caeca (Chapter 5). Larger fish showed increased relative gut length and well-developed pyloric caeca corresponding to diets consisting primarily of algae. Intertidal chlorophytes were particularly important.

(2) What life history traits do *G. cyanea* exhibit?

A broad size-range of otoliths were examined for length-at-age (Chapter 6). The von Bertalanffy growth equation was: $L(t) = 427\ \text{mm}\ L_S\ (1 - e^{-0.29(t+0.25)})$. Growth was relatively rapid through the juvenile phase (up to 5 yrs) and the average maximum size ($L_{inf} = 427$ mm L_S) was achieved by the age of 10 yrs. Body lengths beyond this point represented a wide-range of ages signifying a decoupling of age and size. The slowing of somatic growth and determinate growth pattern was not represented by the positively linear otolith weight-age relationship.

(3) Do the life history and demographic attributes of *G. cyanea* display ontogenetic change?

The presumed size-at-settlement (17 mm L_S) and large average maximum size (L_{inf} = 427 mm L_S) observed in this study indicates that *G. cyanea* passes through many magnitudes of size through the course of life. This study found important life stages where resource-use changed. Similar ontogenetic changes have been reported for other marine fishes (e.g. Schmitt & Holbrook 1984, Stoner & Livingston 1984, Clements & Choat 1990, Green 1996, McAfee & Morgan 1996), and implies that fish may have significantly different ecological functions at different stages of their lives (Stoner 1980). As juveniles in tidepools, *G. cyanea* are carnivorous and may be subject to high levels of intra- and inter- specific competition and density-dependent effects. Given the high ingestion of *Ulva* in large individual adults, it is possible that *G. cyanea* have an important influence on macroalgal biomass at locations around LHI (Chapter 5).

Research needed for conservation and management

Interest into girellids and their exploitation is increasing. In the past decade, several management actions have taken place. Minimum legal lengths on the eastcoast of Australia restrict catches of congeneric species to sizes > 230 to 300 mm L_T. No size limit has been imposed on *G. cyanea* but preliminary yield-per-recruit models by Ferrell (2005) indicated 265 mm L_S (N.B. converted from 300 mm L_T) was sensible; although, mortality rates used in the calculations were arbitrary. This study suggests this size limit would likely protect fish transitioning to maturity. However, such a management measure would prove politically difficult, since almost 82 % of fish biting on hook-and-line within this study fall below this size (Fig. 6.5). Moreover, observations of LHI locals demonstrated preferred eating, known locally as "pannies", at sizes 200-300 mm L_S (M.L. pers. obs.). Socio-economic aspects of the recreational fishery at LHI are important for the successful management of this species. A better management strategy would be to ensure adequate protection of suitable and representative rocky intertidal areas. Sanctuary of sufficient juvenile fish until sexual maturity is achieved would do much towards conservation of the important LHI population of *G. cyanea*.

No girellids have yet been deemed vulnerable species, but concerns are developing from historical harvesting pressure, observed population changes and recognition that little is known of their biology. *G. cyanea* have been nominated for a near-threatened listing (Pogonoski et al. 2002) and three species have been assessed for the IUCN Red List (IUCN 2011). Conservation status is deduced by comparisons of past abundance with current population composition. Overfishing on the mainland (Pogonoski et al. 2002) and recent trends suggesting large decreases in fished areas on LHI (Aquenal 2010) emphasizes urgency in precautionary management strategies for *G. cyanea*. These should include plans that address the pressure of target catches and bycatch for *G. cyanea*, as well as identifying the risks of habitat degradation through climate change (Edgar et al. 2009).

Since populations of marine fishes are often connected into metapopulations (Gilpin & Hanski 1991, Crowder et al. 2000, Hixon et al. 2002), further research is required on movement and dispersal. Tagging studies will help elucidate home-range and help to determine efficient sizes for sanctuary zones that will prove effective for *G. cyanea*. An understanding of changes in the population in the longer term will benefit from genetic analyses (Roman & Palumbi 2003) of *G. cyanea* across its distributional range (i.e. Middleton Reef, Lord Howe Island, New Zealand). A greater understanding of reproduction is required. Preliminary findings presented in this study offer a good baseline for further work. Concentrated underwater observations by researchers and increased awareness by recreational divers over spring and summer months may contribute to the limited knowledge of spawning behaviour, timing and location. More needs to be discovered about intrinsic rates of increase. Information such as rates of fecundity and recruitment to the breeding population and fishery would help predict responses to exploitation. Further information on age- and/or size- specific reproductive output could allow better management. For example, sexual maturity is shown to occur dimorphically in *G. tricuspidata* in Australia (Gray et al. 2000), although not in New Zealand (Morrison 1990).

