

Wild Fisheries



Northern Territory Mud Crab Fishery: 2007 Stock Assessment



**SARDI Aquatic Sciences Publication No. F2007/000926-1
SARDI Research Report Series No. 244**

T.M. Ward, D.W. Schmarr and R. McGarvey

SARDI Aquatic Sciences
2 Hamra Avenue West Beach SA 5024

April 2008



**Government
of South Australia**

Northern Territory Mud Crab Fishery: 2007 Stock Assessment

T.M. Ward, D.W. Schmarr and R. McGarvey

April 2008

SARDI Aquatic Sciences Publication No: F2007/000926-1

SARDI Research Report Series No. 244

This publication may be cited as:

Ward, T.M. Schmarr, D.W. and McGarvey, R. (2007). Northern Territory Mud Crab Fishery: 2007 Stock Assessment. Report to Northern Territory Department of Primary Industries and Mines.

South Australian Research and Development Institute
SARDI Aquatic Sciences
2 Hamra Avenue
West Beach SA 5024

Telephone: (08) 8207 5400
Facsimile: (08) 8207 5406
<http://www.sardi.sa.gov.au>

Disclaimer:

The authors warrant that they have taken all reasonable care in producing this report. The report has been through the SARDI Aquatic Sciences internal review process, and has been formally approved for release by the Editorial Board. Although all reasonable efforts have been made to ensure quality, SARDI Aquatic Sciences does not warrant that the information in this report is free from errors or omissions. SARDI Aquatic Sciences does not accept any liability for the contents of this report or for any consequences arising from its use or any reliance placed upon it.

© 2007 SARDI Aquatic Sciences

This work is copyright. Apart from any use as permitted under the *Copyright Act 1968*, no part may be reproduced by any process without prior written permission from the author.

Printed in Adelaide: April 2008

SARDI Aquatic Sciences Publication No F2007/000926-1
SARDI Research Report Series No. 244


Author(s): Ward, T.M. Schmarr, D.W. and McGarvey, R.

Internal Reviewers: Dr Tony Fowler, Cameron Dixon, Dr Mark Grubert, Dr Rik Buckworth

External Reviewers: Professor Carl Walters, Professor Malcolm Haddon, Dr Ian Knuckey

Approved by: Steven Clarke

Signed:



Date: 7 April 2008

Distribution: NT DPIFM to distribute

Circulation: Public Domain

TABLE OF CONTENTS

LIST OF FIGURES.....	VI
LIST OF TABLES.....	IX
EXECUTIVE SUMMARY.....	11
1. INTRODUCTION.....	13
1.1. PROJECT SCOPE AND TERMS OF REFERENCE.....	13
1.1.1. <i>Background</i>	13
1.1.2. <i>Terms of reference</i>	13
1.2. AIMS AND OVERVIEW OF REPORT.....	14
1.2.1. <i>Rationale and aims</i>	14
1.2.2. <i>Overview of the report</i>	14
1.3. BIOLOGY OF THE MUD CRAB, <i>SCYLLA SERRATA</i>	15
1.3.1. <i>Taxonomy</i>	15
1.3.2. <i>Description</i>	15
1.3.3. <i>Distribution</i>	16
1.3.4. <i>Stock Structure</i>	17
1.3.5. <i>Reproduction</i>	17
1.3.6. <i>Parasitic sterilisation</i>	17
1.4. NT MUD CRAB FISHERY.....	18
1.4.1. <i>Overview</i>	18
1.4.2. <i>Commercial Fishery</i>	18
1.4.3. <i>Recreational Fishery</i>	19
1.4.4. <i>Fishing Tour Operator Sector</i>	20
1.4.5. <i>Indigenous Sector</i>	20
1.5. CURRENT MANAGEMENT FRAMEWORK.....	21
1.5.1. <i>Stakeholder Consultation</i>	21
1.5.2. <i>Management Objectives</i>	21
1.5.3. <i>Performance Indicators and Reference Points</i>	21
1.5.4. <i>Management Framework</i>	21
1.6. PREVIOUS RESEARCH, MONITORING AND STOCK ASSESSMENT.....	21
1.6.1. <i>Overview</i>	21
1.6.2. <i>Early Research 1990-1995</i>	22
1.6.3. <i>1996 Stock Assessment Workshop</i>	22
1.6.4. <i>1999 National Research Strategy Workshop</i>	22
1.6.5. <i>2004 Stock Assessment Workshop</i>	22

1.6.6. *FRDC Abundance and Habitat Project*23

2. CATCH AND EFFORT DATA FOR THE NT MUD CRAB FISHERY 24

2.1. INTRODUCTION.....24

2.2. TOTAL CATCH, EFFORT AND CPUE.....24

 2.2.1. *Annual Patterns*24

 2.2.2. *Spatial Patterns*25

 2.2.3. *Seasonal Patterns*28

 2.2.4. *Freight data*28

2.3. DISCUSSION.....35

3. SEXUAL DIMORPHISM, SIZE AT SEXUAL MATURITY, SEX RATIO AND MEAN SIZE OF CRABS IN CATCHES 37

3.1. INTRODUCTION.....37

3.2. SEXUAL DIMORPHISM37

3.3. SIZE AT MATURITY37

3.4. SEX RATIO41

3.5. MEAN SIZE OF COMMERCIAL CATCH45

 3.5.1. *Inter-annual pattern*45

 3.5.2. *Intra-annual Pattern*45

3.6. DISCUSSION.....48

4. GROWTH PATTERNS OF NT MUD CRABS 50

4.1. INTRODUCTION.....50

4.2. METHODS50

4.3. CARAPACE WIDTH AT FIRST CAPTURE50

4.4. TIME AT LARGE52

4.5. GROWTH INCREMENT52

4.6. GROWTH PARAMETERS.....54

4.7. DISCUSSION.....58

5. OTHER MODELLING..... 59

5.1. INTRODUCTION.....59

5.2. ENHANCED WETHERALL ANALYSIS.....59

5.3. YIELD-PER-RECRUIT61

5.4. RECRUITMENT ADJUSTED SEASONAL DEPLETION MODEL.....65

5.5. DISCUSSION.....68

6. EFFECT OF CHANGE IN MINIMUM LEGAL SIZE 69

6.1.	INTRODUCTION.....	69
6.2.	SIZE COMPOSITION OF CATCH IN 2006.....	69
6.3.	SIZE COMPOSITION OF CATCH 1990-2006.....	71
6.4.	PROPORTION OF FEMALES THAT REACH SECOND MATURE INSTAR	75
6.5.	DISCUSSION.....	77
7. POTENTIAL FOR USING DATA FROM DEPLETION STUDIES FOR FUTURE ASSESSMENT OF NT MUD CRABS.....		78
7.1.	INTRODUCTION.....	78
7.2.	METHODS	78
7.3.	RESULTS	79
7.4.	DISCUSSION.....	86
8. GENERAL DISCUSSION		89
8.1.	AVAILABLE INFORMATION AND CRITICAL KNOWLEDGE GAPS	89
8.2.	STATUS OF THE RESOURCE AND UNCERTAINTY.....	91
8.3.	IMPLICATIONS FOR FUTURE HARVEST LEVELS AND PATTERNS.....	94
8.4.	RECOMMENDATIONS FOR THE DEVELOPMENT OF A HARVEST STRATEGY	95
8.5.	RESEARCH TO ENHANCE FUTURE STOCK ASSESSMENT	96
REFERENCES.....		99
APPENDIX 1.....		100

LIST OF FIGURES

Figure 1-1. Mud crab <i>Scylla serrata</i>	16
Figure 1-2. Map showing the locations of the six mud crab fishing regions in the Northern Territory. Note that the each region is defined by its colour and that name of each region is in capital letters. Source: DPIFM.....	19
Figure 2-1. Annual catch, effort and CPUE for the NT mud crab fishery from 1983 to 2006.	26
Figure 2-2. Regional patterns in catch (t) and effort (potlifts) for the NT mud crab fishery between 1983 and 2006. Data for several years have been omitted for confidentiality reasons.....	27
Figure 2-3. Percentage of catch and effort by region for the NT Mud Crab Fishery between 1983 and 2006. Data are omitted for some years due to confidentiality issues.	29
Figure 2-4. Regional patterns in CPUE (kg.potlift ⁻¹) for the NT Mud Crab Fishery between 1983 and 2006. Data for several years have been omitted for confidentiality reasons.	30
Figure 2-5. Number of grids fished and CPUE per year in the NT Mud Crab Fishery.....	31
Figure 2-6. Monthly pattern in catch and effort for the NT Mud Crab Fishery between 1983 and 2006. Data for January 1983, 1984, 1986, 1993 and 1994, and February 1984, 1993 and 1995 have been omitted for confidentiality reasons.....	32
Figure 2-7. Monthly pattern in CPUE for the NT Mud Crab Fishery between 1983 and 2006. Data for January 1983, 1984, 1986, 1993 and 1994, and February 1984, 1993 and 1995 have been omitted for confidentiality reasons.	33
Figure 2-8. Catch and corresponding freight data for the NT Mud Crab Fishery from 1989-2005.	34
Figure 3-1. Length-weight relationship for female (red) and male (blue) mud crabs sampled from market monitoring from 1990-2006.....	39
Figure 3-2. Female and male size at maturity for crabs from Beagle Gulf and the Gulf of Carpentaria captured and tagged during the wet and dry seasons in studies carried out from 1999 to 2006.....	40
Figure 3-3. Annual (left) and monthly (right) sex ratios by number of mud crabs (female red, male blue) captured in Beagle Gulf and the Gulf of Carpentaria from 1990-2006.....	42
Figure 3-4. Monthly sex ratio for mud crabs captured in Beagle Gulf from 1997-2006 (females red, males blue).	43
Figure 3-5. Monthly sex ratio for mud crabs captured in the Gulf of Carpentaria from 1997-2006 (females red, males blue).	44
Figure 3-6. Mean monthly carapace width for mud crabs captured in Beagle Gulf and the Gulf of Carpentaria from 1990-2006 (left). Mean annual carapace width for mud crabs captured in Beagle Gulf and the Gulf of Carpentaria from 1990-2006 (right). Females red, males blue.	45

Figure 3-7. Mean monthly carapace width for mud crabs captured in Beagle Gulf from 1997-2006. Females red, males blue.....46

Figure 3-8. Mean monthly carapace width for mud crabs captured in the Gulf of Carpentaria from 1997-2006. Females red, males blue.....47

Figure 4-1. Distribution of carapace width at first capture for recaptured crabs tagged in Beagle Gulf and the Gulf of Carpentaria. (blue = male; red = female).51

Figure 4-2. Distribution of time-at-large (weeks) for crabs recaptured in Beagle Gulf and the Gulf of Carpentaria. (blue = male; red = female).....53

Figure 4-3. Distribution of individual growth increments for crabs recaptured in Beagle Gulf and the Gulf of Carpentaria. (blue = male; red = female)54

Figure 4-4. Von Bertalanffy (VB) growth curves plotted using the parameters calculated from tag-recapture data for all male and female mud crabs and those below MLS using GROTAG, and parameters calculated by Knuckey (1999) and Haddon *et al.* (2005). Dotted lines indicate current minimum legal size (MLS) for male and female crabs.....55

Figure 4-5. Growth increment for recaptured mud crabs in three size classes: (i) starting carapace width greater than the MLS (i.e. 130 and 140 mm for male and female crabs, respectively), starting carapace width of 100-130 mm and 110-140 mm for male and female crabs respectively, and crabs with a starting carapace width less than 100 and 110 mm for males and females, respectively.57

Figure 5-1. Estimates of total mortality derived for female (red) and male (blue) mud crabs from the NT commercial fishery using the enhanced Wetherall analysis.60

Figure 5-2. Observed and predicted relative length distribution of female and males in the NT Mud Crab Fishery in 2005 and 2006.61

Figure 5-3. Effect of MLS on the yield-per-recruit for several von Bertalanffy growth curves. Old MLS = 130 mm for males and 140 mm for females. New MLS = 140 mm for males and 150 mm for females. Note that y-axes are different for each graph.63

Figure 5-4. Effect of changing F on the yield-per-recruit and optimum MLS for several von Bertalanffy growth curves. From top to bottom F = 1, 2, 5, and 10. Note that y-axes are different for each graph.....64

Figure 5-5. Optimal MLS by fishing mortality (F) for several von Bertalanffy growth curves.65

Figure 5-6. Modelled recruitment estimates given constant fishing power.66

Figure 5-7. Modelled relative fishing power estimates given constant recruitment.....67

Figure 6-1. Proportion of crabs (i) above the new MLS (males >140 mm, females >150 mm), (ii) between the new and old MLS (males >130 mm and <140 mm, females >140 mm and <150 mm), and (iii) below the old MLS (males <130 mm, females <140 mm) during the 2006 observer program.....70

Figure 6-2. Size distribution of female crabs in the NT Mud Crab Fishery 1990-2006. Dotted line represents the MLS established in May 2006. Dashed line represents MLS from 1996 onwards.72

Figure 6-3. Size distribution of male crabs in the NT Mud Crab Fishery 1990-2006. Dashed line represents MLS from 1996 onwards. Dotted line represents the MLS established in May 2006.73

Figure 6-4. Percentage of the catch in the NT Mud Crab Fishery 1990-2006 that was below the current MLS of 150 mm for females and 140 mm for males (solid line) and below a 5 mm increase from the 2005 MLS (broken line). 2006 data includes data from before and after the May 1 introduction of the new MLS.74

Figure 6-5. Proportion of immature, 1st and 2nd instar female mud crabs in the NT Mud Crab Fishery between 1990 and 2006.76

Figure 7-1. Schematic map of the sampling design for depletion studies conducted by DPIFM from 1997-2004 (reprinted from Hay et al. 2005).....78

Figure 7-2. Data and standard Leslie depletion model regression line for each of the 18 depletion experiments at Blockoff Creek and Twin Sisters Creek. Each point represents a day of depletion experiment. The y-value is the daily catch rate as the number of mud crabs captured per day by all 50 pots within the depletion zone. The x-value is the cumulative number of crabs captured in all days of each depletion experiment, up to but not including the day shown for each point.81

Figure 7-3. Estimates of the number of mud crabs in the depletion zone at Blockoff Creek and Twin Sisters Creek prior to the start of each depletion experiment (N_1) calculated using the Standard Leslie depletion model and a maximum likelihood Poisson estimate.....82

Figure 7-4. Proportion of mud crabs captured per day (q) within the depletion zone in Blockoff Creek and Twin Sisters Creek for each depletion experiment calculated using the standard Leslie depletion model and a maximum likelihood Poisson estimate.....83

Figure 7-5. Comparison of initial abundance estimates from the Poisson and Leslie methods with the day 1 catch and catch per day for each depletion experiment in Blockoff Creek and Twin Sisters Creek.....84

Figure 8-1. CPUE in the Queensland (kg.fishing-day⁻¹) and NT (kg.potlift⁻¹) Gulf of Carpentaria Mud Crab Fisheries from 1990 to 2006. Arrow indicates the last year of data available to Haddon *et al.* (2005).92

LIST OF TABLES

Table 7-1. Start and finish dates and locations of the 18 depletion experiments used in our analyses.....79

Table 7-2. Pearson correlation coefficients between each measure of depletion abundance at Blockoff Creek and Twin Sisters Creek.....85

ACKNOWLEDGEMENTS

Data for this assessment were provided by NT Department of Primary Industries, Fisheries and Mining (DPIFM). We thank Mr Michael Phelan, Dr Mark Grubert and Dr Rik Buckworth (DPIFM) for their assistance interpreting the data and valuable input throughout the course of the assessment. We are particularly grateful to Mr Doug Neville (President NT Crab Fishermen's Association), consultants, Mr Chris Calogeras and Dr Ian Knuckey, Ms Katherine Sarnekis (NT Seafood Council) for their constructive contributions to the project. Special thanks to Mr Peter Pender (Northern Land Council) and Mr Chris Makepeace (Amateur Fishermen's Association of the Northern Territory) for their input. The report was reviewed by Dr Tony Fowler and Mr Cameron Dixon and approved for release by Mr Steven Clarke (SARDI Aquatic Sciences).

EXECUTIVE SUMMARY

1. This report: i) synthesises existing information for the NT Mud Crab Fishery; ii) assesses the status of the NT mud crab resource; iii) identifies implications for future harvest levels; iv) outlines options for improving the harvest strategy; and v) identifies future research needs.
2. Considerable information is available for NT mud crabs, including catch and effort data (1983-present), sex-specific size data from market monitoring (1990-present), tagging data (1997-2004), depletion data (1999-2004) and observer records (2006). Knuckey (1999) interpreted data up to 1995. Stock assessments were conducted in 1996, 2000 and 2004.
3. Existing data provides a consistent picture regarding the status of the NT Mud Crab Fishery. High catch levels and CPUE in 2000 and 2001 were followed by rapid declines in both parameters. Catch and CPUE in 2006 were at their lowest levels since 1995. These declines were associated with an increase in the number of grids fished each fishing year and were strongest in the Gulf of Carpentaria (GoC) where the majority of the catch is taken.
4. The mean size of crabs taken from the GoC declined from 156 mm to 146 mm for males and 161 mm to 152 mm for females between 1997 and 2004, before increasing in 2006 following the introduction of 10 mm increases in MLSs (to 140 mm for males and 150 mm for females). The declines in mean size during 2000 and 2001 may reflect strong recruitment, whereas the declines in mean sizes from 2002 onwards may reflect the increased dependence of the fishery on new recruits and increasingly “knife-edge” selection during this period.
5. Outputs from the recruitment-adjusted seasonal depletion model suggest that the large fluctuations in catch and CPUE over the last decade mainly reflect variations in recruitment rather than changes in fishing power. CPUE in the Queensland and NT GoC fisheries increased concurrently in 2000 and 2001, which suggests that broad-scale environmental factors may have underpinned the high levels of recruitment.
6. Since 2003, CPUE in the Queensland part of the GoC has recovered to levels similar to those in 1999, whereas CPUE in the NT in 2006 remained below the 1996 level. These different CPUE trajectories may reflect differences in the management arrangements: Queensland prohibits the taking of females and the MLS for males is 150 mm, whereas up until 2006 the MLSs in the NT were 130 and 140 mm for males and females, respectively.
7. Our findings support previous assertions that total mortality rates for NT mud crabs are very high (>4.0) in comparison to the accepted estimates of natural mortality (~ 1.2). Under both the current and previous MLSs, yield-per-recruit is maximised for fishing mortalities of approximately 2.0. The MLS that is needed to maximise yield-per-recruit increases as the rate of fishing mortality increases.
8. The 2004 stock assessment correctly identified concerns regarding the sustainability of previous management arrangements and identified changes that could be made to address this situation, including a seasonal closure or increase in the MLS. Representations made on

- behalf of the industry argued strongly for an increase in MLS rather than a seasonal closure. Our analyses suggest that a 10 mm increase was warranted and protected approximately four times as many small crabs as a 5 mm increase in MLS. The 2007 data needed to assess the status of the fishery following the introduction of the new MLSs were not available for this assessment. This assessment should be updated as soon as the 2007 data become available.
9. Tagging data did not provide robust descriptions of the growth patterns, in part because of the absence of growth (recapture) data for crabs above the MLS due to the very high rates of fishing mortality. The growth patterns of NT mud crabs also appear to violate assumptions of the von Bertalanffy growth model.
 10. Critical knowledge gaps include uncertainties in effort data, poor understanding of growth and mortality rates, lack of data on reproductive biology, ecology and population dynamics and lack of an integrated fishery assessment model. Considerable fishery-independent information has been collected. However, these are of limited use for ongoing assessment.
 11. A harvest strategy should be developed for the NT Mud Crab Fishery as soon as possible. The objectives must be informed by broad government policy. This report identifies potential biological performance indicators, notes that reference points should be set to reflect the objectives of the fishery and outlines potential elements of an improved approach to research and assessment to support future management.
 12. One option for addressing uncertainties regarding levels of nominal and effective effort would be to establish a program of fishery-independent surveys using commercial vessels with scientific observers onboard. Some of the catch could be sold to offset costs and the remainder could be released after the insertion of passive integrated transponder (PIT) tags. The market sampling program for NT mud crabs would need to be expanded to include screening for PIT tags. The approach would provide spatially explicit information on the growth and mortality rates that would significantly enhance future stock assessment.
 13. A Ph.D. study would provide a cost effective option for obtaining information on the ecology and population dynamics of mud crabs that is needed to assess the effectiveness of management arrangements that have and could be established. A detailed study of population dynamics would also assist development of an integrated stock assessment model.
 14. The research and assessment program that is established for the NT Mud Crab Fishery would ideally be conducted by scientists located in the NT who work closely with fisheries managers and industry. Commissioning different external scientists to undertake each new assessment is not efficient due to the need for data familiarisation. Scientists from outside the NT could play an ongoing role in supporting local staff to refine approaches to monitoring and stock assessment. Future management arrangements for the fishery should reflect the accuracy and precision of information on stock status. Members of the NT Mud Crab Fishery should have a key role in identifying future management objectives.

1. INTRODUCTION

1.1 Project Scope and Terms of Reference

1.1.1. Background

In February 2007, the South Australian Research and Development Institute (SARDI) won a competitive tender to conduct a stock assessment of the Northern Territory (NT) Mud Crab Fishery. A teleconference was held on 22 March 2007 among representatives of SARDI (Dr Tim Ward), NT Department of Primary Industries, Fisheries and Mining (DPIFM, Mr Michael Phelan and Dr Mark Grubert), the NT Crab Fishermen's Association (Mr Doug Neville), NT Seafood Council (Ms Katherine Sarnekis), and two industry consultants (Mr Chris Calogeras and Dr Ian Knuckey). The purpose of the teleconference was to confirm the purpose of the assessment; i.e. that it would address the terms of reference listed below. It was agreed during the teleconference that the project would build on previous research and assessments and would not involve the development of an integrated stock assessment model for the fishery or the completion of quantitative management strategy evaluation, which were specifically identified as being outside the scope of the project. It was agreed that the project would comment on the value and suitability of developing an integrated stock assessment model for the NT Mud Crab Fishery and/or conducting a quantitative management strategy evaluation.

1.1.2. Terms of reference

The terms of reference for the assessment by NT DPIFM were as follows.

1. *Analyse historical and current commercial, recreational and indigenous catch and effort data relating to mud crabs in the Northern Territory.*
Outcome: Profile trends evident in the data and describe potential future scenarios.
2. *Analyse historical and current market monitoring data.*
Outcome: Profile trends evident in the data and describe potential future scenarios.
3. *Analyse other mud crab research data gained through abundance studies, tagging work, and habitat/environment monitoring.*
Outcome: Profile trends evident in the data and relate to catch/effort data and market monitoring data.
4. *Analyse observer data and market value information.*

Outcome: Profile trends evident in the data and describe potential future scenarios, and describe the costs/benefits of the recent 10 mm minimum size increase in the commercial mud crab fishery.

DPIFM also requested the assessor to undertake the following activities.

5. *Provide an oral/ visual presentation describing the current status of the fishery and likely future scenarios.*

Outcome: Provide a holistic view of the current and future status of the mud crab fishery and describe potential outcomes of varying management arrangements.

6. *Contribute to the production of a stock assessment publication and/ or a peer-reviewed publication.*

Outcome: Assist in documenting the results and outcomes of the stock assessment.

1.2 Aims and Overview of Report

1.2.1 Rationale and aims

The approach taken in this project is consistent with that taken by SARDI Aquatic Sciences in providing information to support the management of South Australia's commercial fisheries. This approach involves using all available information to assess the status of a fishery and identify options for improving methods used to manage and assess the stock. Like SARDI Aquatic Sciences' stock assessment reports for South Australia's commercial fisheries, this report is intended to be a 'living document' that will be updated in future years.

The report addresses the terms of reference for the assessment within the context of the following five objectives.

1. To synthesise existing information for the NT Mud Crab Fishery and identify critical knowledge gaps.
2. To assess the status of the resource, including an explicit consideration of uncertainty.
3. To identify the implications of the assessment for future harvest levels and patterns.
4. To comment on the suitability of the current Performance Indicators and Reference Points and identify options for improving the Harvest Strategy.
5. To identify research that is needed to enhance future stock assessment.

1.2.2 Review of the report

The remainder of this chapter synthesises existing information and provides: a synopsis of the biology of *Scylla serrata*; an overview of the NT Mud Crab Fishery; an outline of the current

management framework; and a summary of the approach and findings of previous stock assessments.

Commercial catch and effort data for the NT Mud Crab Fishery is presented in Chapter 2. The third chapter provides information on the sexual dimorphism, size at sexual maturity, sex ratio and mean size of crabs in catches. Chapter 4 describes the growth patterns of NT mud crabs. Outputs from models similar to those used in previous assessments are used to estimate: (i) changes in mortality rates over time; (ii) factors affecting yield-per-recruit and (iii) the extent to which recent changes in catches and CPUE may reflect variations in recruitment and/or fishing power (Chapter 5).

Chapter 6 assesses the effects of the 10 mm increases in the MLSs that were implemented in May 2006. Chapter 7 assesses the potential for using data from the depletion studies for fishery-independent assessment of the abundance NT mud crabs.

Chapter 8 is the General Discussion of the report. It summarises information available for the fishery and identifies critical knowledge gaps; provides an assessment of the status of the NT Mud Crab Fishery; identifies the level of uncertainty associated with this assessment; outlines the implications of the assessment for future harvest levels; identifies options for revising the current harvest strategy; and identifies research and monitoring that is needed to support future stock assessment.

1.3 Biology of the Mud Crab, *Scylla serrata*

1.3.1 Taxonomy

Four species in the genus *Scylla* De Haan 1833 occur in the Indo-West Pacific Region and are known as mud crabs (Imai et al., 2004; Keenan et al., 1998). Mud crabs are true crabs (Brachyura) and belong to the Family Portunidae. Two species occur in northern Australian waters: *S. serrata* (Forsk., 1775) and *S. olivacea* (Herbst, 1796). However, *S. olivacea* accounts for less than 1% of the catch in the NT Mud Crab Fishery (Knuckey 1999).

1.3.2 Description

S. serrata has a broad smooth shell (carapace) with nine equally sized spines on either side of the eyes. It has five pairs of legs. The first pair are chelae or claws, the following three pairs are walking legs and the last pair of legs are swimming paddles (Figure 1-1). The colour of mud crabs ranges from dark brown to blue and mottled green. A detailed description of this species is provided by Keenan *et al.* (1998).

Mud crabs grow by moulting, whereby the shell splits and the crab forces itself backwards out of the shell. The crab then expands to a larger size and the shell hardens.

Mud crabs moult often and grow quickly. In the Northern Territory they reach 100-120 mm carapace width (all sizes are based on carapace width) after approximately one year. Mud crabs reach sexual maturity at 130-150 mm (18 months) depending on sex and location (Knuckey 1999). As juveniles, male and female mud crabs are difficult to differentiate. At maturity females develop a large, rounded, pigmented abdominal flap which is modified to carry and protect the eggs, whereas males have a thin, unpigmented triangular abdominal flap. Elongate filamentous setae develop on the pleopods of mature females. Males develop very large claws compared to the females.

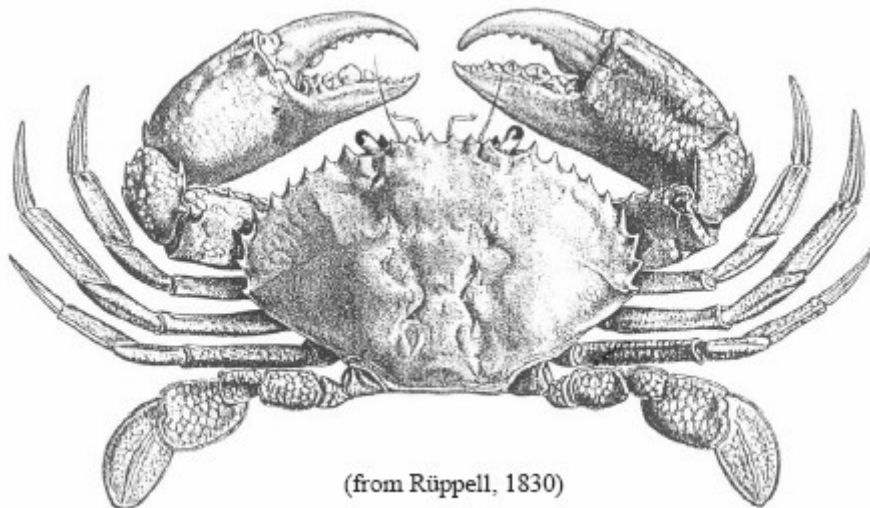


Figure 1-1. Mud crab *Scylla serrata*.

1.3.3 Distribution

Mud crabs are distributed throughout the Indo-West Pacific region usually in tropical and subtropical, mangrove and estuarine habitats. In Australia, the mud crab extends from the mid-coast of New South Wales north through Queensland, across northern Australia and down to Exmouth Gulf in Western Australia.

The early life-history of mud crabs in the NT is poorly understood. However, it is believed that juveniles generally live in the mangrove zone of inter-tidal areas where they scavenge for plant and animal matter.

1.3.4 Stock Structure

Analysis of mitochondrial DNA revealed two separate clades of mud crab geographically separated by Torres Strait (Gopurenko and Hughes, 2002). Analysis of molecular variance revealed no significant difference between crabs collected in the Adelaide River and Roper River, but significant differences between crabs collected in the western and eastern Gulf of Carpentaria.

1.3.5 Reproduction

Female maturity is determined by the presence of a mature abdominal flap and long filamentous setae on the pleopods. By ~136 mm most mature females have mated. Sperm is present in male crabs larger than 110-120 mm. Functional maturity in males is determined by the presence of 'mating scars' on the sternum and first walking leg (Knuckey 1999). Mating scars have been observed on males as small as 125 mm, but are more common on males between 150 to 165 mm.

Mating occurs after a mature female, or an immature female approaching maturity, has moulted and the shell is still soft. When a female is about to moult, a male will hold her underneath him with the first pair of his walking legs. In this 'doubled' position, which may be maintained for up to one week, the male protects the female until she can defend herself. The female is turned upside down during mating, with her abdominal flap forced open and around carapace of the male. The male transfers gelatinous bags of sperm into the female. Females can mate more than once per season and can spawn up to three times from a single mating (Ong 1966).

Around November and December, which may be several months after mating, females migrate offshore to spawn. Specimens have been reported up to 50 km from land. The eggs (up to 8 million) that develop in the ovaries are fertilized as they are transferred onto feather like structures under the female's abdominal flap. The eggs hatch into free-swimming larvae called zoea approximately 20-40 days after fertilization. The zoea drift inshore with the currents, and moult through the megalopa phase to become juveniles with carapace widths of 3 - 5 mm. Mud crabs are thought to live for 3 to 4 years.

1.3.6 Parasitic sterilisation

The sacculinid parasite *Loxothylacus iblei* occurs in mud crabs in northern Australia. This parasite causes sterilisation of the infected crab, changes the morphology of the abdominal flap and causes the infected crabs to be significantly smaller than uninfected crabs (Knuckey *et al.*, 1995). The infection prevalence in the commercial catch in northern Australia is around 2-7%. The prevalence of *Loxothylacus iblei* is routinely recorded in NT market monitoring and fishery independent data.

1.4. NT Mud Crab Fishery

1.4.1 Overview

The NT Mud Crab Fishery is based on the capture of a single species, the green mud crab (*Scylla serrata*). Small catches of *S. olivacea* are also taken but this accounts for less than 1% of the catch (Knuckey, 1999). The fishery has four sectors: commercial, recreational, fishing tour operators, and indigenous fishers.

1.4.2 Commercial Fishery

Commercial fishers target mud crabs using rectangular steel-mesh pots that are baited with red meat or fish.

Prior to the 1980s, mud crabs could be taken on a General Fishing Licence with no limit on pot numbers. In 1980, a specific mud crab fishery was established with 61 licences issued and no restriction on pot numbers. By 1982, the number of licences peaked at 112. Active management of the fishery began in 1984 in response to growing effort. A \$5 pot fee was introduced, but there was no limit on the number of pots.

In 1985, a significant attempt was made to restrict fishing effort: the number of licences was capped at 55; the number of pots per licence was set at 60; Darwin Harbour and several surrounding creeks were closed to commercial crabbing; and a minimum size limit of 130 mm was set for both male and female mud crabs. The maximum number of licences was further reduced to 49 in 1988.

The mud crab fishery was declared a managed fishery in 1990. The fishery is unzoned. However, catch and effort is recorded by grid number and reported with respect to six regions: West, Darwin, Arnhem, Blue Mud Bay, Roper and Borroloola (Figure 1-2). A Management Plan was established for the NT Mud Crab Fishery in 1991, setting the number of licences at 49 with a maximum of 60 pots per licence. The Management Plan was amended in 1993 to protect berried female mud crabs. In 1996, the minimum size limit for females was increased to 140 mm and the use of restricted bait nets in the McArthur River area was prohibited.

In 2000, the total catch for the fishery exceeded 1000 t for the first time and a review of the Management Plan commenced. In the following year, the release of commercially unsuitable (e.g. damaged or soft shelled) crabs was made a licence condition. The catch was again in excess of 1000 t in 2001. A strategic assessment of the fishery under the Commonwealth Environment Protection and Biodiversity Conservation Act commenced in 2001.

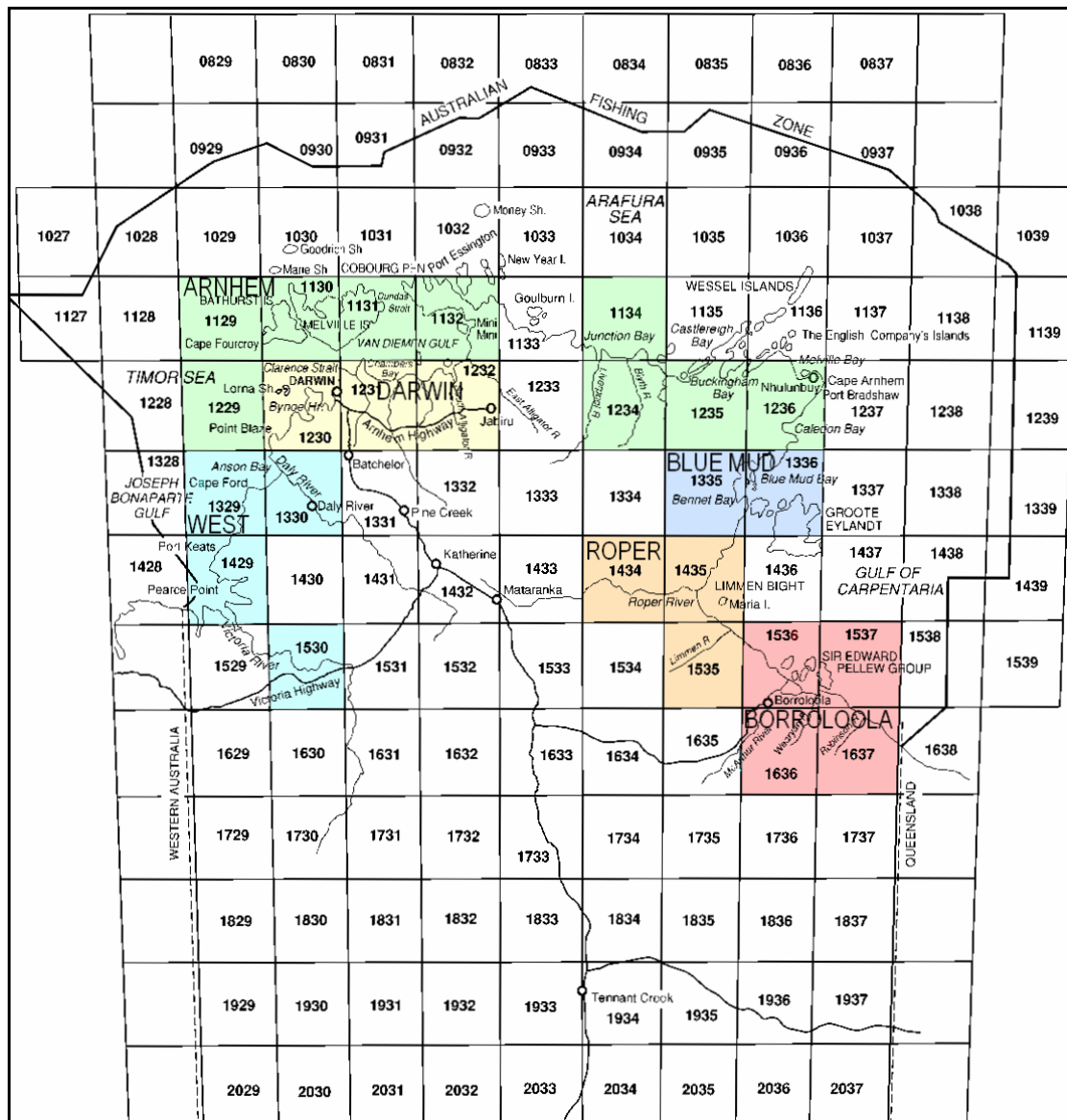


Figure 1-2. Map showing the locations of the six mud crab fishing regions in the Northern Territory. Note that the each region is defined by its colour and that name of each region is in capital letters. Source: DPIFM.

Between 2002 and 2006 the catch and CPUE declined rapidly. Following a stock assessment workshop in 2004, a new Management Plan was introduced in 2006 which established a minimum legal limit of 140 mm for males and 150 mm for females. In 2006, all but two of the 49 licences were active.

1.4.3 Recreational Fishery

Recreational fishing for mud crabs was first regulated in 1972, when crabbers were required to register up to three pots for a \$5.00 fee. This system remained in place until 1985, when the commercial fishery became more actively managed. At this point, recreational crabbers were no

longer required to register their pots, but a minimum size limit of 130 mm was introduced for male and female crabs.

As part of the Management Plan introduced in 1991, recreational crabbers were entitled to use five pots each, with a boat limit of 10 pots. Along with pot limits, recreational fishers were limited to possess 10 crabs per person and 30 crabs per vessel. Five years later, the minimum size limit for female mud crabs was raised to 140 mm. These size limits for male and female crabs remain in place for the recreational sector.

Controls on the recreational sector include a possession limit of up to 10 crabs per person and 30 mud crabs for each vessel (with three or more people aboard). Recreational fishers use pots similar to the commercial fishery. They also use dillies, hand spears, hand-held hooks, hook and line, hand nets, cast nets and drag nets.

According to the National Recreational and Indigenous Fishers Survey (NRIFS, Henry and Lyle, 2003) the recreational catch in the Northern Territory in 2001 was 82,371 crabs or 65 t from a national total of 819,886 mud crabs or 815 t. Nationally, over 91% of mud crabs were caught in pots and over 74% were caught from a boat. In addition to the total national recreational catch, 1,759,843 mud crabs were released.

1.4.4 Fishing Tour Operator Sector

A Fishing Tour Operator (FTO) licence allows a person to conduct the commercial activity of taking people on fishing tours. Only recreational fishing gear can be used and the catch cannot be sold, traded or bartered. The recreational pot and possession limits apply on such tours.

There are currently approximately 150 licensed FTO in the Northern Territory, but the targeting of mud crab is not a primary activity. However, mud crabs are taken occasionally and in 1999 the reported catch from this sector was in the vicinity of 1 t, 20% of which were released. Licensed FTOs can be considered as commercial operators, but their clients fish as members of the recreational sector and normal recreational pot and possession limits apply.

1.4.5 Indigenous Sector

Mud crabs are a significant food source for coastal Aboriginal people. Section 53 of the *Fisheries Act* guarantees Aboriginal people the right to utilise fish and other aquatic resources for food and traditional use such as ceremonies and customs, without the need to abide by either the recreational or commercial regulations. Mud crabs taken under these arrangements cannot be

sold. Aboriginal people are entitled to use recreational fishing gear, but most often spear or harvest crabs by hand.

The National Recreational and Indigenous Fishing Survey (Henry and Lyle, 2003) found that in northern Australia in 2001, 86,573 of a total 108,462 mud crabs were captured by indigenous fishers in the NT. In contrast to the recreational sector, a majority of the harvested by indigenous fishers crabs were captured either by spear (29,345) or hand (63,203). The size and methods of the indigenous mud crab catch highlight the importance of this resource as a traditional food source for indigenous people in the NT.

1.5 Current Management Framework

1.5.1 Stakeholder Consultation

The Mud Crab Fishery Advisory Committee (MCFAC) provides the main forum for stakeholders to provide advice to the Director of Fisheries regarding the management of the fishery.

1.5.2 Management Objectives

The Management Plan for the NT Mud Crab Fishery focuses on containing fishing effort and protecting the breeding stock through minimum size limits. The management objective is to ensure that the sustainability of the fishery is maintained.

1.5.3 Performance Indicators and Reference Points

The performance indicators for the NT Mud Crab Fishery are total commercial catch, total commercial effort and the overall mean size of crabs in the commercial catch. The reference points for commercial catch are a 50% increase in one year or a 10% decrease in two consecutive years. The reference point for effort is a 10% annual increase in commercial effort for two or more consecutive years. The reference point for crab size is a 5 mm reduction in median carapace width over two or more consecutive years.

1.5.4 Management Framework

The Management Plan indicates that when reference points are exceeded the MCFAC will review the situation and provide advice to the Director of Fisheries.

Previous Research, Monitoring and Stock Assessment

1.5.5 Overview

The NT Mud Crab Research Program was established in 1990 (Knuckey 1999). A monitoring program was also established in the early 1990s. Each year, staff of DPIFM provided advice to

the MCFAC regarding the status of the fishery. Stock assessment workshops were conducted in 1996, 1999, 2000 and 2004.

1.5.6 Early Research 1990-1995

Knuckey (1999) documented the increases in annual catch and effort from ~25 t and ~100,000 potdays in 1983 to ~260 t and ~600,000 potdays in 1995, and concluded that the recorded catch was usually within 10% of the actual catch and that potday was a reliable measure of effort. The problems associated with the use of annual CPUE as an index of abundance of crabs were noted, especially the effects of seasonal changes in CPUE on the estimate of mean annual CPUE.

Tagging experiments conducted during this period provided valuable information on the growth rates and reproductive biology of *S. serrata* in the NT. The study concluded that exploitation rates in the fishery were high and recommended that “a cautious approach should be adopted with respect to further expansion of the fishery”.

1.5.7 1996 Stock Assessment Workshop

The Stock Assessment Workshop held in 1996 concluded that exploitation rates in fished areas were probably >70% of the available stock, and that the fishery depended on newly recruited crabs rather than those accumulated from several breeding seasons (Walters *et al.* 1997). Although exploitation rates were high there were good recruitments during the 1980s and early 1990s. Walters *et al.* (1997) noted that there was a partial spatial refuge for female crabs because of their offshore migration into unfished areas, but concluded that the stock was fully exploited and that finer scale spatial management arrangements may be warranted in the fishery.

1.5.8 1999 National Research Strategy Workshop

The workshop developed a five year national research strategy for mud crabs and identified three key areas for research.

1. To develop a process to estimate relative productivity of mud crab habitat based on satellite imagery and abundance estimation techniques.
2. To use validated commercial catch and effort data as an index of stock abundance.
3. To develop a fishery independent index of stock abundance based on juvenile pre-recruit abundance.

1.5.9 2004 Stock Assessment Workshop

The Stock Assessment Workshop held in 2004 concluded that the NT Mud Crab Fishery was under stress, and that level of effort and harvest and/or fishing mortality rates were too high. The main results supporting this assessment were: reductions in the mean size of mating males; reductions in the size of both sexes in commercial catches; a higher rate of fishing mortality than

pre-1996; spatial expansion of fishing activities; temporal expansion of the fishing season; and increases in fishing power. The reviewers noted large variations in recruitment between years, and suggested that the similarities in the interannual patterns in the Queensland and NT portions of the Gulf of Carpentaria were indicative of a strong broad-scale environmental effect. The final report recommended that fishing mortality, especially in females, must be reduced and identified several options for achieving this outcome, including a closed season, spatial closures, increases in the minimum legal sizes, additional input controls and the introduction of a quota system.

1.5.10 FRDC Abundance and Habitat Project

This project aimed (i) to quantify types and areas of critical mud crab habitat using satellite imagery and (ii) to develop methods for estimating mud crab abundance within habitat types (Hay *et al.*, 2005). The results suggested that >90% of adult crabs were removed from the Gulf of Carpentaria region of the NT Mud Crab Fishery in 2003 and approximately 19-23% of adult crabs were removed from the Adelaide River/Darwin region in the same year.

2.0 CATCH AND EFFORT DATA FOR THE NT MUD CRAB FISHERY

2.1 Introduction

This chapter describes the spatial and temporal patterns in catch, effort and CPUE for the NT Mud Crab Fishery from 1983 to 2006. The data were extracted from the DPIFM logbook database and provided to SARDI in the form of a spreadsheet with catch (kg) and effort (pot lifts) data for each licence collated by month, grid square and fishing area (Figure 1-2). Only information that is non-confidential (i.e. based on data from five or more fishers) is presented in this report.

2.2 Total Catch, Effort and CPUE

2.2.1 Annual Patterns

Catch

The total annual catch in 1984 was just over 24 t and increased steadily to reach 264 t in 1995. Catch increased to 573 t in 1996 and peaked at 1139 t in 2001 before declining to 265 t in 2006 (Figure 2-1), noting that a 10 mm increase in the commercial MLS was implemented in May of that year.

Effort

Two measures of annual effort (fishing days and potlifts) are reported to illustrate the effect of 'double potting' (i.e. lifting pots twice per day) on catches and catch rates (Figure 2-1). Effort (potlifts) rose steadily from 129,000 potlifts in 1984 to 659,000 potlifts in 1995. Effort increased rapidly over the next three years and ranged between 976,200 and 1,065,560 potlifts per year from 1998 to 2002, before declining to 676,000 potlifts in 2006. Fishing effort in days followed a similar trend to effort in potlifts. The trend was almost identical up until 1994, when double potting started to be reported in the fishery. Double potting resulted in an additional 12-25% of total potlifts per pot per fishing day, except in 2005 and 2006 when double potting resulted in additional 8-10% potlifts.

Catch-per-unit-effort ($CPUE_L$ and $CPUE_d$)

$CPUE_L$ and $CPUE_d$ are the catch (kg) divided by the number of potlifts and the number of fishing days, respectively. From 1983 to 1995, $CPUE_L$ and $CPUE_d$ were fairly stable, ranging from 0.2 to 0.5 kg.potlift⁻¹ and 10 to 30 kg.day⁻¹, respectively. After 1995, $CPUE_L$ increased to >0.6 kg.potlift⁻¹ in 1996 and 1997, then dipped to 0.5 kg.potlift⁻¹ in 1998, before increasing rapidly over the next two years to reach >1.0 kg.potlift⁻¹ in 2000 and 2001. As the catch dropped over the next two years, the $CPUE_L$ dropped rapidly back to pre-1996 levels of ~0.4 kg.potlift⁻¹

from 2003 onwards. $CPUE_d$ followed a similar trend to $CPUE_L$ after 1995, except $CPUE_d$ was higher relative to pre-1995 levels due to the effects of 'double potting'. The relative effectiveness of single and double potlifts is poorly understood. An agreed measure of effort needs to be established for the fishery.

2.2.2 Spatial Patterns

Catch

Interannual trends in the catch from Borroloola and Roper River follow the same general trend as the entire fishery, with a steady rise in catches between 1983 and 1995, a rapid rise between 1996 and 2001, and a rapid decline from 2001 to 2006 (Figure 2-2). The trend for Darwin was different from that in Borroloola and Roper River, with catches remaining comparatively stable from 1983 to 2006.

Borroloola and Roper River regions are the two most important regions in the fishery, and collectively contribute 45-80% of the total annual catch in most years (Figure 2-3). Darwin region, and in recent years Blue Mud Bay and Arnhem regions, also support significant catches. West region contributes only a small proportion of the total catch (Figure 2-3).

Effort

Spatial patterns in fishing effort are similar to the spatial patterns in catch, with most fishing occurring in Borroloola and Roper River, and effort in Darwin remaining relatively stable over time.

$CPUE_L$

Regions within the Gulf of Carpentaria (i.e. Borroloola, Roper River and Blue Mud Bay) have consistently higher levels of $CPUE_L$ than other regions in the fishery (Figure 2-4). All regions showed a significant rise in $CPUE_L$ during the period 1999-2002, but the peaks in Gulf regions during this period were higher than those in other parts of the fishery.

$CPUE_L$ for the Borroloola, Roper River and Blue Mud Bay regions follow the same trend as $CPUE_L$ for the entire fishery, with a steady rise between 1983 and 1995, high levels of $CPUE_L$ between 1996 and 2002, and a return to pre-1996 levels from 2003 to 2006 (Figure 2-4). The Darwin region followed a similar trend, although the decline in $CPUE_L$ appears to have occurred a year earlier than in the Gulf regions (Figure 2-4).

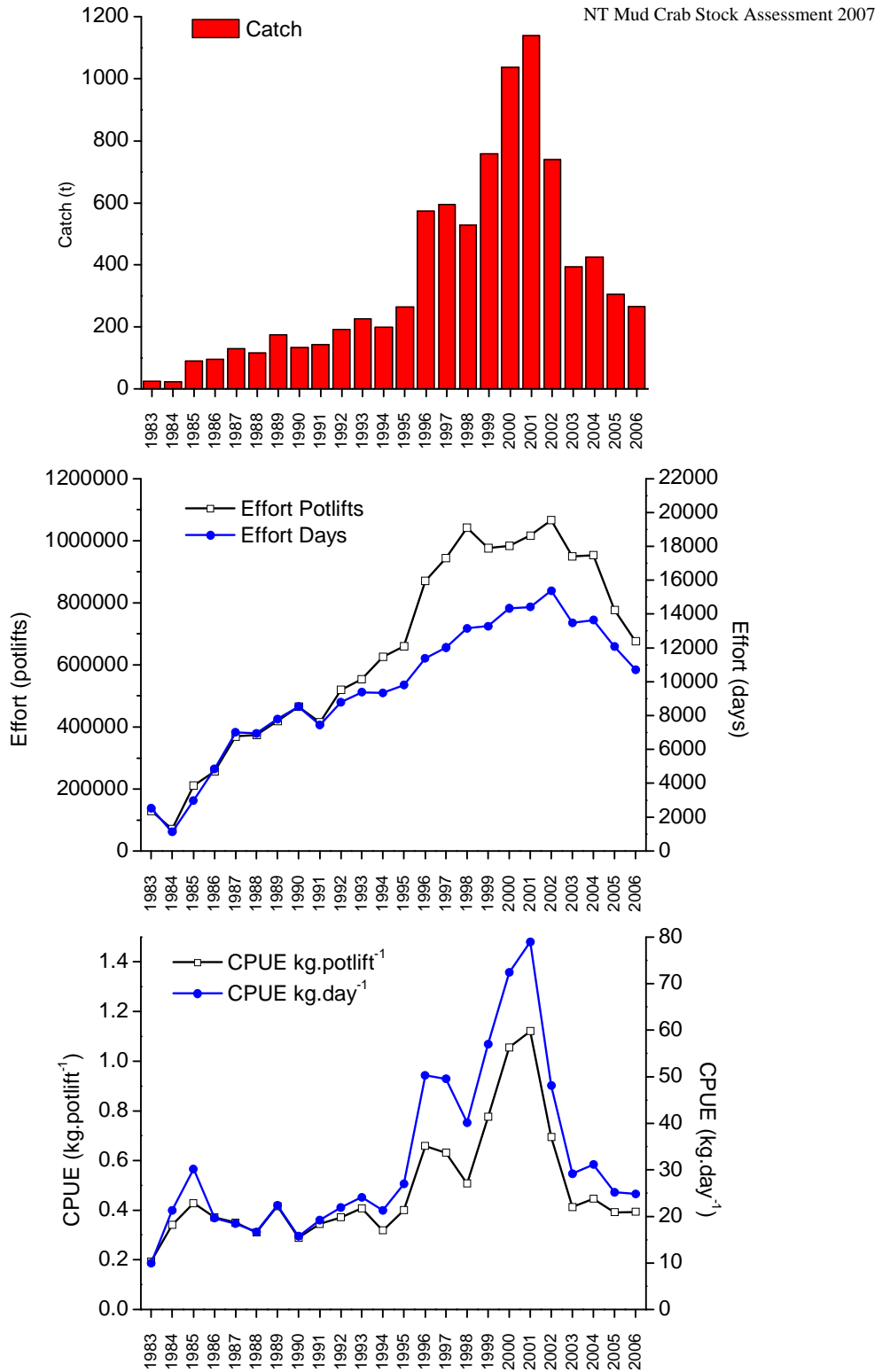


Figure 2-1. Annual catch, effort and CPUE for the NT mud crab fishery from 1983 to 2006.