Major conclusions

Extended life spans accompanied with slow growth rates and low natural mortality rates have been identified to render a marine species vulnerable to extinction through human activities that include overexploitation (Roberts & Hawkins 1999). Furthermore, several studies (summarised by Musick 1999) point out that maximum sustainable yields may be higher in *r* than *K* strategists. Suitable management frameworks are clearly difficult without knowledge of life history traits specific to the species to be managed. This study has determined that *G. cyanea* is long-lived but may be reasonably fast growing to sexual maturity with an extended reproductive span (Chapter 6). These intermediate life history characteristics combined with the current location of sanctuary zones that incorporate key intertidal grazing areas (Chapter 5) and where relatively high abundances have been observed (Chapter 4) will work towards the sustainable management of *G. cyanea* at Lord Howe Island. Additionally, it is recommended that future monitoring strategies encompass comparisons inside and outside of no-take areas at regular intervals (preferably within each season) in order to determine possible harvest effects long before the population reaches overexploitation. Also, fish frames discarded from local fishers should continue to be utilised for extended age-based assessments.

Monitoring of the age compositions of catches from both targeted and opportunistic (e.g. from fisher-supplied frames) sampling schedules in the future may benefit from the robust nature of the otolith weight-age relationship (Chapter 6). Random samples of otolith weights in the population and the derivation of age estimates from the otolith weight-age relationship will be relatively inexpensive and may enable larger sample sizes to be collected over time. To understand whether this relationship persists over time a re-examination at regular time intervals would be required, however. Additionally, despite marginal increment analysis confirming deposition of annuli in *G. tricuspidata* (Gray et al. 2010), proper calibration of the annual periodicity of increment formation in *G. cyanea* would be worthwhile (Worthington et al. 1995, Francis & Campana 2004).

Given the high ingestion of *Ulva* in large individual adults, it is possible that densities of *G. cyanea* have an important influence on macroalgal biomass at locations around LHI (Chapter 5). There are currently no studies on the potential role they play in the top down effects or regulation of macroalgal species or nitrogen cycling. This would be a particularly interesting avenue for further study, as it appears that *G. cyanea* behave as temperate species utilising rocky reefs, gaining little resource from coral environments (Chapter 4), yet may contribute much to the health of these systems.

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Appendices

Appendix 1: Archived collections of *G. cyanea*

Location	Latitude	Longitude	Collection Year
Australian Museum Specimens List [a]			
Solitary Islands (NSW)	28°59'54S	153°31'22E	*ns*
Norfolk Island	29°4'31S	167°56'13E	1975
Middleton Reef	29°27'28S	159°7'7E	1936
Sandon Point (Wooli)	29°40'51S	153°19'30E	*ns*
Elizabeth Reef	29°57'25S	159°4'32E	1987
The Entrance (NSW)	33°19'49S	151°29'25E	1982
Lord Howe Island	33°31'23S	159°2'56E	1973
Broken Bay (NSW)	33°34'7S	151°17'33E	*ns*
Long Reef (Sydney)	33°44'8S	151°18'32E	*ns*
Port Jackson (Sydney)	33°50'2S	151°15'35E	*ns*
Botany Heads (Sydney)	33°58'47S	151°12'7E	*ns*
Pt Kembla (NSW)	34°28'12S	150°53'59E	*ns*
Eden (NSW)	37°4'11S	151°13'42E	1968
Australian Anglers Association Record Authority [b]			
Fingal Bay (NSW)	32°46'7S	152°5'41E	1975
Australian Underwater Federation Spearfishing Records [c]			
Flinders Reef (QLD)	26°58'60S	153°30'0E	1986
La Perouse (Sydney)	33°59'17	151°13'42E	1956

ns denotes specimen collections without accompanying collection dates on database.

Sources: [a] http://data.gbif.org, [b] www.aaawa.iinet.net.au/NationalAAAFishingRecords.html,
[c] McDade M (2008) QLD Spearfishing Records (Australian Underwater Federation: Queensland)
Accessed September 2011: www.auf-spearfishing.com.au

Appendix 2: Dissemination of research results

During the project, preliminary results were presented to peers at a wide range of national and international scientific meetings:

Université de la Mer, IPEV Research Cruise MD 153 ZONECO 12, 6th-25th February 2006, RV Marion Dufresne, Auckland-Noumea-Sydney

Australian Marine Science Association 44th Annual Conference, 9th-14th July 2006, Cairns, Australia

UTS 8th Multidisciplinary Postgraduate Research Conference, 8th September 2006, Sydney, Australia

Student Conference on Conservation Science 27th-29th March 2007, University of Cambridge, UK

4th MBA Postgraduate Workshop, 2nd-4th April 2007, University of Liverpool, UK

Final results will be circulated in the following forums:

Publication of results and background information on bluefish in a DECC Technical Report.

Articles in the Lord Howe Island local newsletter, *The Signal*.

Data entered into the *Fishbase.org* world information system for fish biology.

Additionally, the three data chapters of this thesis will form the basis of scientific papers that will be submitted to peer-review journals within the following year.