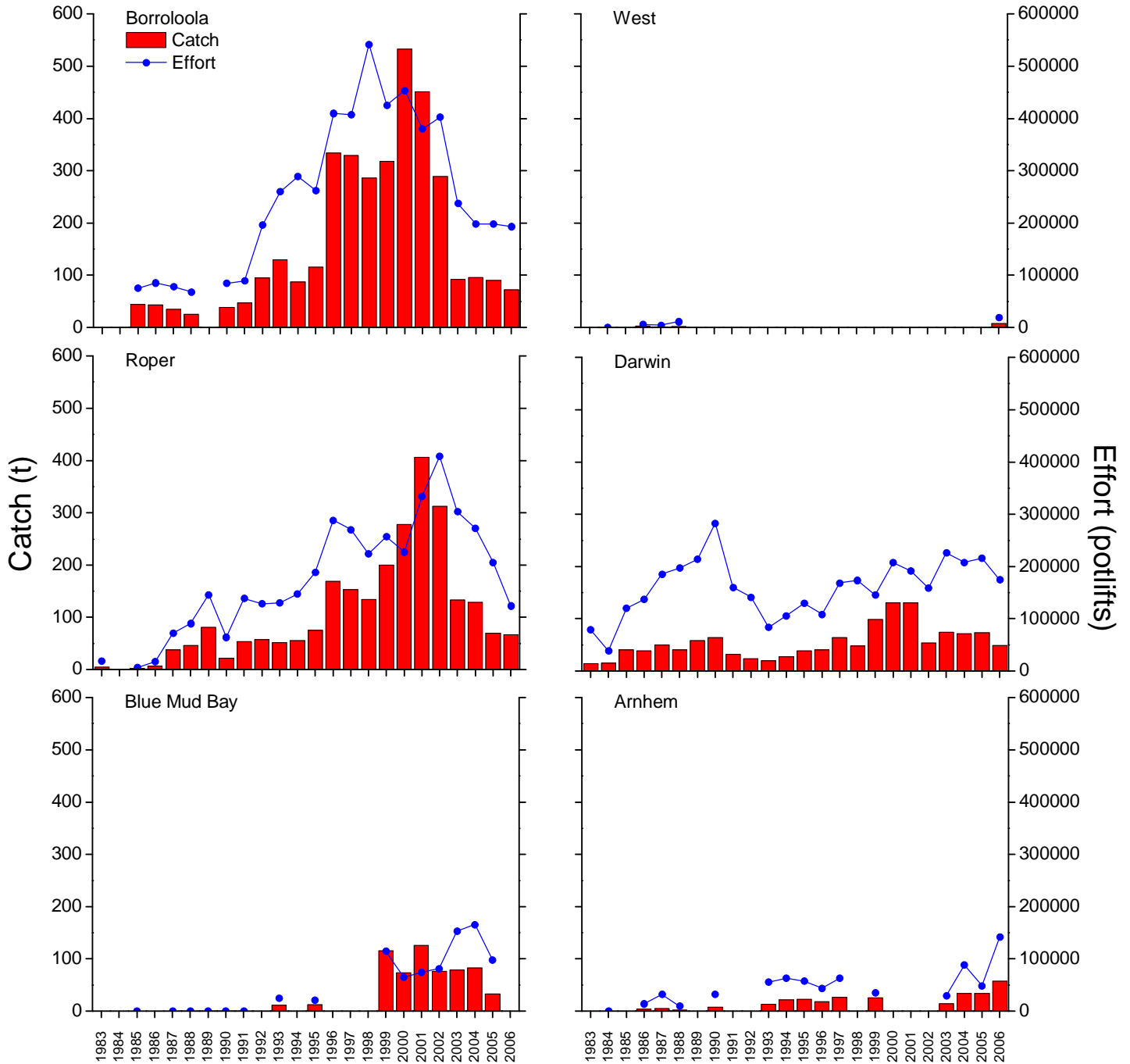


Figure 2-2. Regional patterns in catch (t) and effort (potlifts) for the NT mud crab fishery between 1983 and 2006. Data for several years have been omitted for confidentiality reasons.

Spatial expansion

The number of grids fished during each fishing year is shown in Figure 2-5. The increase in the number of grids fished per year since 2003 reflects the spatial expansion of the fishery into new locations ($p = 0.015$). After 1995, there was a strong negative correlation between number of grids fished and CPUE ($r = 0.73$), i.e. the number of grids fished increased as CPUE decreased. The number of grids fished was particularly low in 2001 and 2002, when catches and CPUE were high.

*2.2.3 Seasonal Patterns**Catch*

Intra-annual patterns of catch have changed since 1983 (Figure 2-6). In the 1980s and early 1990s, catches were low in December through to March, and increased from April to the peak in July before decreasing in the period through to November. In the late 1990s, catches increased from December to March, until the monthly catch in those months was approximately one third or more of the monthly catch from April to November. In recent years, as the total annual catch has declined, monthly catches in December to March have decreased to 1980 levels.

Effort

Intra-annual patterns in effort are similar to the variations in catches, with significant fishing occurring during the entire year in the high catch years of 2000-2002, but being predominately conducted from April to November in other years.

CPUE_L

The highest *CPUE_L* are generally recorded from April to November (Figure 2-7). The highest monthly *CPUE_L* were recorded in 2000 and 2001.

2.2.4 Freight data

Estimates of catch from logbooks and freight data for 1989-2005 are shown in Figure 2-8. These independent estimates of the commercial catch are similar from 1998 onwards.

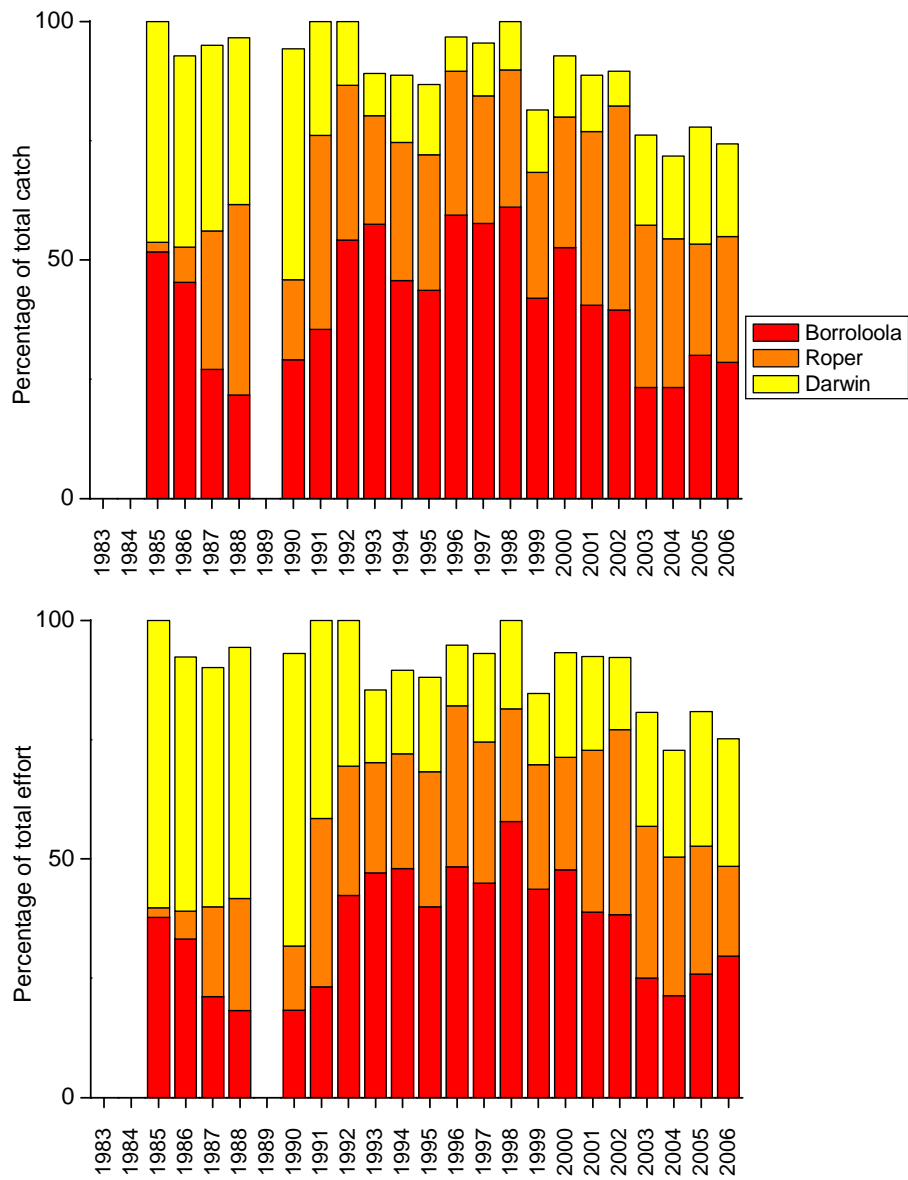


Figure 2-3. Percentage of catch and effort by region for the NT Mud Crab Fishery between 1983 and 2006. Data are omitted for some years due to confidentiality issues.

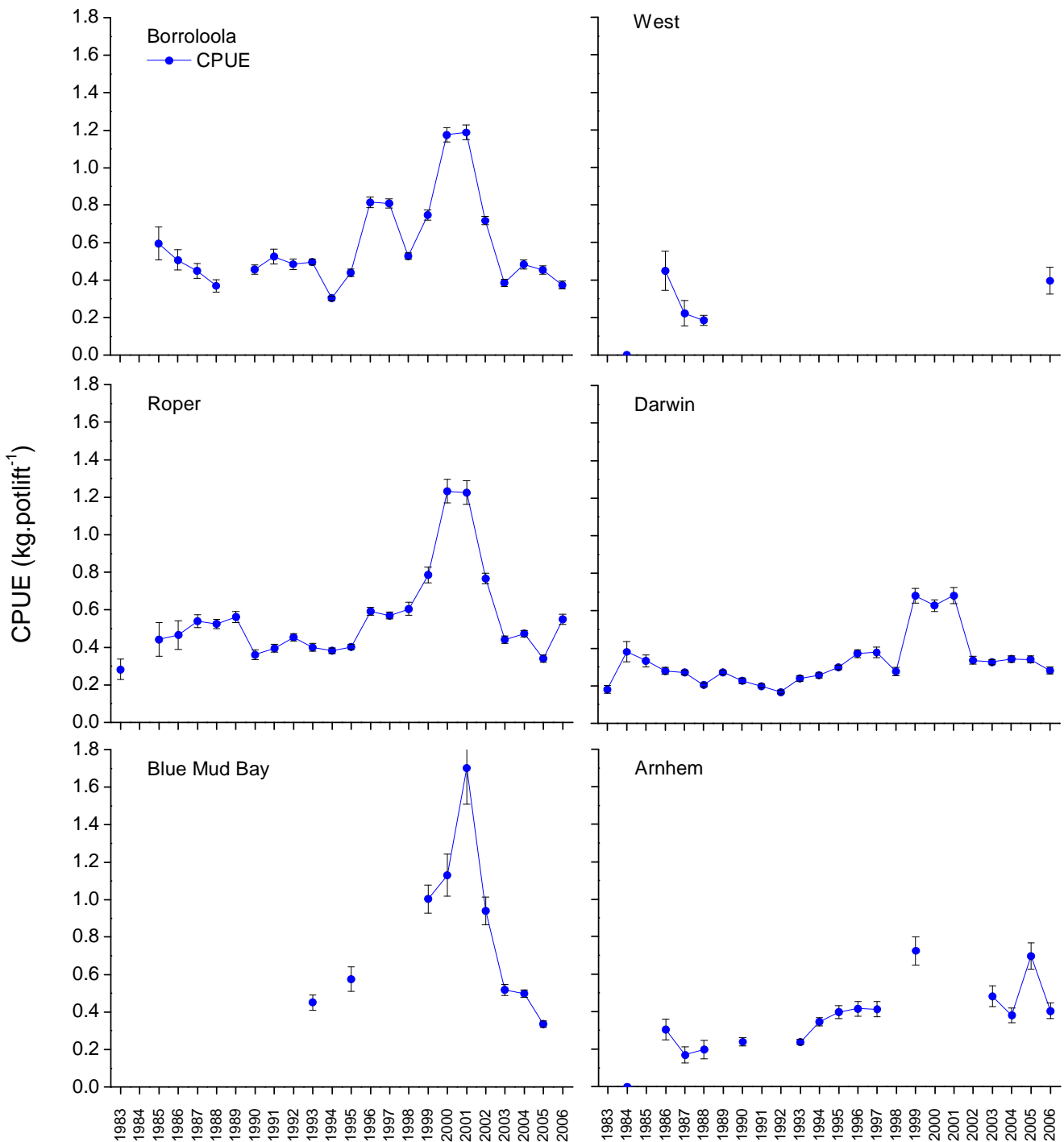


Figure 2-4. Regional patterns in CPUE (kg.potlift⁻¹) for the NT Mud Crab Fishery between 1983 and 2006. Data for several years have been omitted for confidentiality reasons.

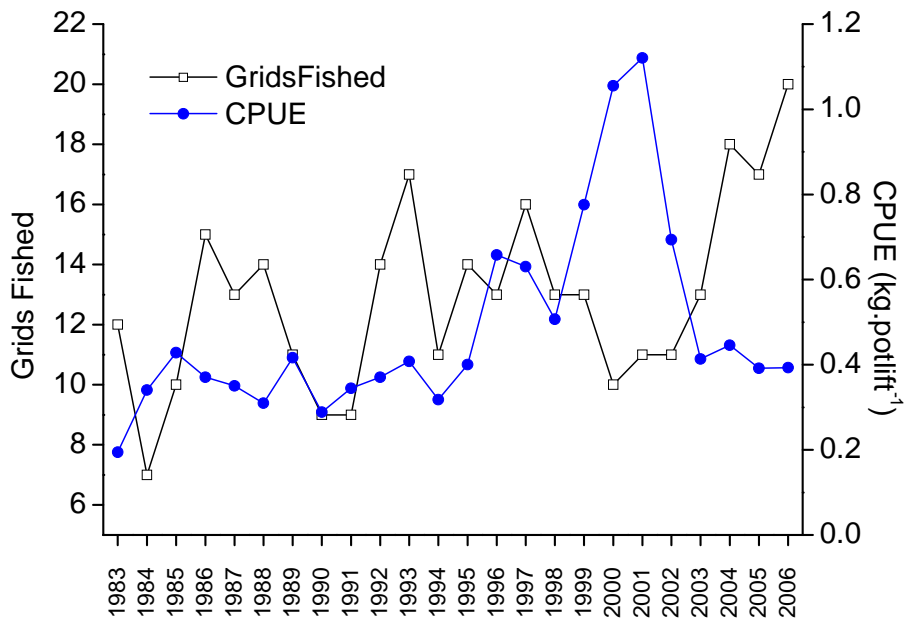


Figure 2-5. Number of grids fished and CPUE per year in the NT Mud Crab Fishery.

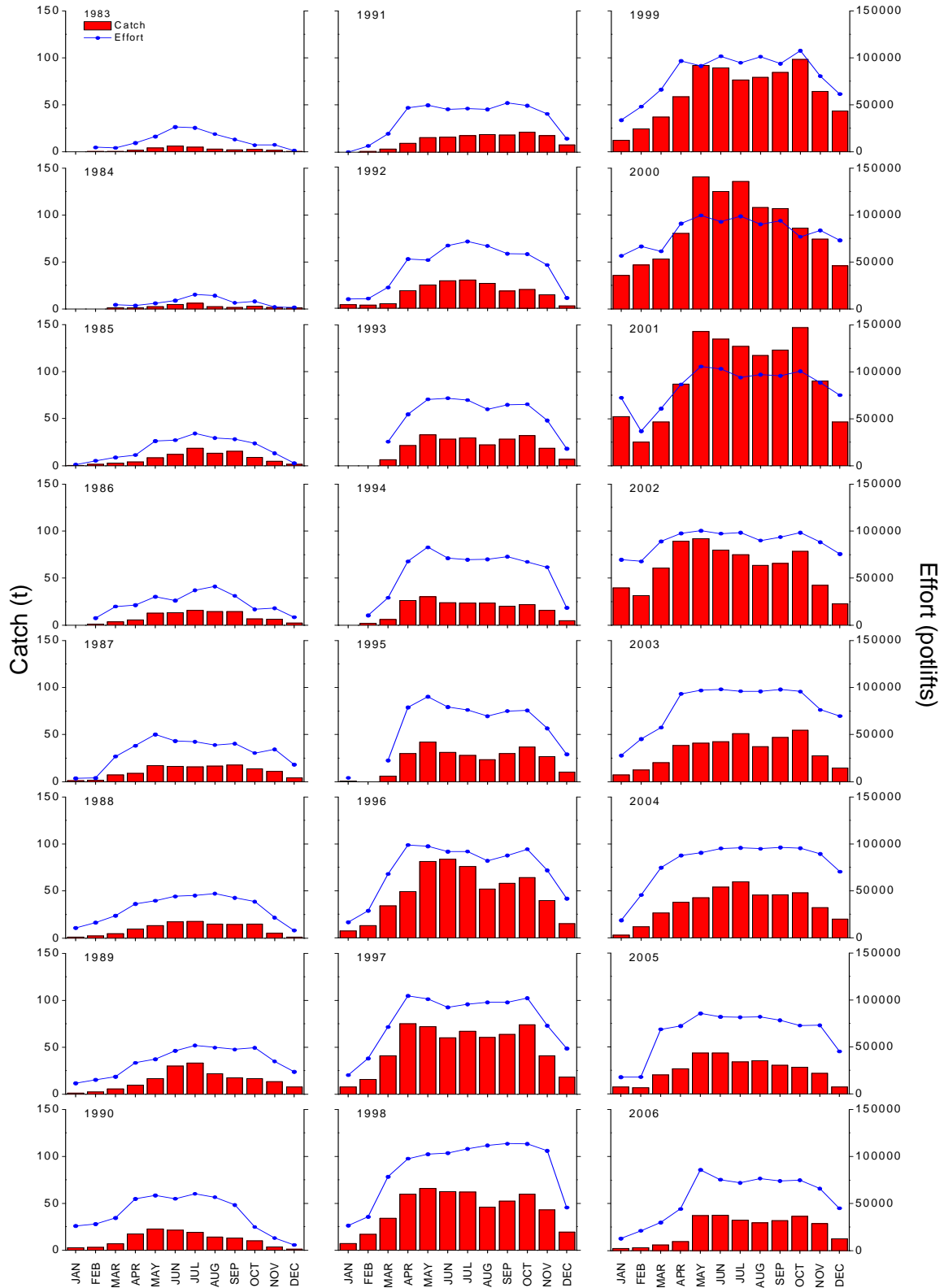


Figure 2-6. Monthly pattern in catch and effort for the NT Mud Crab Fishery between 1983 and 2006. Data for January 1983, 1984, 1986, 1993 and 1994, and February 1984, 1993 and 1995 have been omitted for confidentiality reasons.

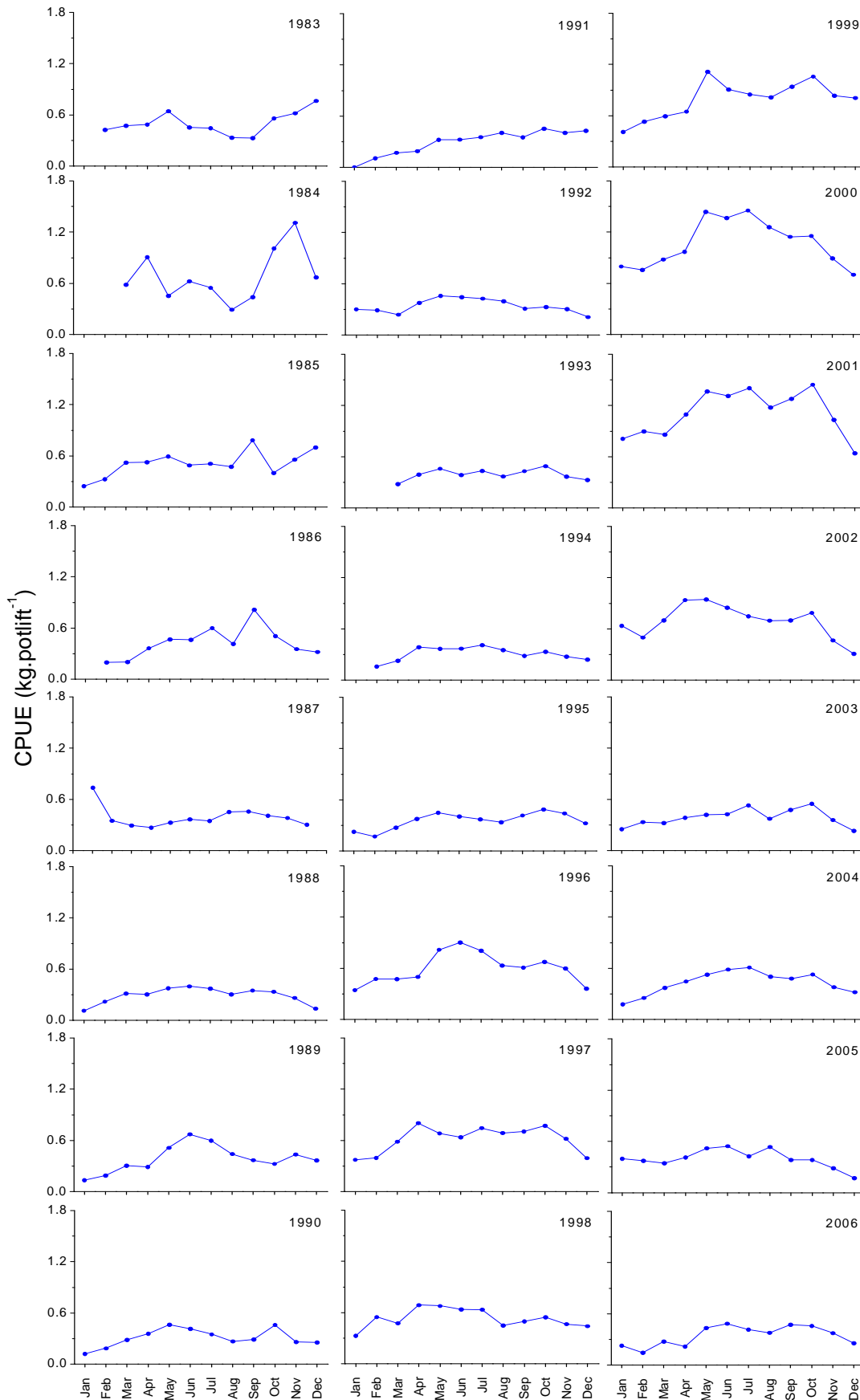


Figure 2-7. Monthly pattern in CPUE for the NT Mud Crab Fishery between 1983 and 2006.

Data for January 1983, 1984, 1986, 1993 and 1994, and February 1984, 1993 and 1995 have been omitted for confidentiality reasons.

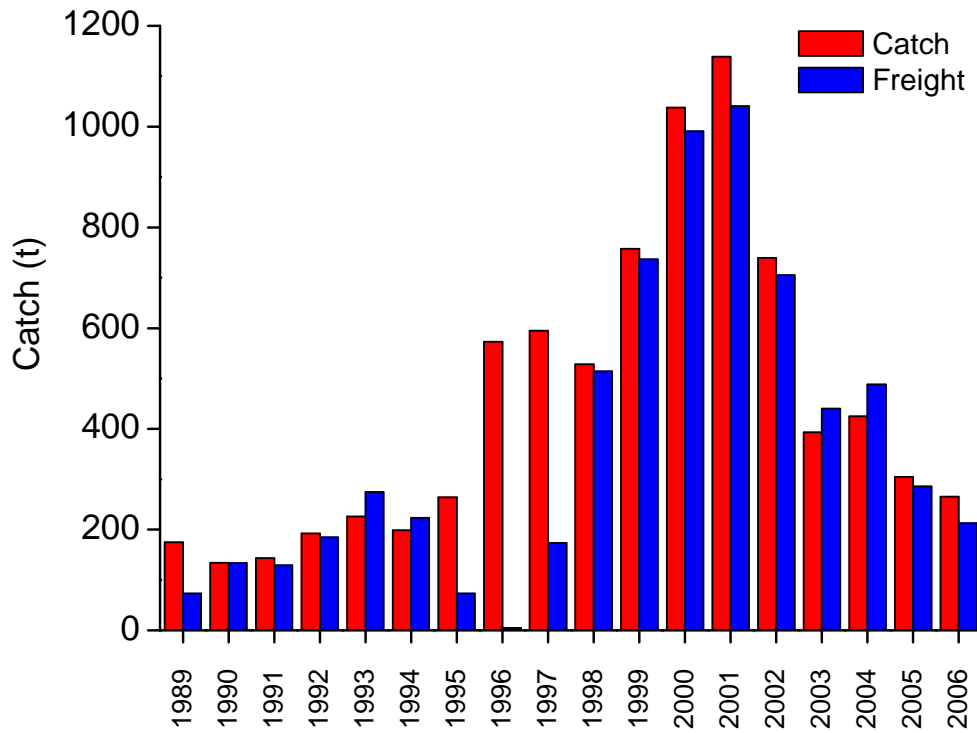


Figure 2-8. Catch and corresponding freight data for the NT Mud Crab Fishery from 1989-2005.

2.3 Discussion

As is the case in most fisheries, the accuracy of the fishery-dependent data for the NT Mud Crab Fishery is poorly understood. However, the similarity of the annual catch estimates derived from logbooks and freight records provide some evidence to suggest that under-reporting of catch may not be a significant issue in this fishery (Figure 2-8).

The NT Mud Crab Fishery operates in a complex habitat in some of the most remote parts of Australia and it is logistically difficult to ensure/measure compliance with management arrangements. Numerous anecdotal reports by police, scientists, managers and fishers suggest that over-potting (i.e. using more than 60 pots per licence per day) is a significant issue in the Gulf of Carpentaria. However, data on compliance/non-compliance rates that are needed to assess the significance of this problem were not provided for this assessment. If over-potting were occurring at a significant level, estimates of effort would be negatively biased (i.e. underestimate actual effort) and the estimates of $CPUE_L$ would be positively biased (i.e. over-estimate actual CPUE). A significant change over time in the rate at which over-potting occurs in the fishery would seriously impede the interpretation of trends in CPUE. An increase over time in over-potting would tend to mask a decline in CPUE resulting from a decline in abundance.

Despite the uncertainties in the effort data, the increases in both catch and $CPUE$ in 2001 and 2002 are likely to have been related to increases in crab biomass. Similar increases in these parameters occurred in the Queensland Gulf of Carpentaria Mud Crab Fishery in this period, which suggest that these increases may be related to broad environmental factors (Haddon *et al.* 2005). The rapid decline in catches to pre-1996 levels following the 2000 and 2001 peaks is a significant concern for the NT Mud Crab Fishery, particularly because effort levels remained at or above 1996 levels from 2003 onwards.

$CPUE$ is generally considered to be a useful (although not necessarily unbiased) index of stock abundance in pot/trap fisheries. The potential discrepancy between nominal and effective effort commonly limits the use of $CPUE$ data to monitor changes in stock abundance. The declines in $CPUE_L$ and $CPUE_d$ after 2002 are likely reflect a major decline in mud crab abundance over this period. If effective effort increased during this period (e.g. by increased over-potting), as is known to occur in many fisheries during periods of reduced abundance, then the decline in biomass during this period would be greater than suggested by the $CPUE_L$ trend. The increase in the number of grids fished in the period during which $CPUE_L$ declined suggests that effective effort may have increased as fishers “worked harder” to catch mud crabs. The declines in catch and $CPUE$, following the peaks in 2001 and 2002, to levels similar to those caught prior to 1996 suggest that the biomass declined after 2002. If effective effort from 2003 onwards was

significantly higher than it was during the period prior to 1996, then the current biomass is likely to be lower than it was before 1996.

SEXUAL DIMORPHISM, SIZE AT SEXUAL MATURITY, SEX RATIO AND 3. MEAN SIZE OF CRABS IN CATCHES

3.1 Introduction

This chapter (i) compares the length-weight relationship and size-at-sexual-maturity of male and female mud crabs; and (ii) describes the spatial and temporal patterns in the sex ratios and mean sizes of crabs taken in the NT Mud Crab Fishery during 1990 to 2006. Catch data analysed in this chapter were extracted from the market monitoring database by DPIFM staff and provided to SARDI as a spreadsheet with data on the sex (male/female), carapace width (mm) and wet weight (g) of individual crabs and the date and location (grid square, fishing area) of fishing (Figure 1-2). Information used to estimate size-at-maturity was obtained from tagging studies conducted by the DPIFM in Beagle Gulf and the Gulf of Carpentaria from 1997 to 2004. Data were provided to SARDI as a spreadsheet with sex (male/female), carapace width (mm) at capture and recapture, and date and location of capture and recapture. All size data are presented as carapace width.

3.2 Sexual Dimorphism

The length-weight relationships of male and female mud crabs differ substantially. Male and female mud crabs each reach a maximum size of approximately 200 mm (Figure 3-1). However, female crabs rarely exceed 1.5 kg in weight whereas males can reach over 2.0 kg. This difference in total weight reflects the large size of the first chelae (claws) of male crabs compared to those of females.

3.3 Size at Maturity

Maturity/immaturity was determined by morphological characteristics (see Chapter 1). Mature females have an abdominal flap which is broad and darkly pigmented (in contrast to the sternum) and has setae along the periphery. Mature males have large chelae. 'Loxy crabs' that were affected by the sacculinid parasite *Loxothylacus iblei* were excluded from the analyses. The size at which 50% of crabs reach sexual maturity (L_{50}) was determined by fitting the Punt logistic curve (using binomial error) to the proportion of mature (Stage 4) crabs in each 5 mm size class (Figure 3-2). The data was broken down into wet (December-May) and dry (June-November) seasons based on the strong trend in sex ratio observed over a 12 month period (Figure 3-3).

In Beagle Gulf, approximately 50% of females and males were sexually mature at 132.1 mm and 127.4 mm respectively in the dry season, and 133.8 mm and 124.6 mm respectively in the wet

season. At the old MLS, 86% of females and 67% of males were sexually mature in the dry season and 80% of females and 79% of males were mature in the wet season. At the current MLS 98% of females and 97% of males were mature in the dry season and 97% of females and 98% of males were mature in the wet season.

In the Gulf of Carpentaria, approximately 50% of females and males were sexually mature at 129.9 mm and 123.8 mm respectively in the dry season, and 136.3 mm and 126.5 mm respectively in the wet season. At the old MLS, 93% of females and 79% of males were sexually mature in the dry season and 70% of females and 71% of males were mature in the wet season. At the current MLS 99% of females and 97% of males were mature in the dry season and 96% of females and 96% of males were mature in the wet season.

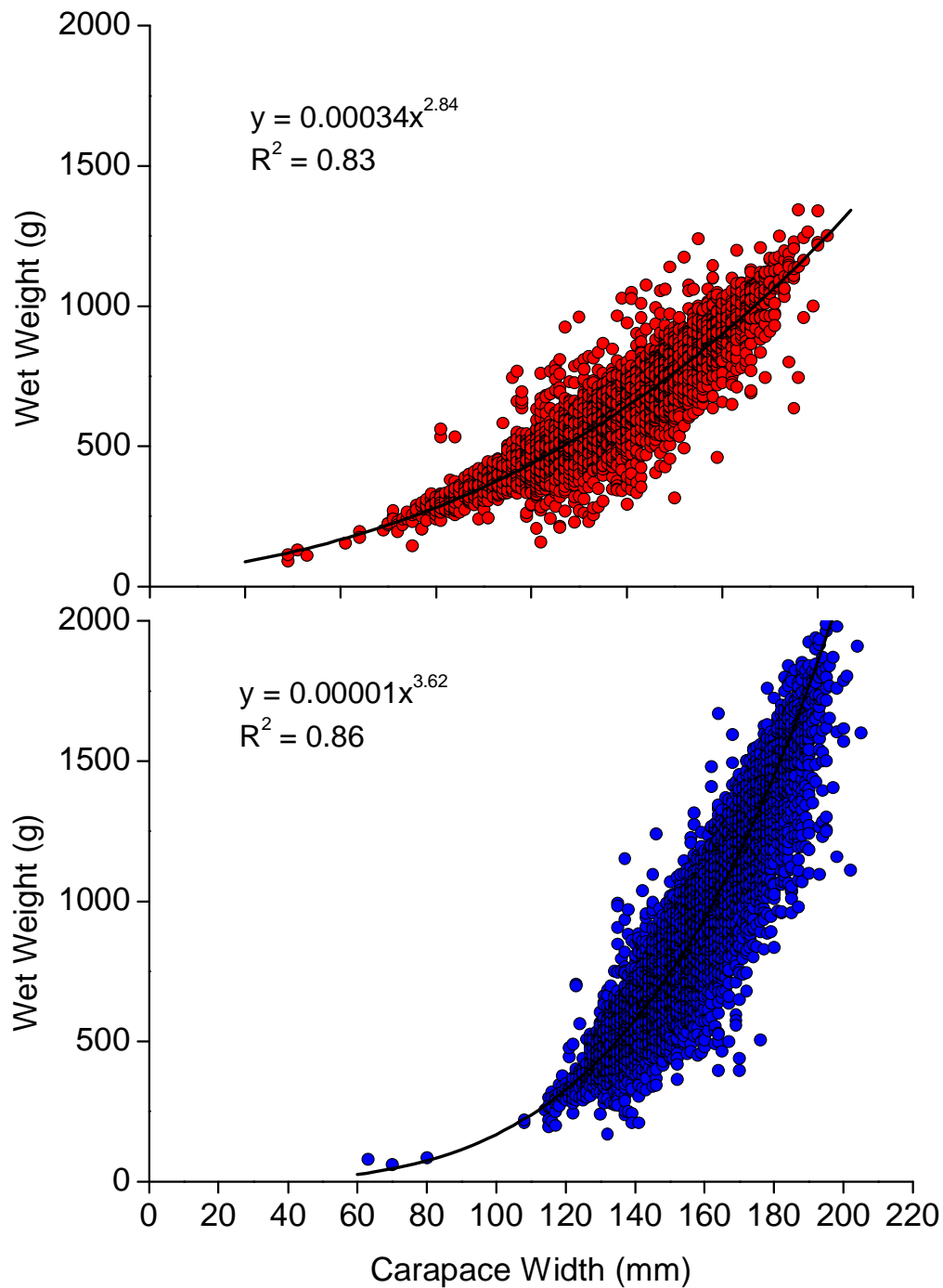


Figure 3-1. Length-weight relationship for female (red) and male (blue) mud crabs sampled from market monitoring from 1990-2006.

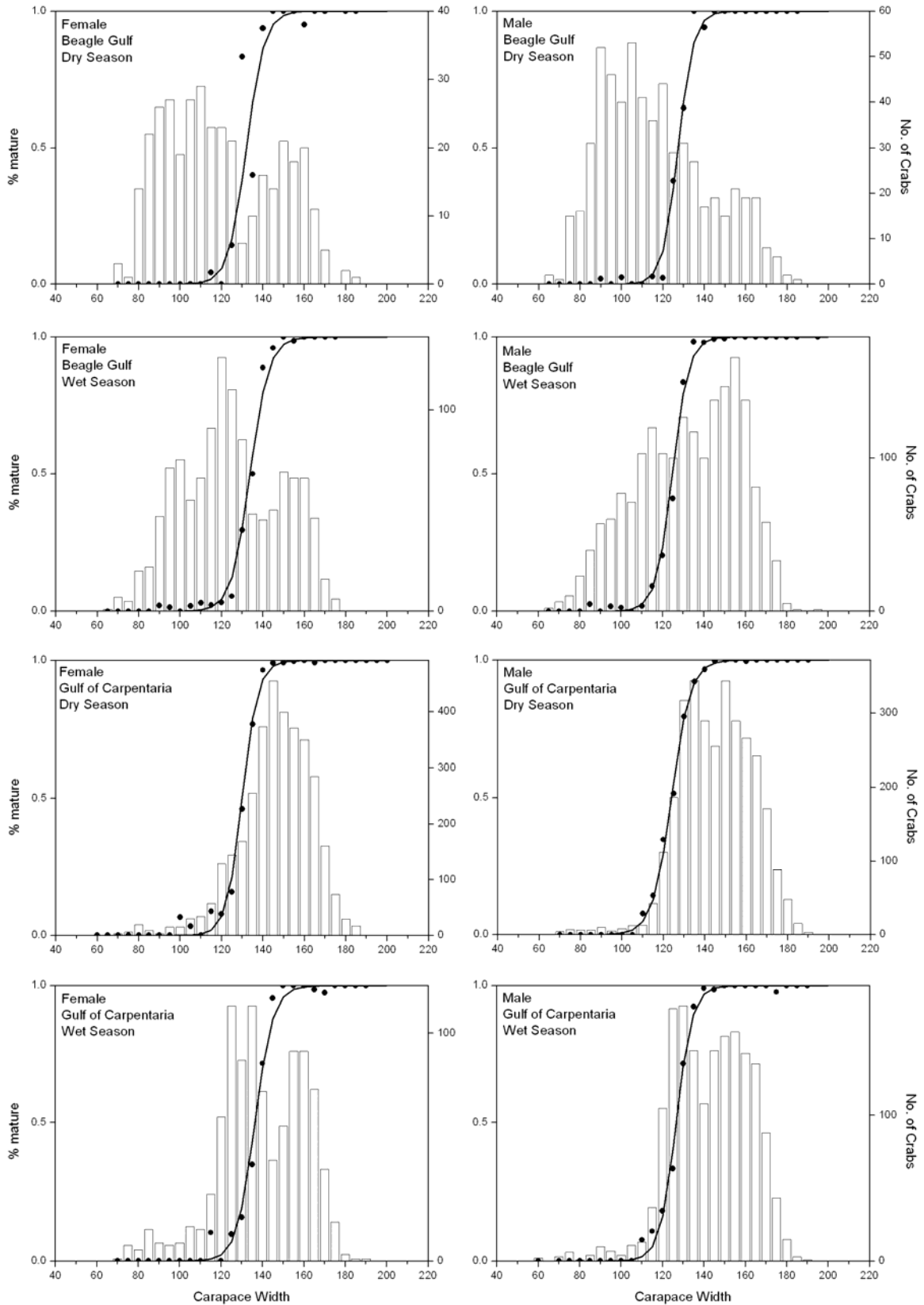


Figure 3-2. Female and male size at maturity for crabs from Beagle Gulf and the Gulf of Carpentaria captured and tagged during the wet (December-May) and dry (June-November) seasons in studies carried out from 1999 to 2006.

3.4 Sex Ratio

Mean annual sex ratios (by number) in Beagle Gulf and the Gulf of Carpentaria are presented in Figure 3-3. Males dominated total annual catches in Beagle Gulf, while in the Gulf of Carpentaria the sex ratio was approximately 1:1 in most years (Figure 3-3). However, the proportion of females in catches from the Gulf of Carpentaria have been greater than 1:1 in three of the four years since 2003 inclusive.

Historically, males have comprised over 80% of the catch taken during March in both Beagle Gulf and the Gulf of Carpentaria. The proportion of females in the catch generally increases from March onwards and peaks in September to November in both regions. The low proportion of females in catches during February to April may be due to migration of females offshore during the preceding months to spawn (Knuckey 1999). During this period, male abundance tends to decline due to the depletion of their abundance due to fishing.

Sex ratio data for each year and location (Figure 3-4 and 3-5) shows that that the monthly pattern in sex ratios is more variable than suggested by Figure 3-3, suggesting that the timing and magnitude of female migration differs between years. Rather than a gradual increase and decrease in the sex ratio over the year as suggested by Figure 3-3, the data for individual years suggest that the onset of female migration can be quite abrupt and the timing variable.

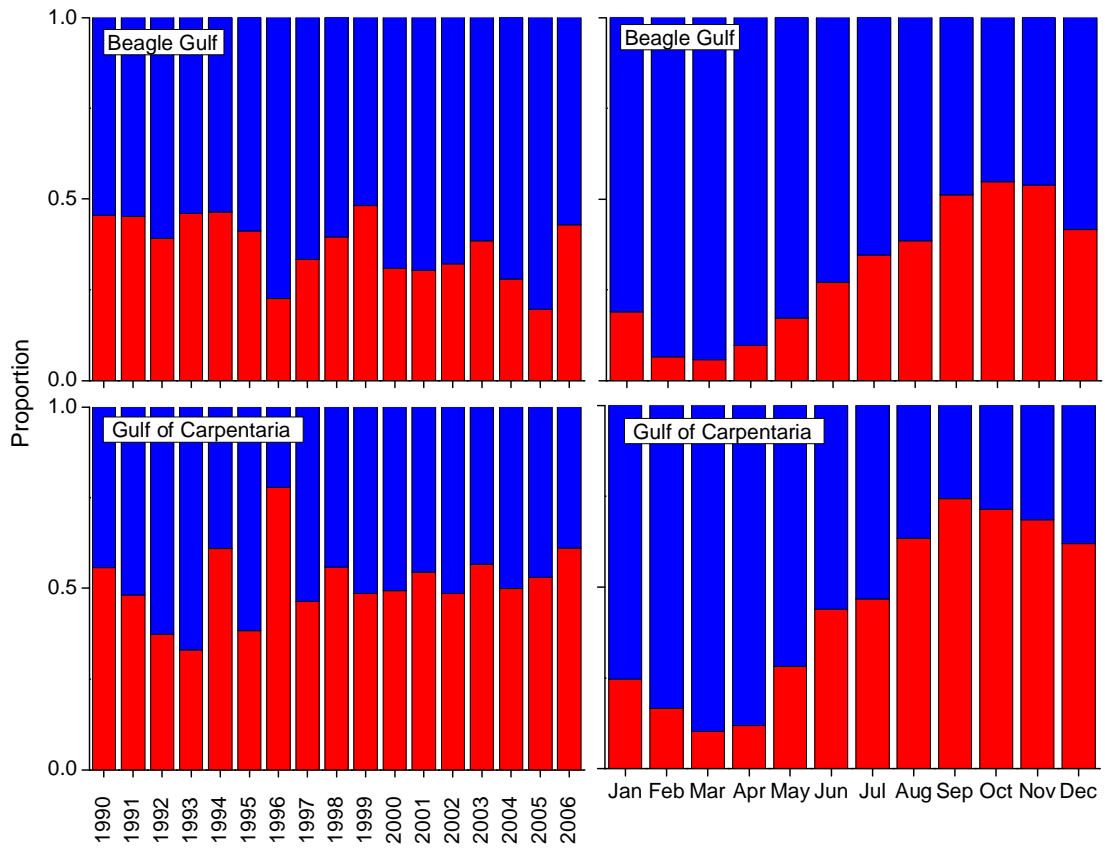


Figure 3-3. Annual (left) and monthly (right) sex ratios by number of mud crabs (female red, male blue) captured in Beagle Gulf and the Gulf of Carpentaria from 1990-2006.

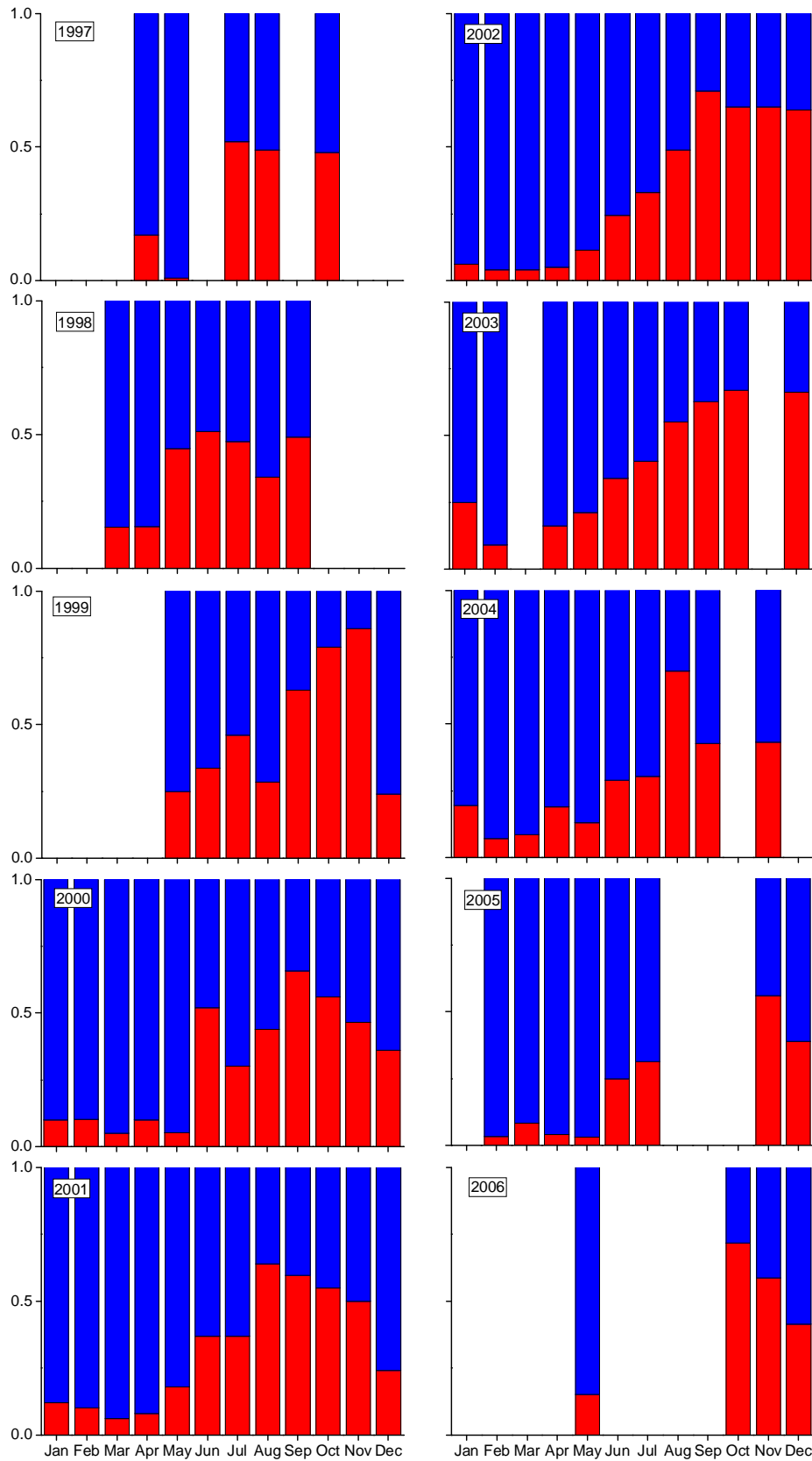


Figure 3-4. Monthly sex ratio for mud crabs captured in Beagle Gulf from 1997-2006 (females red, males blue).

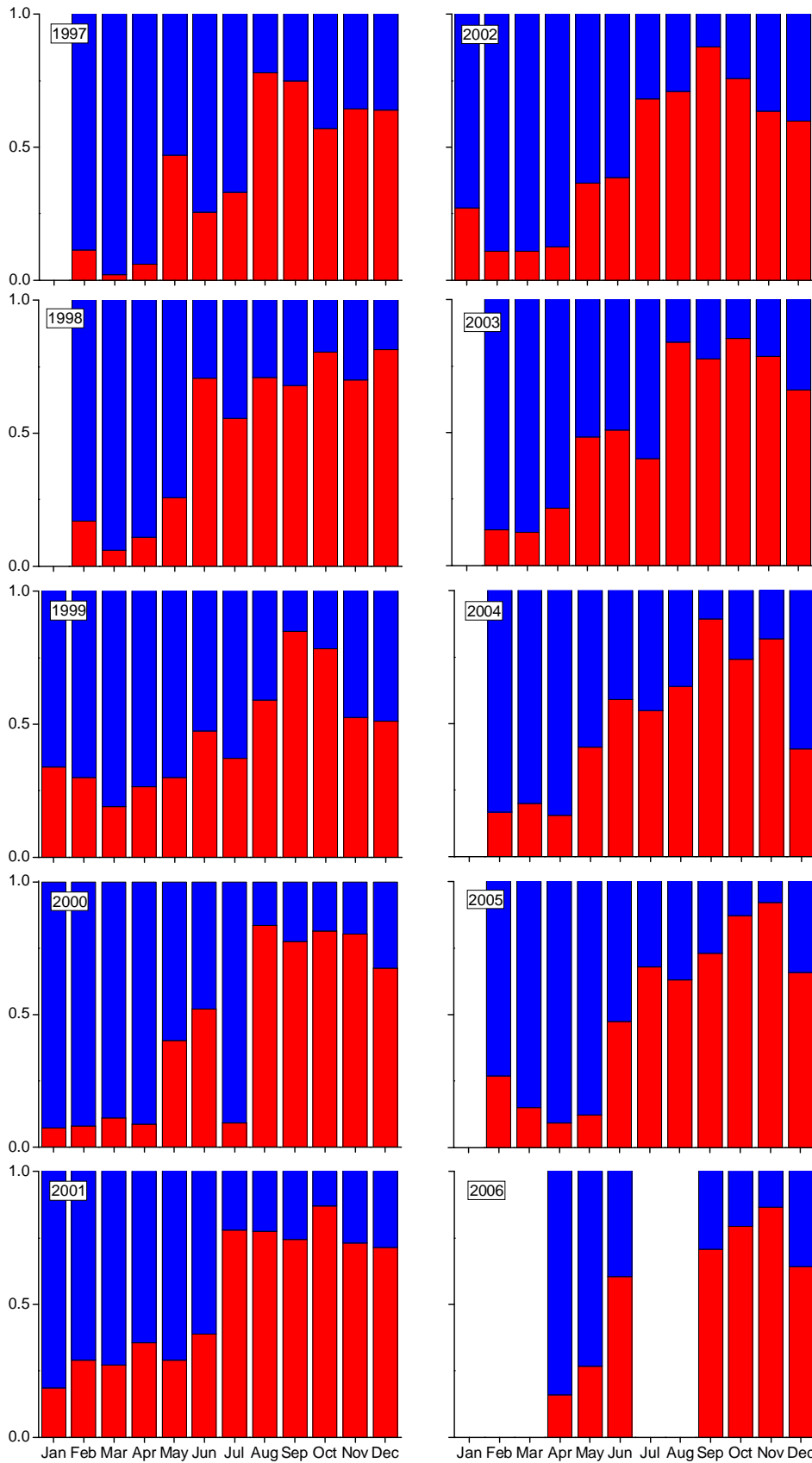


Figure 3-5. Monthly sex ratio for mud crabs captured in the Gulf of Carpentaria from 1997-2006 (females red, males blue).

3.5 Mean size of commercial catch

3.5.1 Inter-annual pattern

Both male and female crabs are larger in Beagle Gulf than the Gulf of Carpentaria. There was no clear trend over time in mean size of male and female mud crabs in Beagle Gulf from 1990 to 2006 (Figure 3-6). In contrast, in the Gulf of Carpentaria there was a clear decline in the average size of both male and female crabs from 1996 through to 2005, with an increase in average size in 2006 when the minimum legal size was increased.

3.5.2 Intra-annual Pattern

There was a consistent intra-annual trend in the mean size of male and female crabs in both Beagle Gulf and the Gulf of Carpentaria (Figure 3-6). In general, the mean size of crabs tended to be low early in the year to increase to a maximum size around the middle of the year and then to decrease again towards the end of the year (Figure 3-7 and 3-8). Mean crab size is significantly larger in Beagle Gulf than in the Gulf of Carpentaria

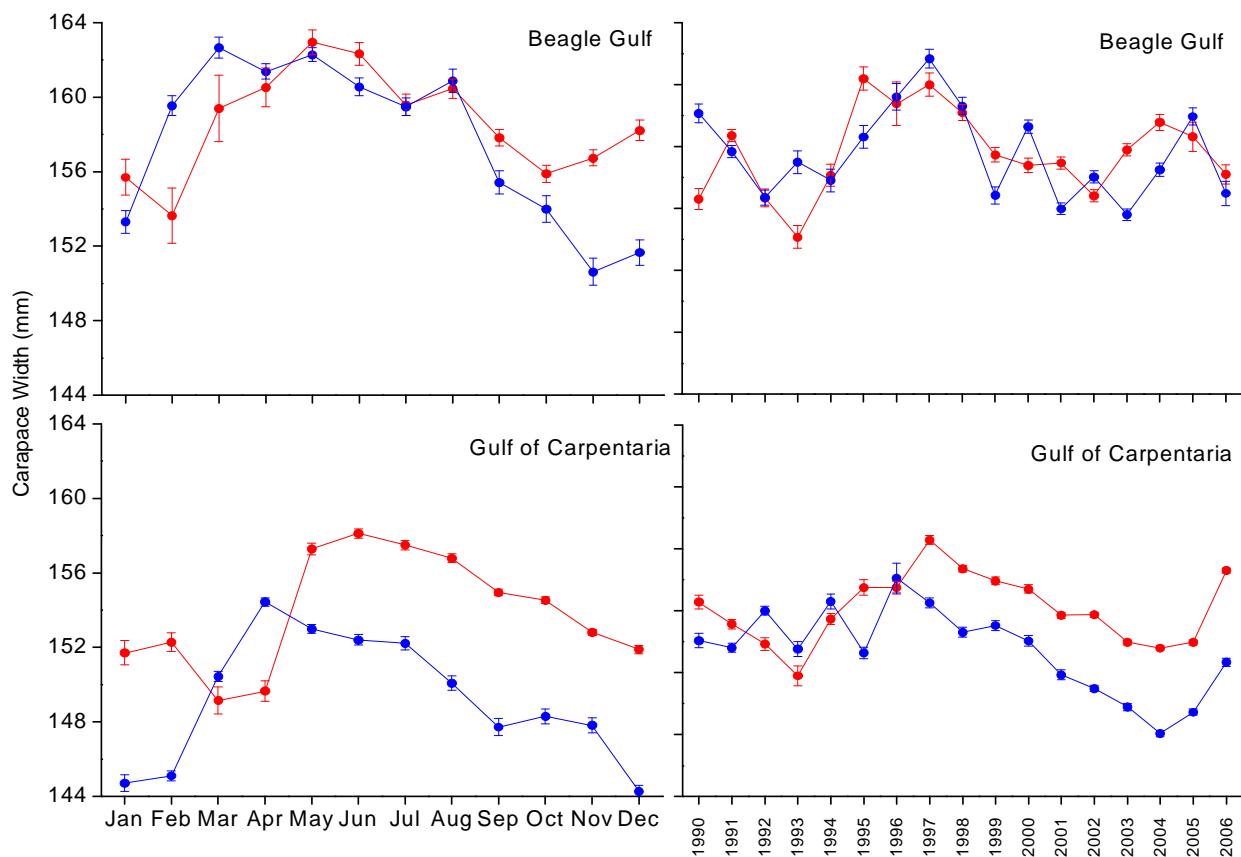


Figure 3-6. Mean monthly carapace width for mud crabs captured in Beagle Gulf and the Gulf of Carpentaria from 1990-2006 (left). Mean annual carapace width for mud crabs captured in Beagle Gulf and the Gulf of Carpentaria from 1990-2006 (right). Females red, males blue.

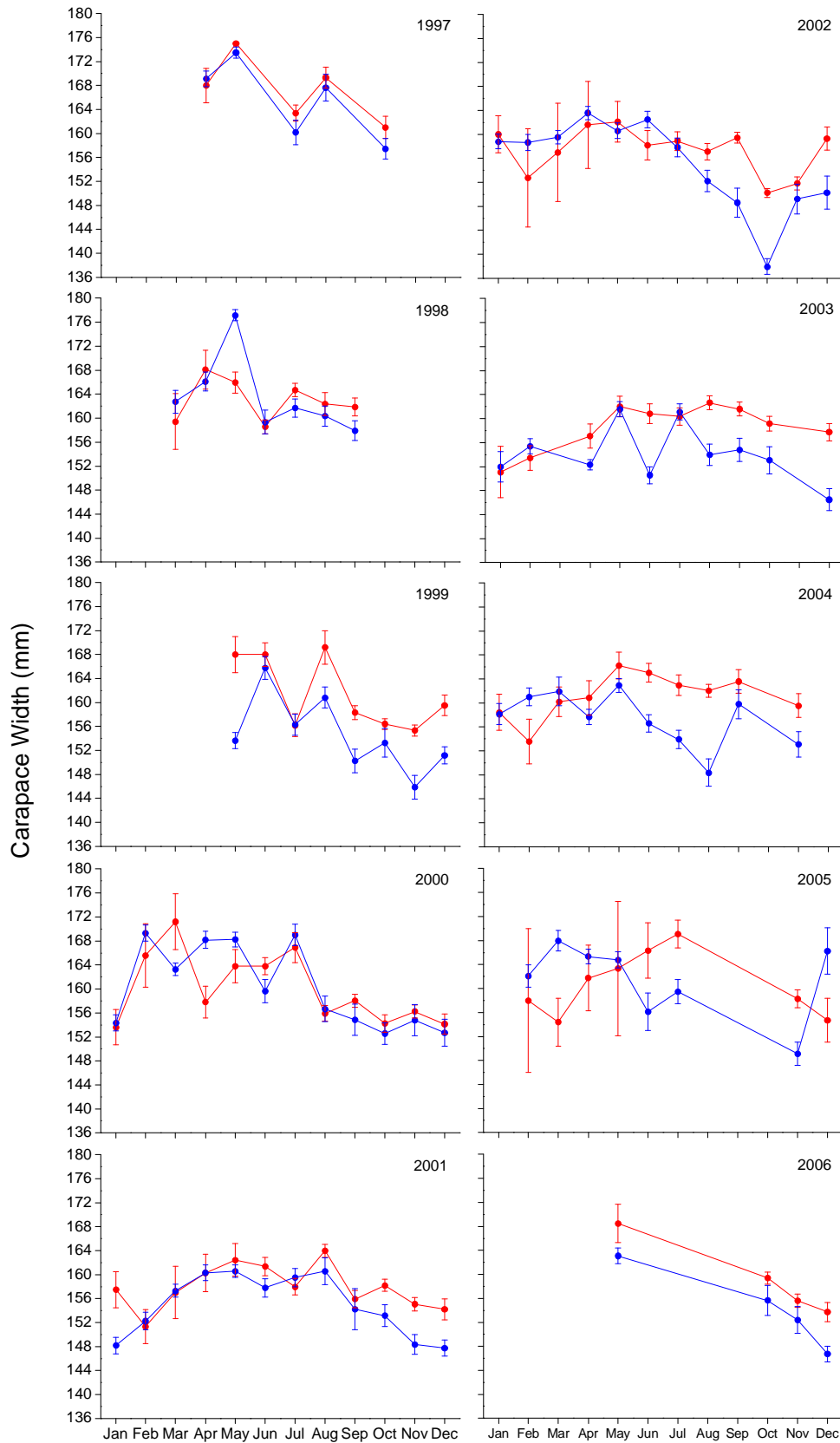


Figure 3-7. Mean monthly carapace width for mud crabs captured in Beagle Gulf from 1997-2006. Females red, males blue.

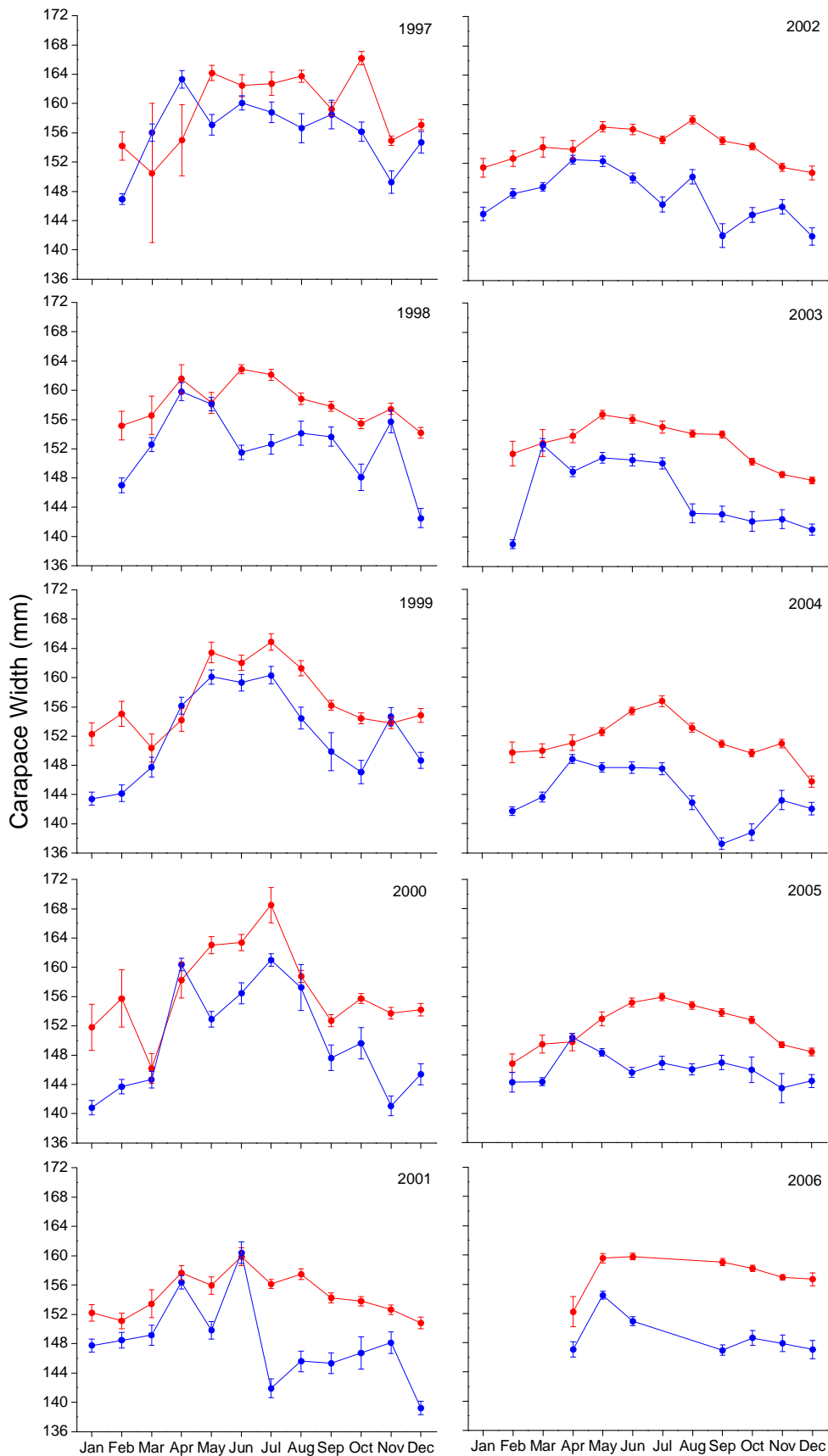


Figure 3-8. Mean monthly carapace width for mud crabs captured in the Gulf of Carpentaria from 1997-2006. Females red, males blue.

3.6 Discussion

Data on the size and reproductive characteristics of mud crabs in catches were obtained from a market sampling program conducted by scientific staff. As such, the categorisations and measurements can be safely assumed to have a high degree of accuracy and precision. However, the small numbers of outliers on Figure 3-1 suggest that some of the entries in the market monitoring database may need to be checked. The major uncertainties in the market sampling data are associated with the accuracy of the collection details and the degree to which the samples represent the total catch, which are both unquantified. The detailed analysis of the tagging data in Chapter 4 suggests that the measurement error associated with crabs from the market monitoring program is 1.5 mm for males and 2 mm for females, which may not be significant for the purposes of this chapter.

The large difference in the growth patterns and maximum weight of male and female crabs emphasises the need to present sex ratio data by numbers rather than by weight and the suitability of presenting size data separately for each sex. The relatively high proportion (>50% by number) of females in most catches from the Gulf of Carpentaria since 2003 may reflect the increase in fishing effort late in the season (see Figure 2-6) when females become more susceptible to capture than males (Figure 3-3). This high proportion of females caught in recent years may have had a detrimental effect on levels of egg production.

Size-at-maturity data showed that for the old MLS, around three quarters of crabs at the MLS were mature; while for the current MLS at least 96% of crabs were mature at the MLS. The introduction of the 10 mm larger MLS appears to have protected a significant number of mature crabs below the MLS.

The reduction in the mean size of mud crabs in the Gulf of Carpentaria is also indicative of increased fishing mortality and the trend towards “knife-edge selection” in this location (Haddon *et al.* 2004). The effectiveness of the change in MLS in the GoC is shown by the significant increase in mean size in 2006. The change in the size distribution of crabs in commercial catches over time shown in Chapter 6 shows that this decrease in mean size is the result of the reduction in the proportion of large crabs in catches. This trend would have had the effect of reducing the yield-per-recruit (Chapter 5) and level of egg production, and increasing the proportion of immature females in catches. When considered in conjunction with the recent declines in total catches and CPUE outlined in Chapter 2, this information raises serious concerns regarding the sustainability of the fishery under the previous size limits. It should also be noted that size limits alone, i.e. in the absence of other effective controls on effort or catch, cannot necessarily assure the sustainability of a fishery, especially for short-lived species in fisheries (mud crabs probably

live for 3-4 years) with high fishing mortality rates. This is because there is no buffer against poor recruitment, and one or two years of poor recruitment can result in stock collapse, as there are no controls in place to protect crabs above the MLS. Additional management arrangements, such as seasonal closures or the prohibition on the taking of females (as in Queensland Mud Crab Fishery), can be used to address this issue.

4. GROWTH PATTERNS OF NT MUD CRABS

4.1 Introduction

In this chapter we used tagging data to estimate growth parameters for mud crabs in the NT. Staff of DPIFM provided SARDI with data from tagging studies conducted in Beagle Gulf and the Gulf of Carpentaria between 1997 and 2004. The data were provided to SARDI in the form of a spreadsheet with sex (male/female), carapace width (mm) at capture and recapture and date and location of capture and recapture.

4.2 Methods

Data provided to SARDI included that from over 4000 crabs recaptured between 1997 and 2004. However, not all data were suitable for use in the statistical analyses. All ambiguous data were excluded, including records with sex categories other than male and female and no location data. Only crabs with starting and recapture carapace widths were used in the growth analyses. Records providing large negative estimates of time-at-large or growth increment were also excluded. This selection process reduced the number of valid recaptures to 1094. The tag recapture data used were date of first capture, initial carapace width, date of recapture, final carapace width, measurement error and bias. These data were analysed using GROTAG (Francis 1988), which was written as an Excel spreadsheet routine using the solver add-in to parameterize the von Bertalanffy growth model.

4.3 Carapace width at first capture

There was a wide range of starting carapace widths (Figure 4-1). Crabs captured (tagged) in Beagle Gulf ranged from 74-178 mm, with males and females ranging from 74-175 mm and 76-178 mm, respectively. Crabs tagged and released in the Gulf of Carpentaria were generally larger (91-192 mm), with males and females ranging from 92-177 mm and 91-192, respectively. A broad size range of crabs was tagged in Beagle Gulf, whereas most crabs from the Gulf of Carpentaria ranged from 115 to 180 mm.

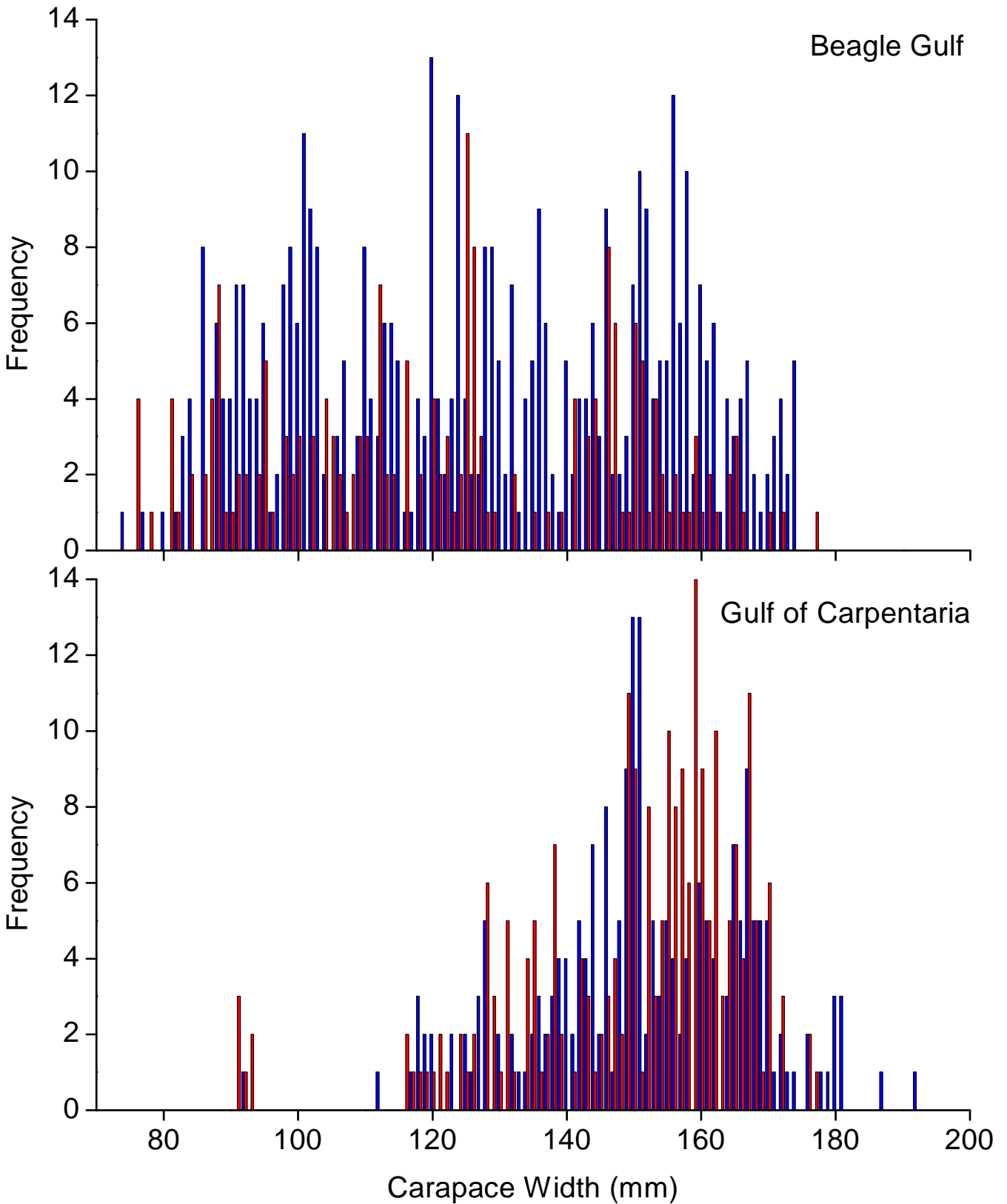


Figure 4-1. Distribution of carapace width at first capture for recaptured crabs tagged in Beagle Gulf and the Gulf of Carpentaria. (blue = male; red = female).

4.4 Time at large

In both Beagle Gulf and the Gulf of Carpentaria, most crabs were recaptured within 16 weeks of release and only 4 crabs were at large for over a year (Figure Figure 4-2). Most crabs at large for longer than 16 weeks were recaptured in Beagle Gulf (Figure 4-2). A large proportion of the recaptures from the Gulf of Carpentaria were within a week of their initial capture. These results suggest the fishing mortality rates in the Gulf of Carpentaria may be very high. Although it was unclear exactly what proportions of recaptures were made by research fishing and commercial fishing, it was evident that a large proportion was from research fishing. The limited time-at-large of most crabs reduced the information on growth patterns that could be gleaned from these data. This highlights the problems associated with relying on research fishing for recaptures when mortality rates are high. In fisheries with very high exploitation rates tagged animals would ideally be returned to the water by commercial fishers and only recaptured by research fishing after a much longer time at large. Alternatively, areas could be set aside solely for research fishing.

4.5 Growth Increment

Since the time-at-large for most crabs was short, the majority had no opportunity to moult, and most growth increments were between -2 and $+2$ mm, which is indicative of the accuracy of the size measurements (Figure 4-3). There was a clear separation of crabs that did not grow at all (<7 mm growth) and those that moulted at least once (>10 mm growth). Crabs with a growth increment of less than 9 mm were used to quantify measurement error and bias. Measurement error was estimated to be 1.5 mm for males and 2 mm for females. Measurement bias was estimated to be -0.55 for males and -0.8 for females.

The growth increments of crabs from Beagle Gulf were between 9 and 83 mm, including 9-83 mm for males and 10-71 mm for females. The growth increments of crabs from the Gulf of Carpentaria were lower (9-52 mm) due to the shorter time at large and ranged from 9-43 mm for males and 10-52 mm for females.

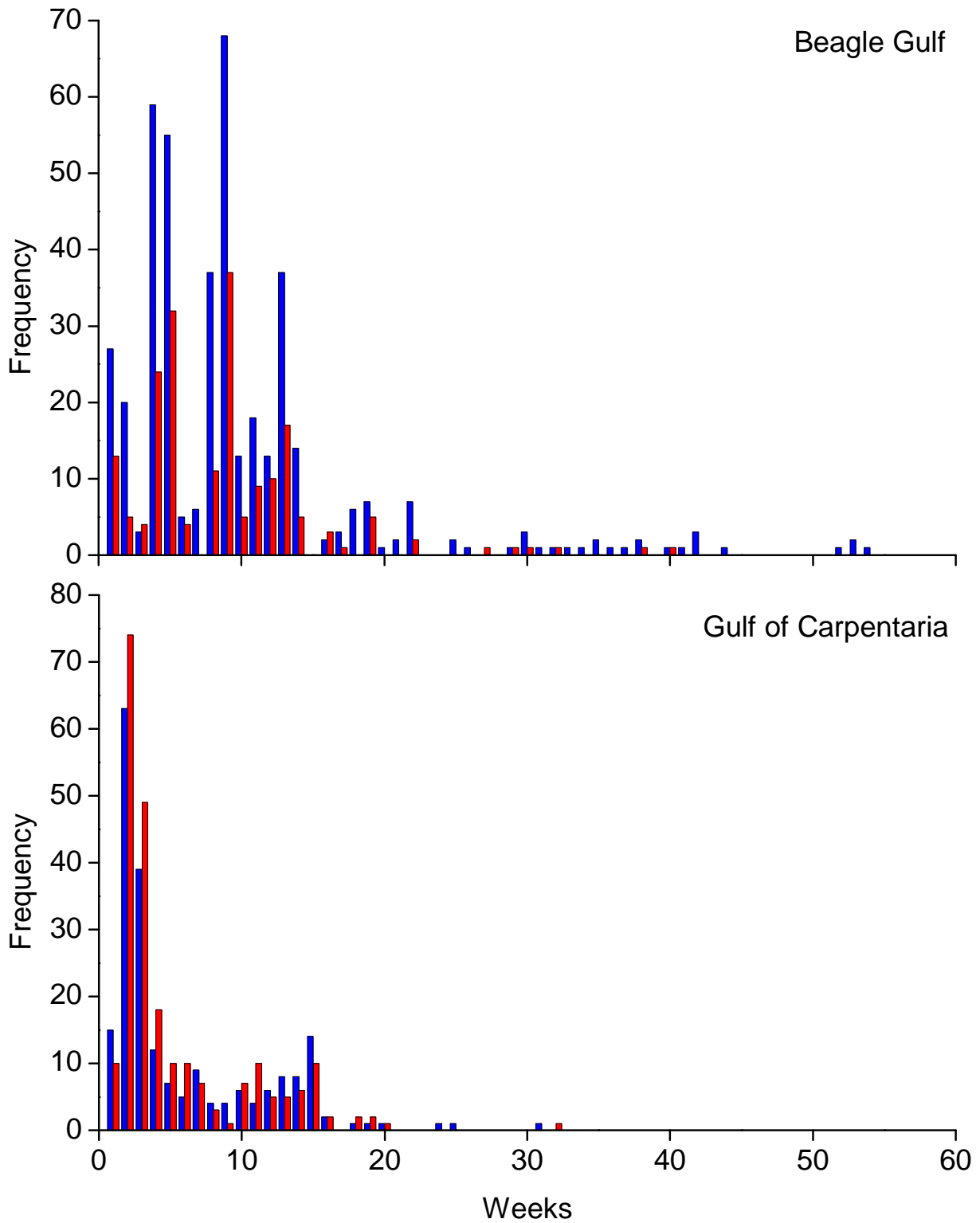


Figure 4-2. Distribution of time-at-large (weeks) for crabs recaptured in Beagle Gulf and the Gulf of Carpentaria. (blue = male; red = female)

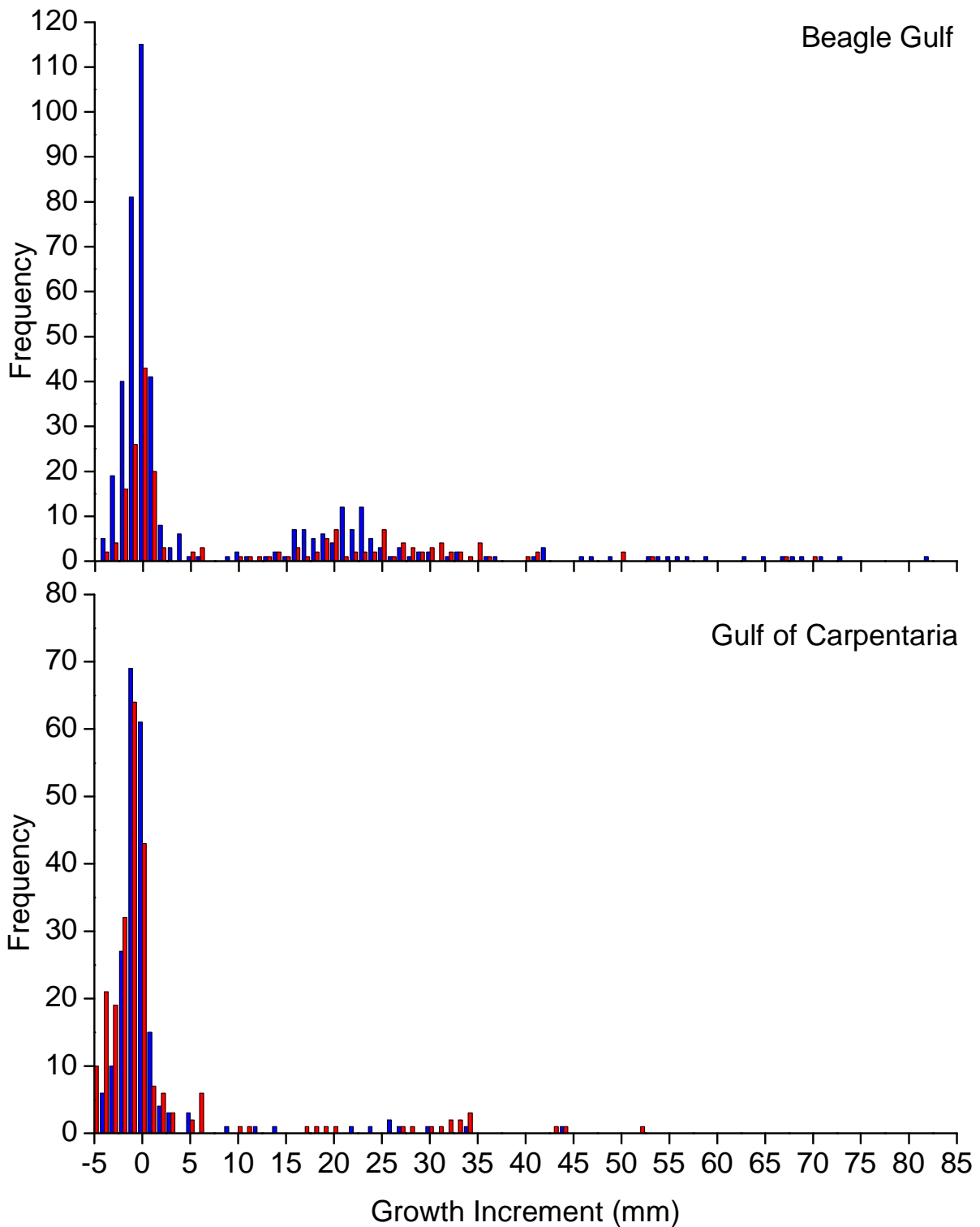


Figure 4-3. Distribution of individual growth increments for crabs recaptured in Beagle Gulf and the Gulf of Carpentaria. (blue = male; red = female)

4.6 Growth parameters

Growth curves based on estimates of L_{∞} and K provided in previous studies (Knuckey 1999; Haddon *et al.* 2005) are plotted in Figure 4-4. Application of the GROTAG model to the recapture data produced estimates of $L_{\infty} = 185.4$ mm and $K = 0.81$ for females and $L_{\infty} = 152.5$

mm and $K = 1.46$ for males. The plots of von Bertalanffy growth curves based on these parameters are also shown in Figure 4-4. These plots clearly indicate that the estimates of these parameters obtained from the tagging data do not reflect the growth patterns of NT mud crabs particularly well. The most obvious problem is that values for L_{∞} (i.e. 185.4 mm and 152.5 mm for females and males respectively) are significantly lower than the observed maximum sizes of crabs in the catch (207 mm for both males and females).

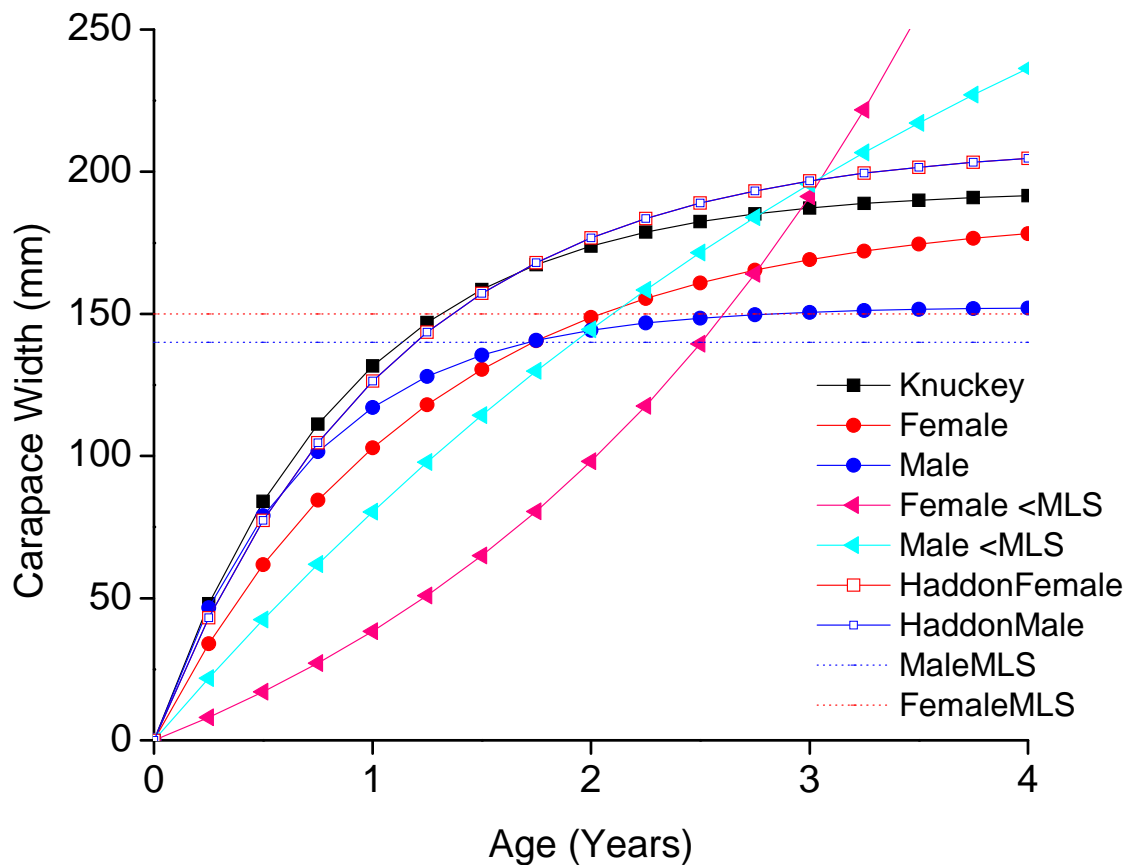


Figure 4-4. Von Bertalanffy (VB) growth curves plotted using the parameters calculated from tag-recapture data for all male and female mud crabs and those below MLS using GROTAG, and parameters calculated by Knuckey (1999) and Haddon *et al.* (2005). Dotted lines indicate current minimum legal size (MLS) for male and female crabs.

Splitting the size data for each sex into three size classes (<100 mm; 100-130 mm and >130 mm for males and <110 mm; 110-140 mm and >140 mm for females) and plotting growth increment against time-at-large (Figure 4-5), shows that very few crabs tagged above the MLS were recorded as having grown during this study. This is because large crabs were not at-large long enough to

moult and grow, which reflects the high rate of fishing mortality identified by previous authors (Knuckey 1999; Walters *et al.* 1997; Haddon *et al.* 2005). Furthermore, the relative growth rates of small and medium sized crabs do not fit a key assumption of the von Bertalanffy growth model, i.e. that growth rates decrease linearly over time. Rather, the average growth rate of female crabs in the intermediate size class was higher (0.43 mm.day^{-1}) than that of the smaller size class (0.29 mm.day^{-1}). In addition, the growth rates for males in the small and intermediate size classes were similar (i.e. 0.24 and 0.28 mm.day^{-1} , respectively). Hence, the von Bertalanffy growth model does not provide an appropriate description of the growth patterns of NT mud crabs.

In response to this lack of growth information for crabs above the MLS, we tested the sensitivity of applying GROTAG only to crabs below the MLS (i.e. we excluded from the analysis the crabs that were above the MLS when tagged). This approach resulted in estimates of growth parameters of $L_{\infty} = 396 \text{ mm}$ and $K = 0.27$ for males and $L_{\infty} = -68.5 \text{ mm}$ and $K = -0.44$ for females. Clearly, these parameter estimates do not describe the growth of crabs above the MLS and up to the observed maximum sizes of mud crabs. However, the growth curves do provide a reasonable description of the patterns of growth of crabs within the range of sizes for which growth data are available (Figure 4-4). Importantly, the best fit to the GROTAG model was obtained when we only used data from crabs that were tagged at less than MLS.

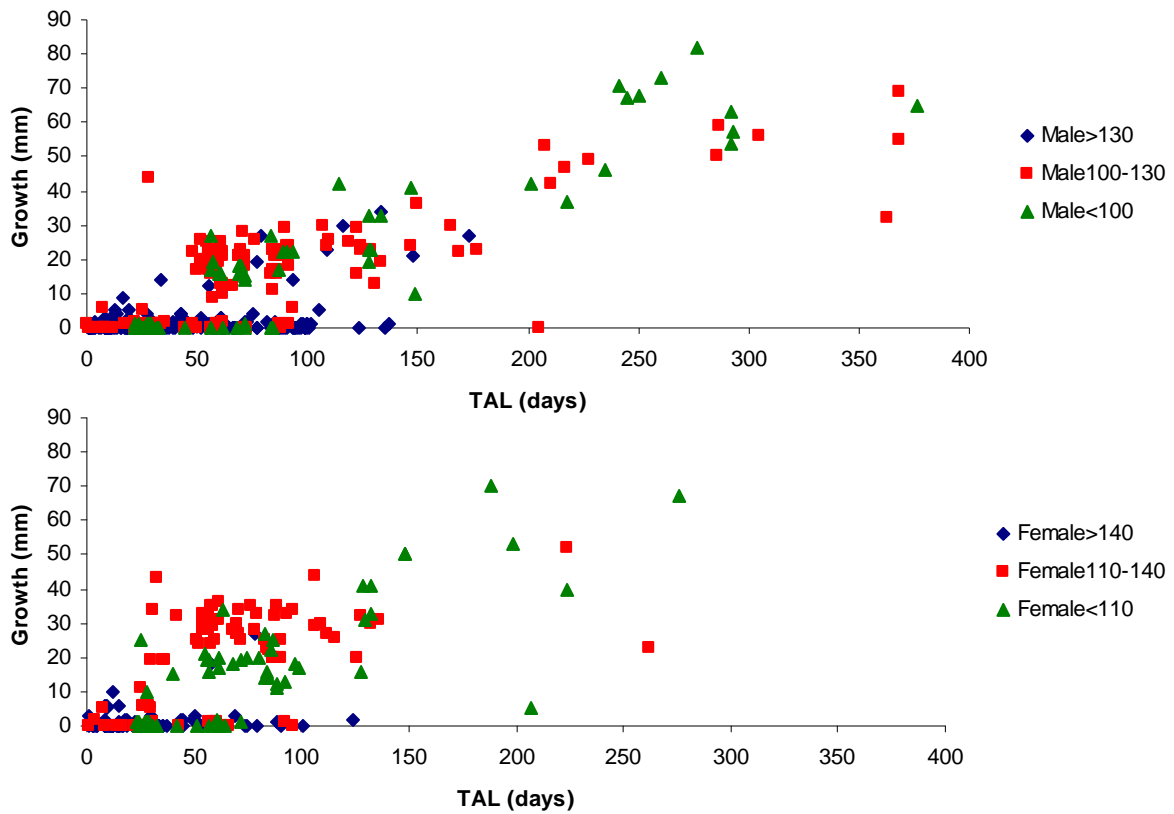


Figure 4-5. Growth increment for recaptured mud crabs in three size classes: (i) starting carapace width greater than the MLS (i.e. 130 and 140 mm for male and female crabs, respectively), starting carapace width of 100-130 mm and 110-140 mm for male and female crabs respectively, and crabs with a starting carapace width less than 100 and 110 mm for males and females, respectively.

4.7 Discussion

The present study highlights the difficulties associated with the use of existing tagging data to describe the growth patterns of NT mud crabs using the von Bertalanffy growth model. Previous studies have also encountered difficulties describing the growth of both male and female mud crabs. Knuckey (1999) did not have enough female recaptures to provide robust estimates of von Bertalanffy growth parameters for each sex separately, so he pooled the available data and provided a single description of growth. Haddon *et al.* (2005) had access to similar growth data to us (i.e. lacking information for large crabs) and, in order to obtain sensible estimates of parameters, fixed L_{∞} for males and females at sizes reflective of the maximum sizes of each sex in the catch, and then generated estimates of K . Our results, and those of previous studies, suggest that future research on the growth patterns of NT mud crabs should involve (i) the development of alternative methods for obtaining growth data especially for large crabs and (ii) the investigation of alternative models for describing growth patterns.

The low rate of recapture for crabs above the MLS may be indicative of high levels of fishing mortality, if the level of non-reporting by commercial fishers is low. Future growth studies will need to address this issue specifically in order to obtain information for the larger size classes. As is the case for most crustaceans, tag shedding could also be an issue for this species and alternative tagging methods may need to be developed. Our results show that there is some potential for measurement error that also needs to be considered, but which may not be a significant problem as the error can be estimated and included in growth modelling.

The investigation of alternative growth models for NT mud crabs should be a high priority for future studies. Our analyses showed that the best fit to the GROTAG model was obtained when we only used data from crabs that were tagged at less than the MLS. However, the parameters obtained from this fit did not provide a good description of the growth pattern across all size classes, but did appear to describe the growth of crabs below the MLS quite well. As NT mud crabs do not fit the assumptions of the von Bertalanffy growth model, it will be necessary for future studies to assess the suitability of growth models that have different assumptions. The establishment of an appropriate growth model for NT mud crabs will be critical for the development of an effective integrated model for the fishery.

The low rate of recapture for crabs above the MLS from the Gulf of Carpentaria supports assertions regarding high rates of fishing mortality that have been made in previous studies of the NT Mud Crab Fishery. Unfortunately, the tagging data are not suitable for estimating total mortality directly because of the lack of information provided on the total number of crabs tagged and how the recaptures were taken (e.g. by research sampling or commercial fishing).

5. OTHER MODELLING

5.1 Introduction

In this chapter, we apply three models that are the same or similar to those previously used to analyse data from NT Mud Crab Fishery. The first model is an enhanced Wetherall analysis that was developed by Professor Norm Hall (Murdoch University) and previously applied to a subset of data for NT Mud Crab Fishery (Appendix 1). We use this model to estimate total mortality (Z) from size distribution data from the commercial catch. The second model is a yield per recruit analysis similar to that used in the 2004 Stock Assessment Workshop (Haddon *et al.* 2005). We used this model to determine yield-per-recruit under different levels of fishing mortality and at several different minimum legal sizes. The third model that we apply is the recruitment-adjusted seasonal depletion (RASD) model used by Knuckey (1999) to investigate the effects of various biological parameters on yield. We use this model to assess the scales of fluctuations in recruitment levels and fishing efficiency that would be required to explain the inter-annual changes in catches and CPUE observed in the NT Mud Crab Fishery over the last two decades.

5.2 Enhanced Wetherall Analysis

In this enhanced Wetherall analysis (see Appendix 1) we use annual size frequency data obtained from the market monitoring database (see Chapters 3 and 7) and estimates of von Bertalanffy growth parameters for males and females obtained in the present study (see Chapter 4) and by Knuckey (1999) for both sexes combined to estimate total mortality (Z). The growth parameters of Hadden *et al.* (2005) were not used in this analysis because in that study L_{∞} was not estimated but fixed, based on the maximum size of crabs in catches. We estimated total mortality separately for each sex and compared the size frequency distributions of the catch that would be expected under these mortality rates with those that were actually recorded in commercial catches.

Estimates of annual total female mortality based on the growth parameters estimated in the present study (i.e. $L_{\infty} = 185.4$ mm, $K = 0.81$) ranged from 3.2 to 4.6 year⁻¹. Estimates of annual, total, male mortality based on our growth parameter estimates ($L_{\infty} = 152.5$ mm and $K = 1.46$) were much higher than those for females ranging from 6.6 to 12.2 year⁻¹ (Figure 5-1). Based on our parameter estimates, total annual mortality of males appears to have fluctuated over the last 16 years, whereas total annual mortality of females has increased over the last 10 years.

Identical analyses using the alternative von Bertalanffy growth parameters of Knuckey (1999) provided much lower estimates of annual total mortality for males and slightly lower estimates of annual total mortality for females. These discrepancies are likely to reflect uncertainties associated with the estimates of both growth parameters (see Chapter 4) and total annual mortality (see Haddon *et al.* 2005). Regardless of which estimates of growth parameters are used, annual total

mortality for each sex was above 4 in 2006. If natural mortality – estimated by Knuckey (1999) using a combination of Beverton and Holt, Pauly and Richter and Efanov methods - is around 1.21 year⁻¹, then fishing mortality must be very high.

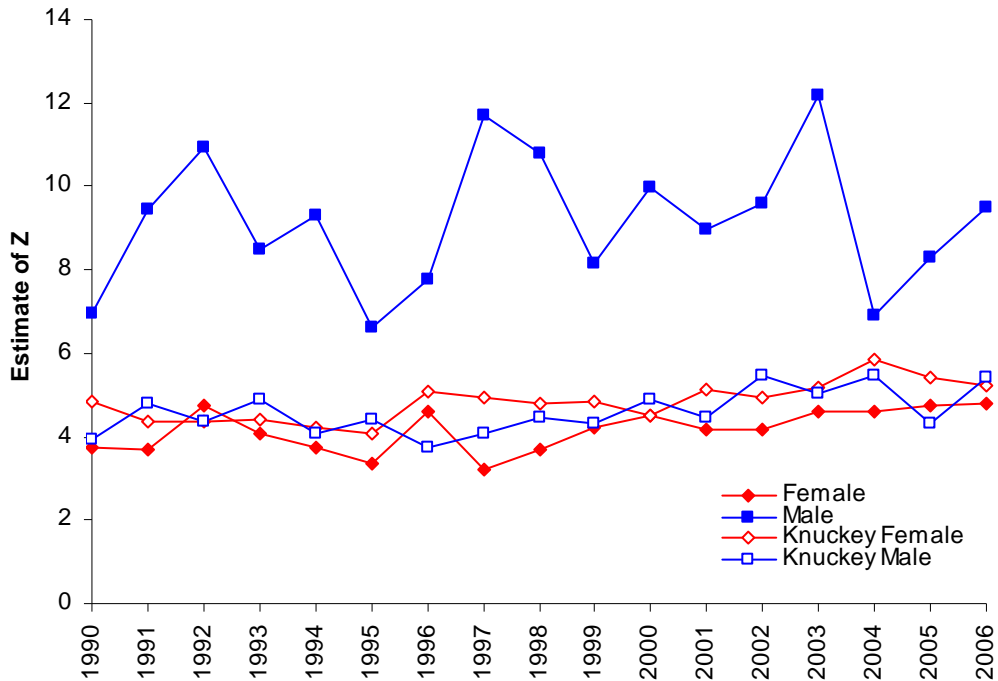


Figure 5-1. Estimates of total mortality derived for female (red) and male (blue) mud crabs from the NT commercial fishery using the enhanced Wetherall analysis.

The estimated size frequency distribution closely matches the observed size frequency distribution for the last two years of data (Figure 5-2). The size frequency plots also display the shift in size due to the change in MLS. Notably, the shape of the curve indicates that the introduction of the new size limit has not shifted the entire curve across or significantly altered the most common size captured, but increased the minimum size of crabs in catches.

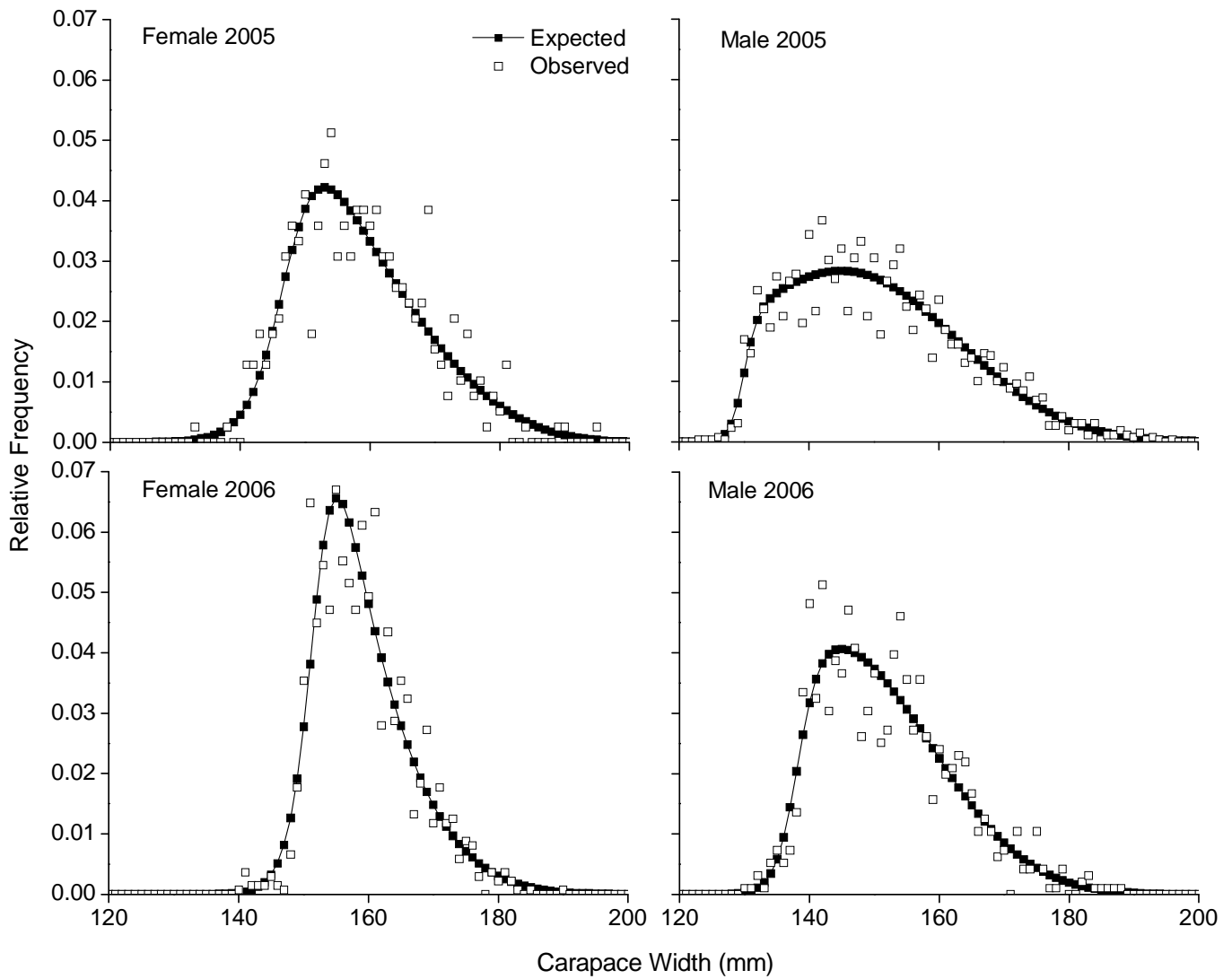


Figure 5-2. Observed and predicted relative length distribution of female and males in the NT Mud Crab Fishery in 2005 and 2006.

5.3 Yield-per-recruit

Due to the difficulties in estimating the growth parameters from the tagging data, we used several sets of growth parameters to examine the effect of changing the MLS on yield. We also determined the optimal MLS at several levels of fishing mortality.

The growth parameters used were those from Knuckey (1999) and our own estimates from GROTAG based on: a) crabs that were tagged at a size less than the MLS, and b) all crab growth data. In each case we calculated the yield-per-recruit using the length-weight relationship established in each of the studies.

In the first analysis, we examined the effect of changing the MLS from 130 mm to 140 mm for males and 140 mm to 150 mm for females. The yield-per-recruit modelling shows the two main effects of making this change (Figure 5-3). Firstly, the optimum fishing mortality (i.e. the peak yield-per-recruit) increased by around 0.2. Second, for most of the growth models the effect of MLS on yield-per-recruit was marginal except for the growth models established in the present study, where the peak yield-per-recruit decreased by up to 26%. This highlights the limitations of previous estimates of mud crab growth parameters, and the need for more growth data and the development of an alternative model to describe mud crab growth.

In the second analysis, we examined the effect of different levels of fishing mortality on the optimum MLS by plotting the output for four different levels of F (Figure 5-4). The main effects observed by increasing F were to increase the optimal MLS and decrease the yield-per-recruit.

To highlight the effect of changing F , we modelled the effect of F on the optimal MLS to maximise yield-per-recruit. The results of this analysis are plotted in Figure 5.5. This analysis clearly shows that regardless of which growth parameters were used as F increases so does the MLS required to maximise yield-per-recruit.

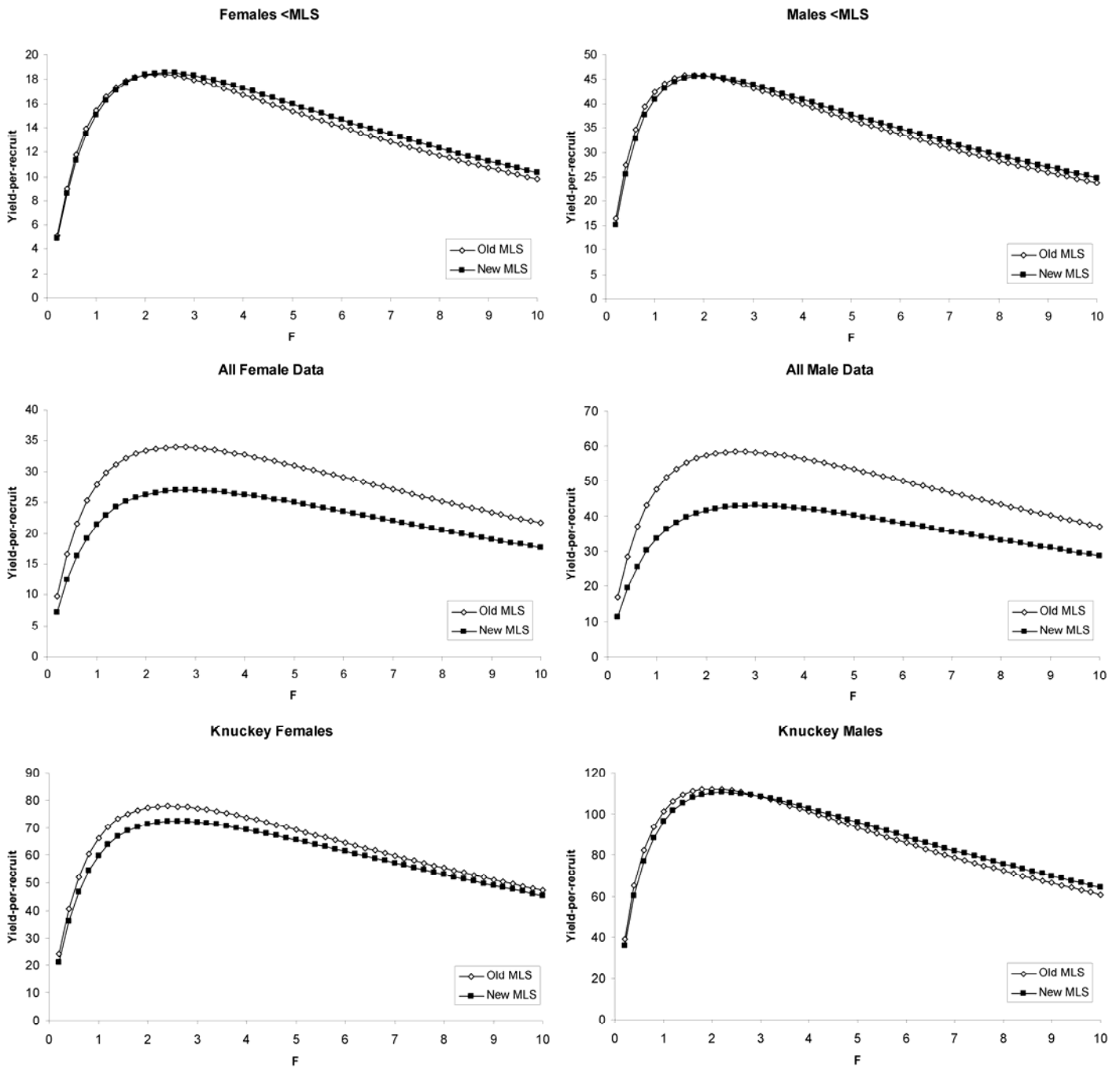


Figure 5-3. Effect of MLS on the yield-per-recruit for several von Bertalanffy growth curves. Old MLS = 130 mm for males and 140 mm for females. New MLS = 140 mm for males and 150 mm for females. Note that y-axes are different for each graph.

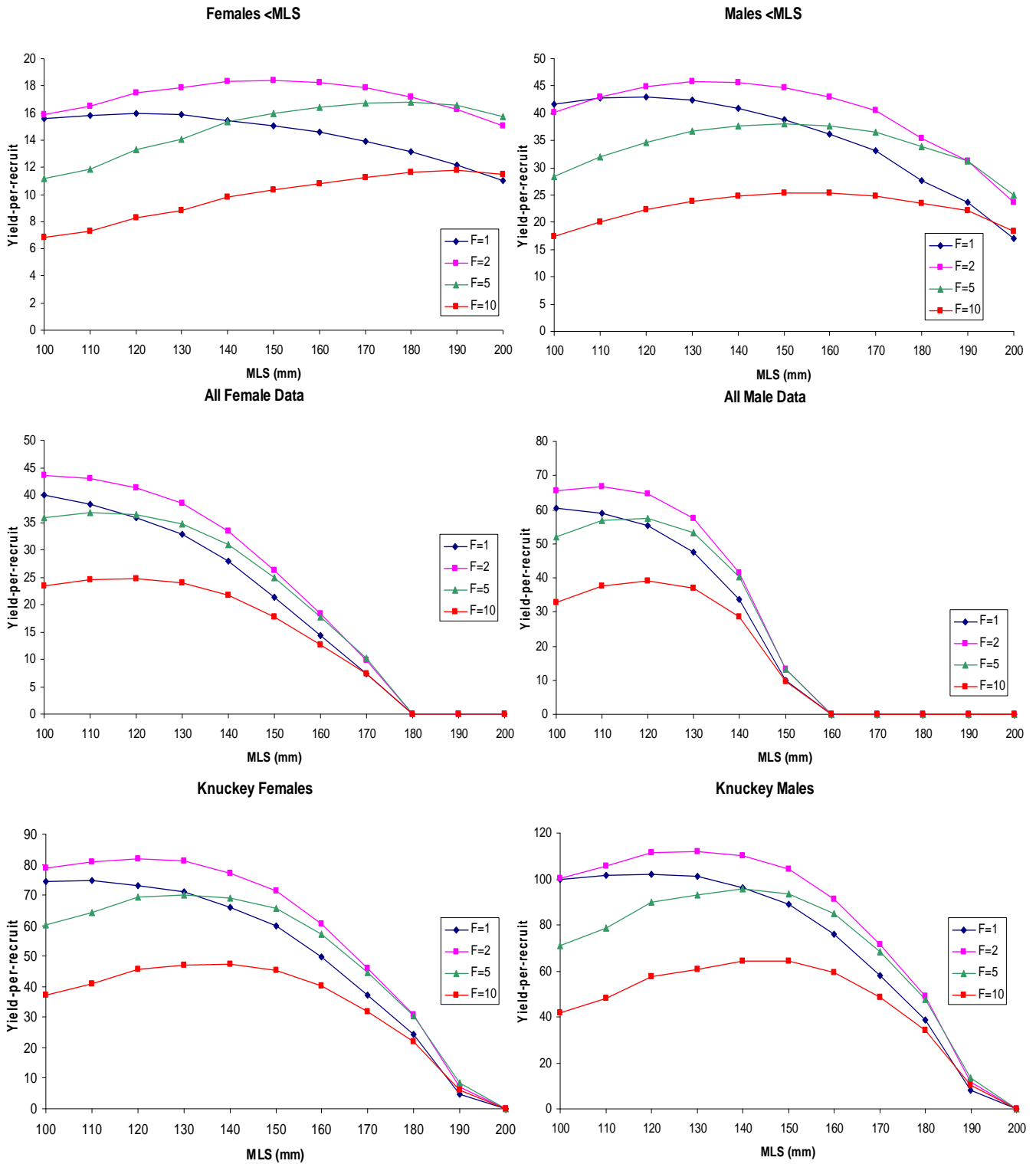


Figure 5-4. Effect of changing F on the yield-per-recruit and optimum MLS for several von Bertalanffy growth curves. From top to bottom F = 1, 2, 5, and 10. Note that y-axes are different for each graph.

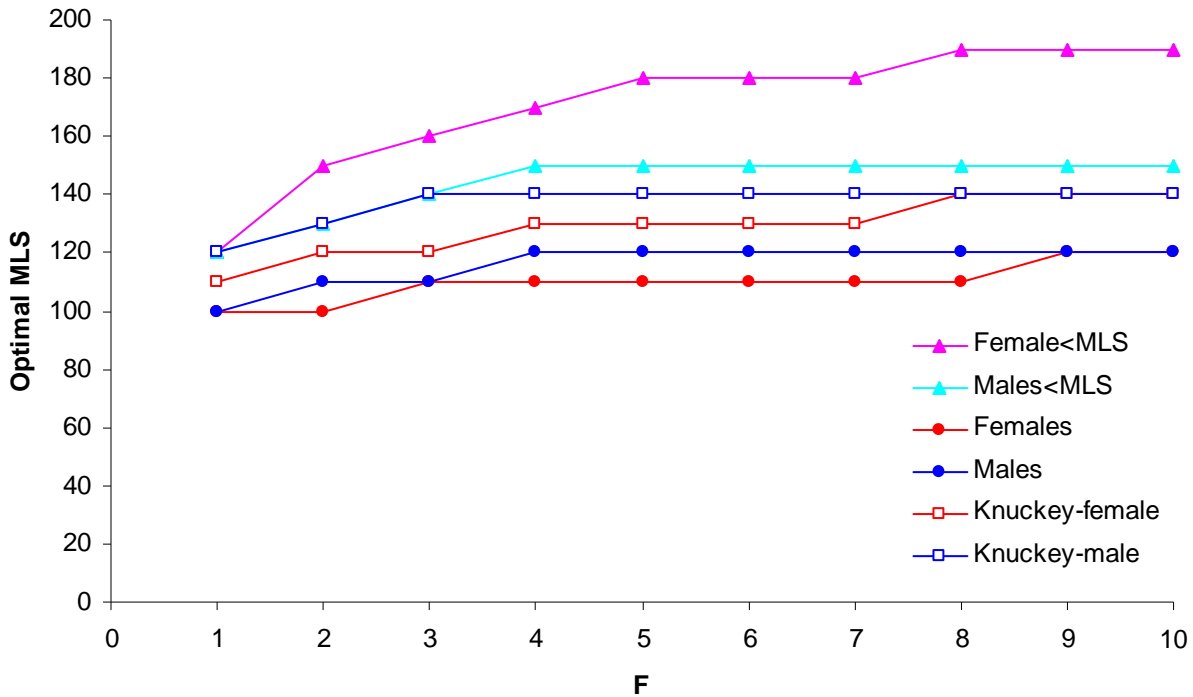


Figure 5-5. Optimal MLS by fishing mortality (F) for several von Bertalanffy growth curves.

5.4 Recruitment Adjusted Seasonal Depletion Model

This analysis uses the Recruitment Adjusted Seasonal Depletion (RASD) Model developed by Knuckey (1999). We used the catch and effort data from 1983 to 2006 and the growth parameters estimated in this study (Chapter 4) for the analysis. We set catchability such that fishing mortality was approximately 5, based on the enhanced Wetherall analysis presented in the previous section of the present chapter. The timing of the female offshore migration reflected the sex ratios obtained from the market monitoring data. We fitted the model to the catch and effort data using the least squares method. The model was used to investigate fluctuations in recruitment or fishing power that would have been required to explain the interannual variations in catches and CPUE observed in the NT Mud Crab Fishery over the last 20 years.

Similar patterns of fluctuation in recruitment and relative fishing power would have been required to explain these interannual variations in catches (Figure 5-6). Very large increases in either recruitment or fishing power, i.e. by a factor of up to 8, are required to explain the large increases in catch and CPUE that occurred in the late 1990s and early 2000s. Interannual fluctuations in recruitment of an order of magnitude, or greater, are both feasible and commonly reported in the literature, whereas annual fluctuations in fishing power of this scale are unlikely in a pot-based fishery. Hence, we conclude that the large increases in catches in the late 1990s and early 2000s mainly reflect strong recruitment levels during this period. Similar increases in catches and CPUE were recorded in the Queensland Gulf of Carpentaria Fishery during this period (see

Haddon *et al.* 2005) and suggest that high levels of recruitment occurred concurrently in both the eastern and western Gulf of Carpentaria. As concluded by Haddon *et al.* (2005), this co-occurrence of the increases in recruitment suggests that they were probably driven by broad-scale variations in environmental factors.

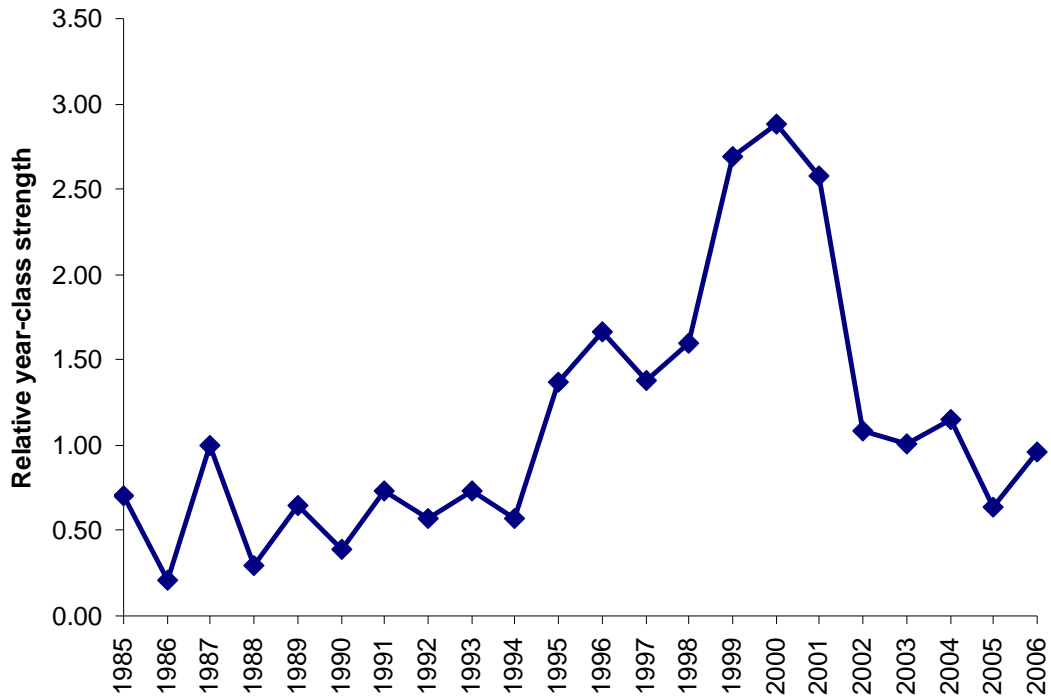


Figure 5-6. Modelled recruitment estimates given constant fishing power.

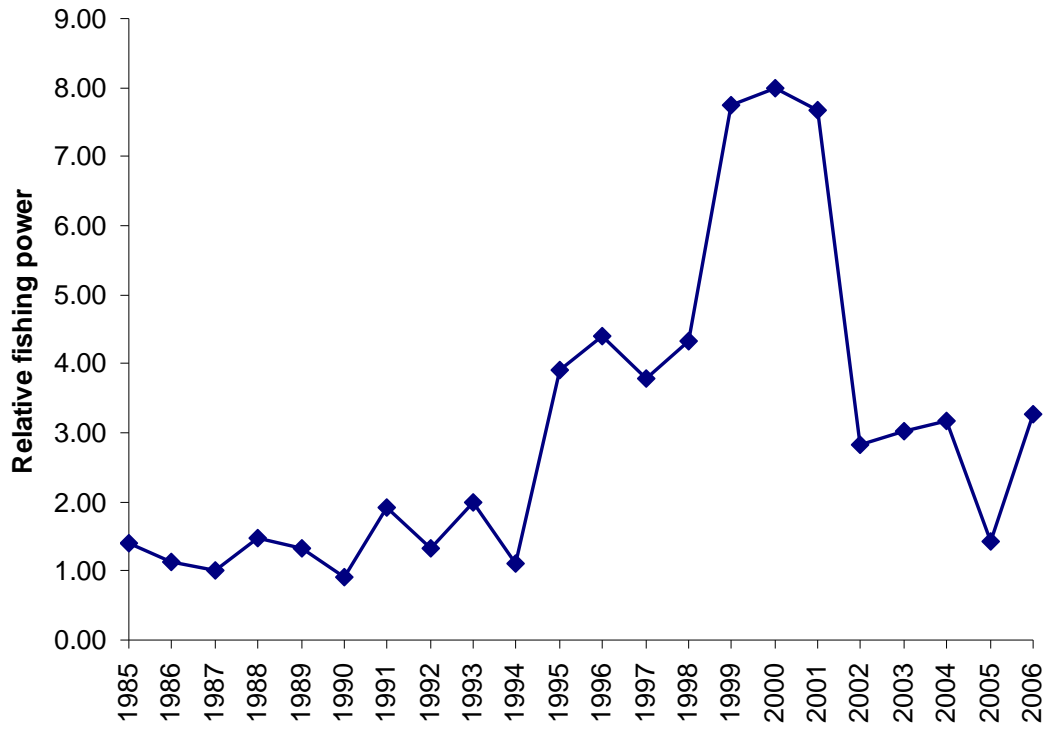


Figure 5-7. Modelled relative fishing power estimates given constant recruitment.

5.5 Discussion

The estimates of total mortality presented here are higher than those suggested in previous studies. For example, Knuckey (1999) suggested that total mortality was 2.5-3.5 and it is likely that current mortality rates are higher than they were in the 1990s. Haddon *et al.* (2005) noted fishing mortality is difficult to estimate precisely at high values (e.g. >1.2). Similar difficulties are associated with estimating high rates of total mortality.

The limitations of the growth descriptions introduce additional uncertainty in our estimates of total mortality. Despite this imprecision, our findings clearly support those of previous studies that suggest rates of fishing mortality in the NT Mud Crab Fishery are very high. Knuckey (1999) suggested that exploitation rates reached 50% in the developmental phase of the fishery leading up to 1995, and that most crabs were caught during their first year in the fishery. Model outputs presented by Knuckey (1999) suggested that at the 130 mm size limit that was in place up to 1995, only about 20% of 1+ female crabs were left in the stock at the time of main offshore spawning migration. Walters *et al.* (1997) suggested that exploitation rates in fished areas were probably over 70% of the available stock and that the fishery depended heavily on newly recruited crabs, and the stock was probably fully exploited. Haddon *et al.* (2005) suggested that levels of fishing mortality in the period leading up to their assessment in 2004 may not have been sustainable. Our results suggest that rates of fishing mortality in recent years may be higher than they were in 1990-95, and are very high by international standards (Fischer and Wolff, 2006).

The difficulties in developing reliable descriptions of growth clearly restrict the application and interpretation of the yield-per-recruit analyses. However, all of the analyses show that under both the current and previous MLSs, yield-per-recruit is maximised for fishing mortalities of around 2.0. Our analyses suggest that rates of fishing mortality may be significantly higher than 2.0. Importantly, the MLS that is needed to maximise yield-per-recruit increases as the rate of fishing mortality increases. Hence, from the perspective of maximising yield, the 2006 increase in MLS was clearly justified.

The outputs of the RASD Model suggest that the recent changes in the fishery catches and CPUE probably reflected fluctuations in recruitment rather than changes in fishing efficiency. This finding emphasises the benefits of the management changes, such as increases in MLS, that are likely to enhance egg production and hence recruitment, and were established when the sustainability of the previous management arrangements came into question (Haddon *et al.* 2005). Currently, insufficient time has passed to assess the effects of these changes in the management arrangements on status of the fishery.

6. EFFECT OF CHANGE IN MINIMUM LEGAL SIZE

6.1 Introduction

In 1985 the minimum legal size (MLS) for the NT Mud Crab Fishery was set at 130 mm for male and female mud crabs. In 1996, the MLS was increased to 140 mm for female crabs. In May 2006 the MLS for males and females were each increased by 10 mm to 140 and 150 mm, respectively. In this chapter, we examine the effect of the recent change in MLS on the fishery by quantifying the percentage of both historical catches and those taken after May 2006 that lay between the old and new MLSs. We also examine the percentage of the catch that would have been protected by a 5 mm increase in MLS. What we cannot determine is what proportion of crabs below the MLS would have grown above the new MLSs and become available to the fishery at a later date and what proportion would have been lost to the fishery through natural or discard mortality. If rates of natural and discard mortality are relatively low, the loss of catch would be minimal and offset by the increase in yield-per-recruit. Conversely, if the rates of natural and discard mortality are high, the loss of catch would be significant and not be offset by the increase in yield (see Chapter 5). An integrated model would be required to thoroughly assess the effect of the increase in MLS on catches in the NT Mud Crab Fishery.

6.2 Size Composition of Catch in 2006

Information on the percentage of the catch that lay between the old and new MLSs was obtained in an observer program conducted by the DPIFM with commercial fishers in July-November 2006. The capture locations were the Adelaide River (November), Bynoe Harbour (July), McArthur River (August), Roper River (July and October) and Wearyan River (September and November).

Mud crabs were placed into three size categories. Crabs that were below the 2005 MLS (males <130 and females <140) were released straight back into the water; crabs that were between the 2005 and May 2006 MLSs (i.e. males ≥ 130 mm and <140 mm and females ≥ 140 mm and <150 mm) were tagged and released back into the water; and crabs that were above the May 2006 MLS (males ≥ 140 mm and females ≥ 150 mm) were kept as commercial catch.

The proportions of crabs observed to be above, below and between the old and new MLSs are displayed in Figure 6-1. This chart indicates that a large proportion (>60%) of crabs caught in and around Beagle Gulf (Adelaide River and Bynoe Harbour) were above the new MLS, and less than 21% were between the old and new MLS. In contrast, in the Gulf of Carpentaria (Roper, McArthur and Wearyan Rivers) less than 43% of crabs were above the new MLS, and over 23% were between the old and new MLS.

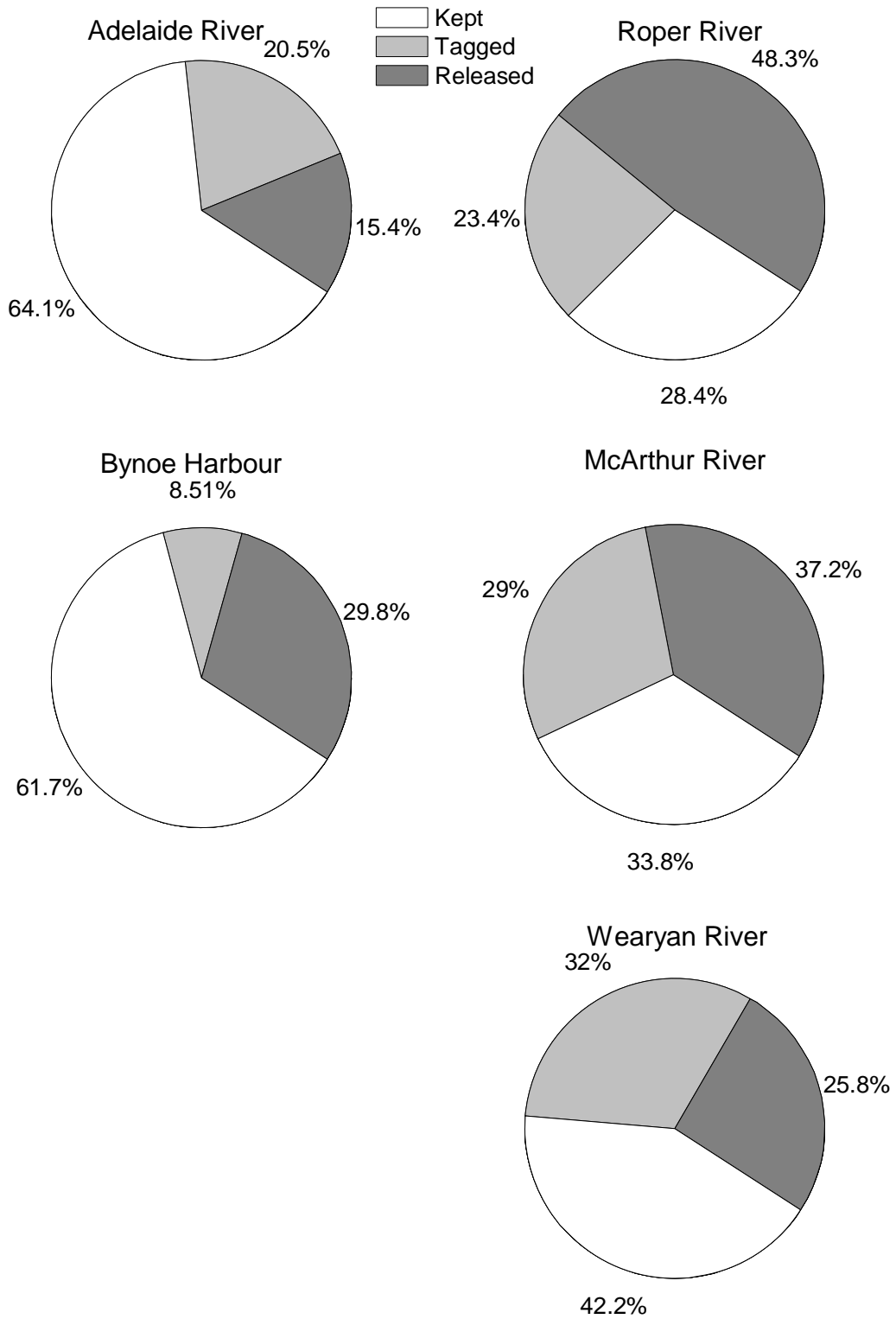


Figure 6-1. Proportion of crabs (i) above the new MLS (males >140 mm, females >150 mm), (ii) between the new and old MLS (males >130 mm and <140 mm, females >140 mm and <150 mm), and (iii) below the old MLS (males <130 mm, females <140 mm) during the 2006 observer program.

6.3 Size Composition of Catch 1990-2006

To investigate the percentage of historical catches that were below the new MLS, we used market monitoring data (Chapter 3) to plot the size distribution of male and female crabs (Figure 6-2 and 6-3) and calculate the percentage of the catch that was below the new MLS in each year. To determine the effect of a 5 mm increase in MLS, we also compared the number of crabs below 145 mm (females) and 135 mm (males) (Figure 6-4).

The size frequency distribution for female crabs in 5 mm increments (Figure 6-2) includes reference lines for the old (dashed lines) and new (dotted lines) MLS. The column to the right of the dashed line (old MLS) indicates the number of female crabs that would have been protected by a 5 mm increase in the MLS (i.e. to 145 mm). The column to the left of the dotted line is the additional female crabs protected by the 10 mm increase in the MLS (i.e. to 150 mm). Over the last ten years, a 10 mm increase in the MLS would clearly have protected many more female crabs than a 5 mm increase.

Between 1990 and 2006, the percentage of female crabs below the new MLS ranged between 5 and 33% (Figure 6.4). In 1997, ~5% of the females caught were below the new MLS and by 2005 this had increased to ~23%. In contrast, the percentage of females that would have been protected by a 5 mm increase in the MLS remained 5% during the entire period from 1997 to 2006. Hence, the increase in MLS to 150 mm protected more than four times as many female crabs as would have been protected by an increase in MLS to 145 mm.

The size frequency distribution for male crabs from 1990 to 2006 in 5 mm increments (Figure 6-3) also includes the old (dashed lines) and new (dotted lines) MLS (note the smaller MLS for males compared to females). Again, significantly more male crabs were protected by the 10 mm increase in MLS than would have been protected by a 5 mm increase.

The percentage of male crabs below the new MLS (140 mm) increased from 3% in 1997 to 17% in 2004 and 13 % in 2005, whereas a MLS of 135 mm would have protected less than 3% of male crabs. Hence, the increase in the MLS to 140 mm protected more than four times as many male crabs as a would have been protected by an increase in the MLS to 135 mm.

The results show that the 10 mm increases in the MLSs for males and female crabs were more than four times as effective as 5 mm increases would have been in protecting mud crabs captured in pots.

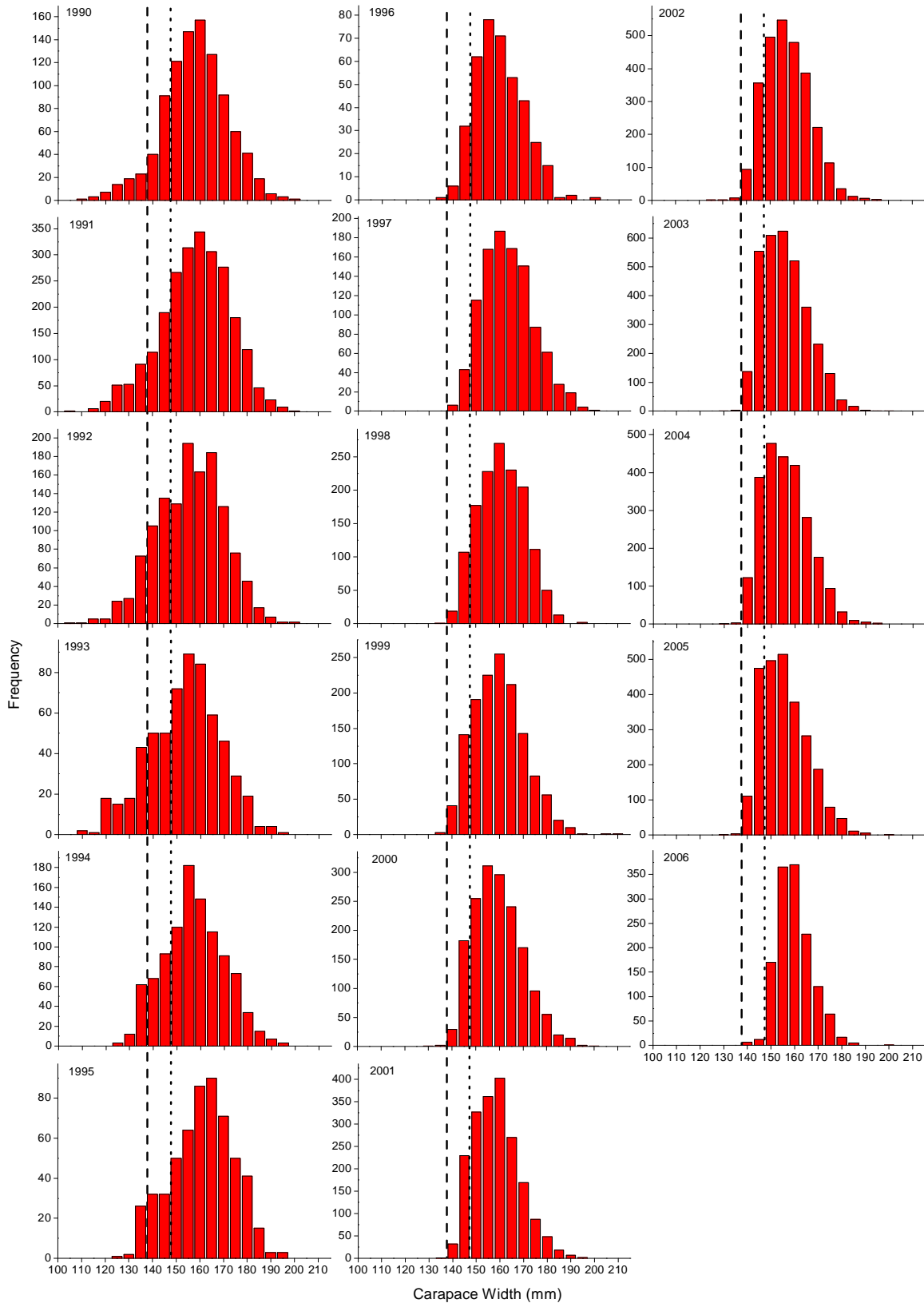


Figure 6-2. Size distribution of female crabs in the NT Mud Crab Fishery 1990-2006. Dotted line represents the MLS established in May 2006. Dashed line represents MLS from 1996 onwards.

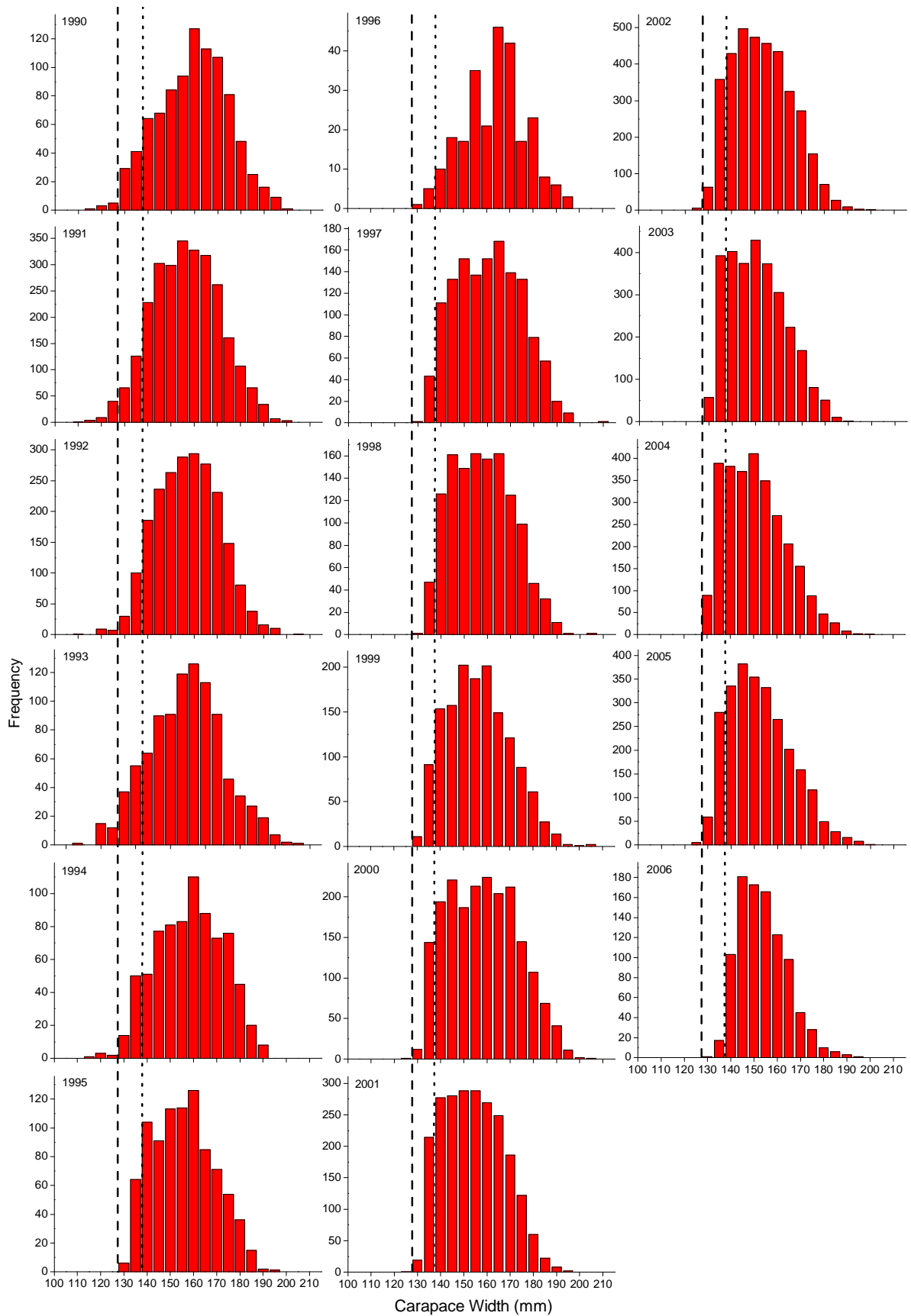


Figure 6-3. Size distribution of male crabs in the NT Mud Crab Fishery 1990-2006. Dashed line represents MLS from 1996 onwards. Dotted line represents the MLS established in May 2006.

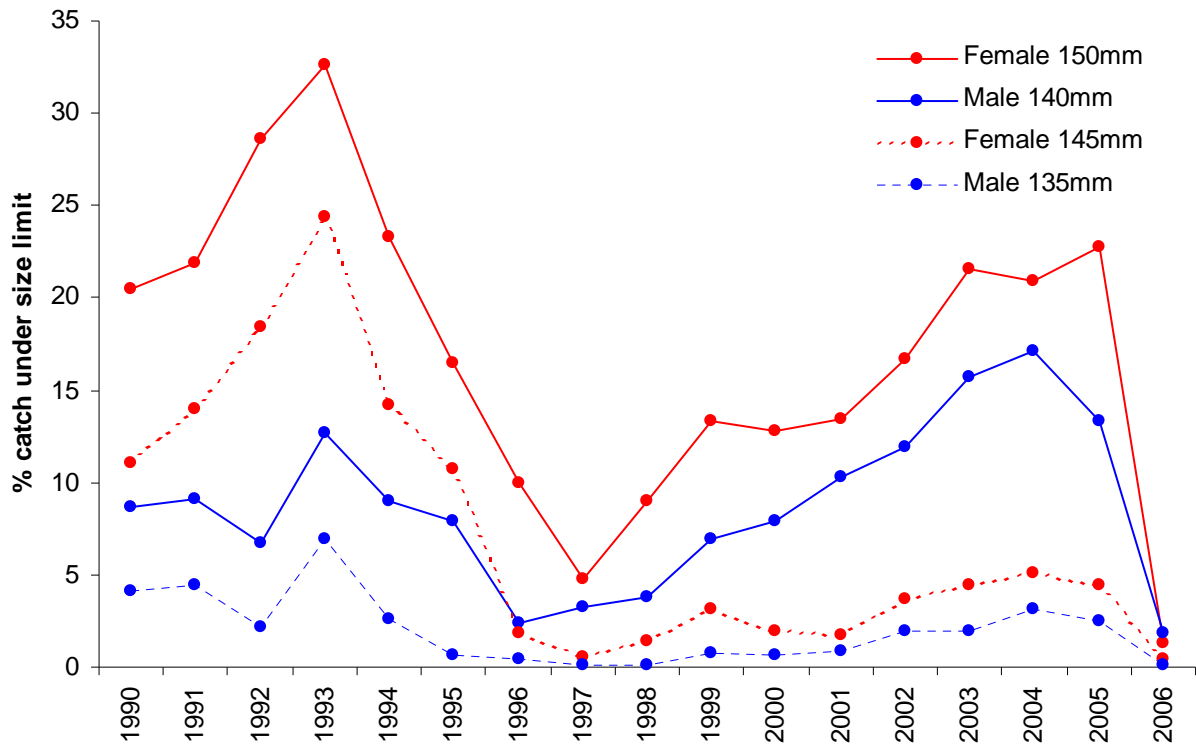


Figure 6-4. Percentage of the catch in the NT Mud Crab Fishery 1990-2006 that was below the current MLS of 150 mm for females and 140 mm for males (solid line) and below a 5 mm increase from the 2005 MLS (broken line). 2006 data includes data from before and after the May 1 introduction of the new MLS.

6.4 Proportion of Females that Reach Second Mature Instar

Following the method of Knuckey (1999), we used tagging data to calculate the relationship between carapace width before the first mature moult (pre-moult width) and after the first mature moult (post-moult). This relationship is: $\text{postmoult width} = 34.984 + 0.9322 \times \text{pre-moult width}$. By adding this increment to the size at first maturity, we estimated the size at which females undergo their second post-maturity moult. We used this information in conjunction with size frequency data from commercial catch, to determine the proportion of immature, and first and second mature instar crabs that were caught for each year from 1990 to 2006.

The results of this analysis are plotted in Figure 6-5. The percentage of immature females in catches from the Gulf of Carpentaria increased from ~3% in 1997 to 9-10% during 2003-2005. In Beagle Gulf immature females did not comprise a significant proportion of catches after 1995. Similarly, in the Gulf of Carpentaria, the proportion of female crabs that reached the second maturity instar decreased from 32% in 1997 to 22-23% in 2003-2005, whereas in Beagle Gulf the proportion of second mature instar females remained above 30% during this period.

Importantly, the proportion of female crabs that reached the second maturity instar increased above 30% in the Gulf of Carpentaria after 2006, when the new minimum legal size (MLS) was introduced. The decrease in 2006 in the proportion of females in Beagle Gulf that reached the second maturity instar may reflect the relatively small effect of the increases in MLS on size of crabs taken from Beagle Gulf.

Introducing the new the MLS in 2006 is likely to have significantly increased egg production by reducing the percentage of immature crabs in the catch and increasing the proportion of female crabs that reach the second mature instar.

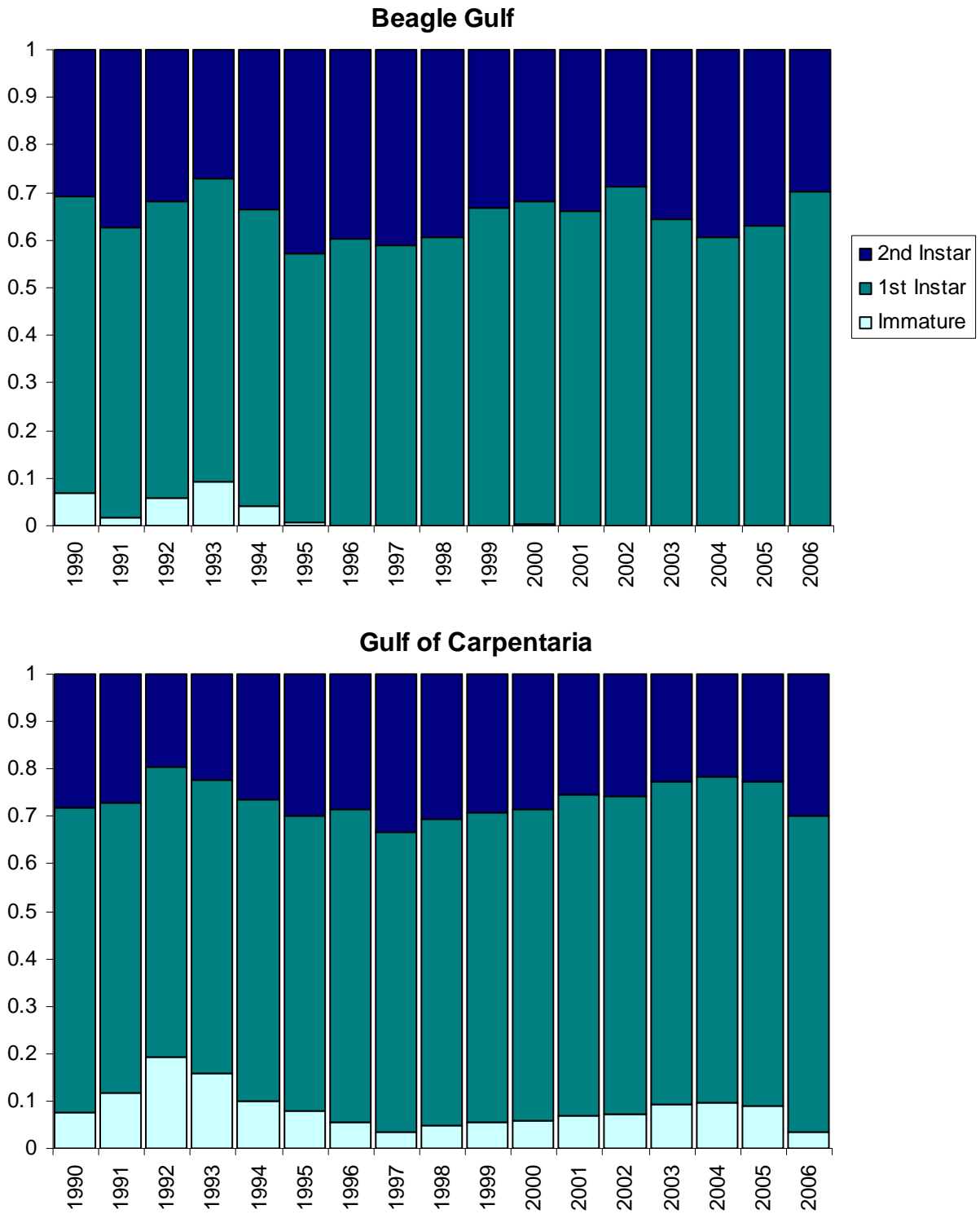


Figure 6-5. Proportion of immature, 1st and 2nd instar female mud crabs in the NT Mud Crab Fishery between 1990 and 2006.

6.5 Discussion

The 10 mm increases in the MLS for male and female mud crabs that were introduced May 2006 were effective in increasing both yield (see Chapter 5) and egg production. As argued by industry in a representation to the NT Government these increases were likely to have had lower impacts on the economics of the fishery than the introduction of a seasonal closure, which would have disrupted markets. The results presented in this chapter clearly show that 5 mm increases in the MLS of male and female mud crabs would have been less than 25% as effective as the 10 mm increases that were established.

The benefits of the increase in MLS (i.e. in reducing fishing mortality) are shown by differences in the changes in mean size of crabs taken from the Gulf of Carpentaria and Beagle Gulf after 2006. In the Gulf of Carpentaria and Beagle Gulf where there was knife-edge selection prior to the change (Haddon *et al.* 2005), the mean size of crabs increased significantly, whereas in Beagle Gulf where mean size of crabs was larger, and there was not knife-edge selection, the increase in MLSs had minimum effects on the mean size of crabs taken.

A major advantage of an increase in MLS is that the short-term reduction in catches, and the effects of natural and discard mortality are at least partially offset by increases in yield-per-recruit. Given the lack of information on rates of natural and discard mortality it is difficult to estimate the effects on catches directly. However, if rates of natural and discard mortality are low for crabs between the old and new MLSs, as is suspected, then the overall effects are likely to be low.

An integrated fishery assessment model would be required to thoroughly assess the effect of the increase in MLS on catches in the NT Mud Crab Fishery. The capacity to undertake a quantitative management strategy evaluation is one of the main arguments for establishing an integrated assessment model for the fishery. The main arguments against this approach are (i) the limitations of the existing data, (ii) the relatively high cost of developing a model (ii) and the potential for using direct fishery-independent measures of relative abundance as the basis for assessing and managing the fishery.

7. POTENTIAL FOR USING DATA FROM DEPLETION STUDIES FOR FUTURE ASSESSMENT OF NT MUD CRABS

7.1 Introduction

In this chapter we present analysis of the data from depletion studies conducted in the NT between 1997 and 2004. The depletion data were provided to SARDI by staff of the DPIFM as a spreadsheet with the location (Adelaide River, Twin Sisters Creek), zone (depletion, buffer) and dates of each study and the sex, carapace width (mm), wet weight (g) and maturity stage of maturity of each crab.

7.2 Methods

The sampling methodology for the depletion studies is described in detail in the FRDC report by Hay *et al.* (2005). The studies were conducted in the Adelaide River in 1997 and 1999-2004 and Twin Sisters Creek (Gulf of Carpentaria) in 1998 and 2002-2004 (Table 7-1). One hundred baited pots were placed at 20 m intervals along the creek. Each creek was divided into three zones – a one kilometre depletion zone enclosed by two 500 m buffer zones (Figure 7-1). Over the course of approximately eight days - five or six days in some experiments - pots were systematically checked every 24 hours on the daylight high tide and rebaited. All crabs caught within the depletion zone were measured, sexed and removed from the study site for the duration of the experiment. We present results from the 50 pots within the designated depletion zone.

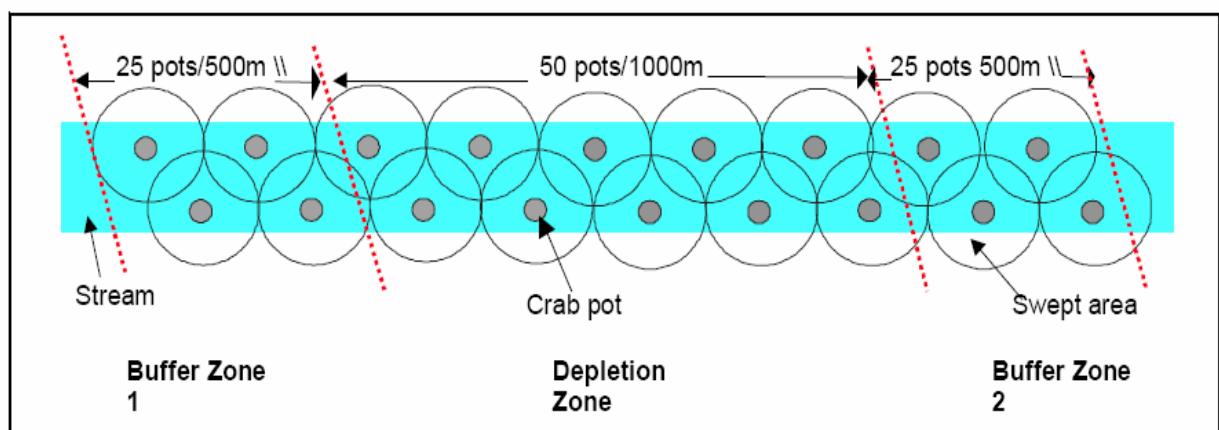


Figure 7-1. Schematic map of the sampling design for depletion studies conducted by DPIFM from 1997-2004 (reprinted from Hay *et al.* 2005)

Table 7-1. Start and finish dates and locations of the 18 depletion experiments used in our analyses.

Depletion Experiment	Start Date	End Date	Site
1	26/05/1997	30/05/1997	Blockoff Creek, Adelaide River
3	21/05/1999	28/05/1999	Blockoff Creek, Adelaide River
4	08/05/2000	15/05/2000	Blockoff Creek, Adelaide River
5	11/05/2001	18/05/2001	Blockoff Creek, Adelaide River
6	03/05/2002	10/05/2002	Blockoff Creek, Adelaide River
9	01/07/2002	08/07/2002	Blockoff Creek, Adelaide River
10	30/07/2002	06/08/2002	Blockoff Creek, Adelaide River
12	08/05/2003	13/05/2003	Blockoff Creek, Adelaide River
15	19/07/2003	24/07/2003	Blockoff Creek, Adelaide River
16	18/09/2003	23/09/2003	Blockoff Creek, Adelaide River
17	26/04/2004	01/05/2004	Blockoff Creek, Adelaide River
2	24/05/1998	31/05/1998	Twin Sisters Creek
7	20/05/2002	27/05/2002	Twin Sisters Creek
8	16/06/2002	23/06/2002	Twin Sisters Creek
11	25/08/2002	30/08/2002	Twin Sisters Creek
13	24/05/2003	29/05/2003	Twin Sisters Creek
14	21/06/2003	26/06/2003	Twin Sisters Creek
18	14/05/2004	18/05/2004	Twin Sisters Creek

We carried out a standard Leslie depletion estimation by regressing daily catch against cumulative catch (Hilborn and Walters 1992). This method gave an estimate of the initial abundance of crabs within the depletion zone (N_1) and the proportion of the catch caught per day (q). We also fitted the data using a Poisson maximum likelihood estimate which gave alternative estimates of N_1 and q . The two estimates of N_1 and q were compared, and N_1 was compared with day-1 catch and the depletion CPUE (catch/day).

7.3 Results

The data and Leslie regression line for the (18) depletion experiments at Blockoff Creek and Twin Sisters Creek are shown in Figure 7-2. The Standard Leslie and Poisson estimators of N_1 and q were very similar at both locations (Figure 7-3, Table 7-2). The initial abundance estimates (N_1) varied over time in each location. In Blockoff Creek, the estimates of initial abundance in May 2000, 2001 and 2002, were much higher than those in any other years. Similarly, in Twin sisters Creek the estimate of initial abundance in May and June 2002 were higher than those recorded at other times. There were strong negative correlations between N_1 and q (>-0.8 , Figure 7-4), i.e. when initial abundance was high the slope of the catch rate was low.

The estimates of initial abundance followed similar general trends to first day catch and catch per day (Figure 7-5). For example, in Blockoff Creek the highest value for each parameter was recorded in May 2000. Similarly, in Twin Sisters Creek the lowest value for each parameter was recorded in May 2003. There were reasonable correlations between estimates of initial abundance, first day catch and catch per day (Table 7-2), although the relationship between initial abundance and catch per day was stronger than the relationship between initial abundance and first day catch. The range of variation in estimates of initial abundance was much higher than the range of variation in either first day catch or catch per day (Figure 7-5). First day catch was the least variable measure of abundance at Blockoff Creek, whereas catch per day showed the lowest range of variability at Twin Sisters Creek.

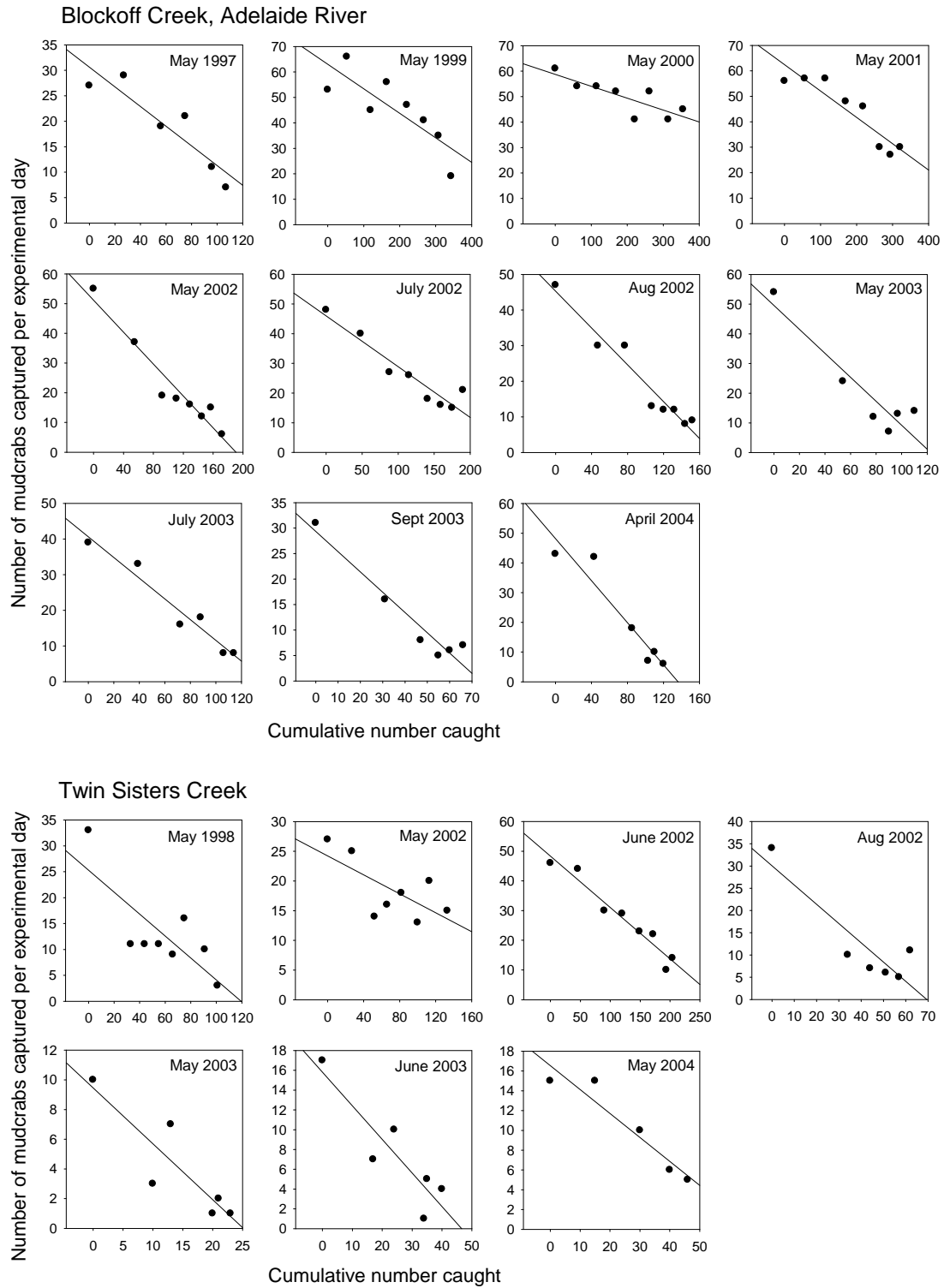


Figure 7-2. Data and standard Leslie depletion model regression line for each of the 18 depletion experiments at Blockoff Creek and Twin Sisters Creek. Each point represents a day of depletion experiment. The y-value is the daily catch rate as the number of mud crabs captured per day by all 50 pots within the depletion zone. The x-value is the cumulative number of crabs captured in all days of each depletion experiment, up to but not including the day shown for each point.

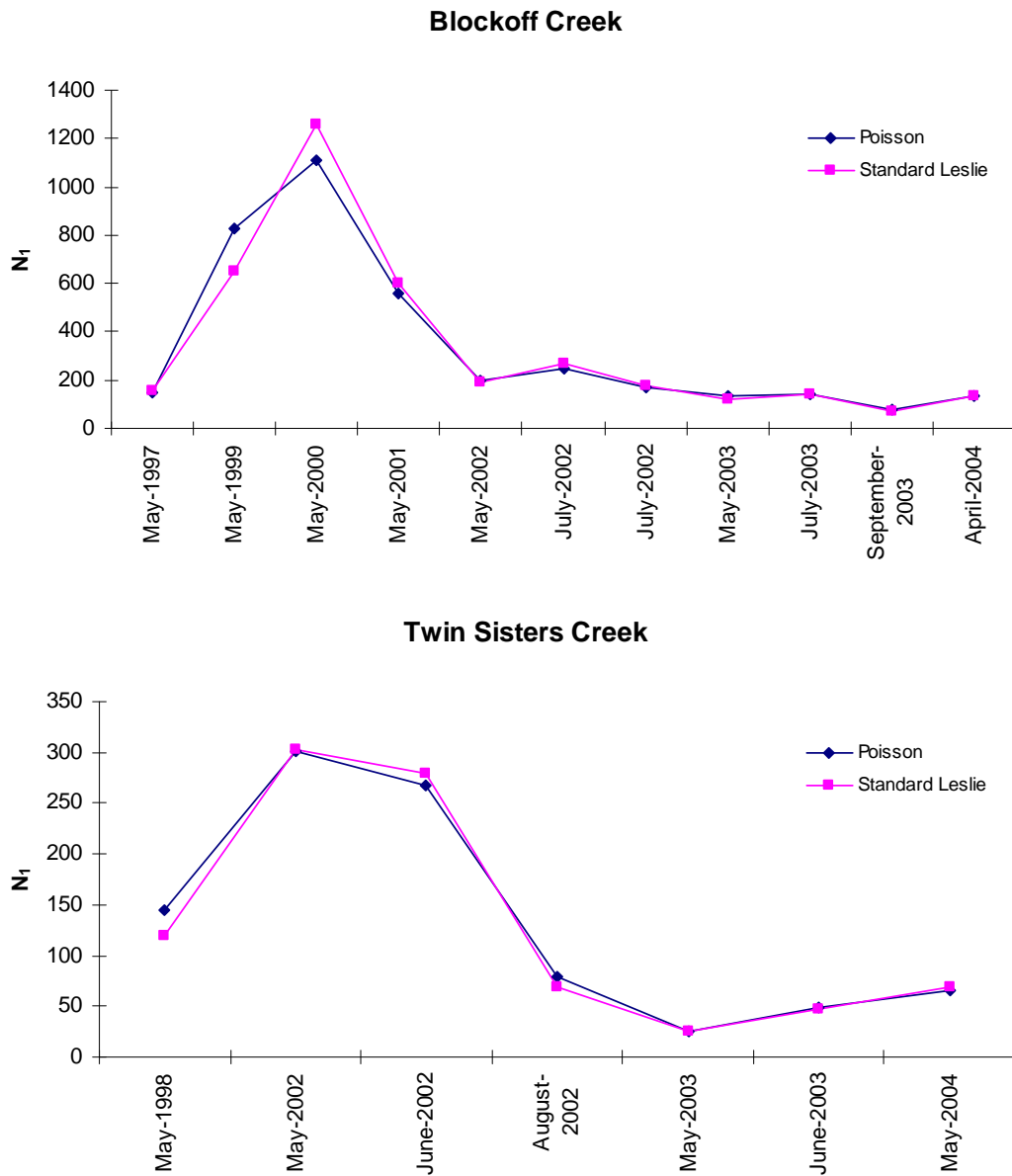


Figure 7-3. Estimates of the number of mud crabs in the depletion zone at Blockoff Creek and Twin Sisters Creek prior to the start of each depletion experiment (N_1) calculated using the Standard Leslie depletion model and a maximum likelihood Poisson estimate.

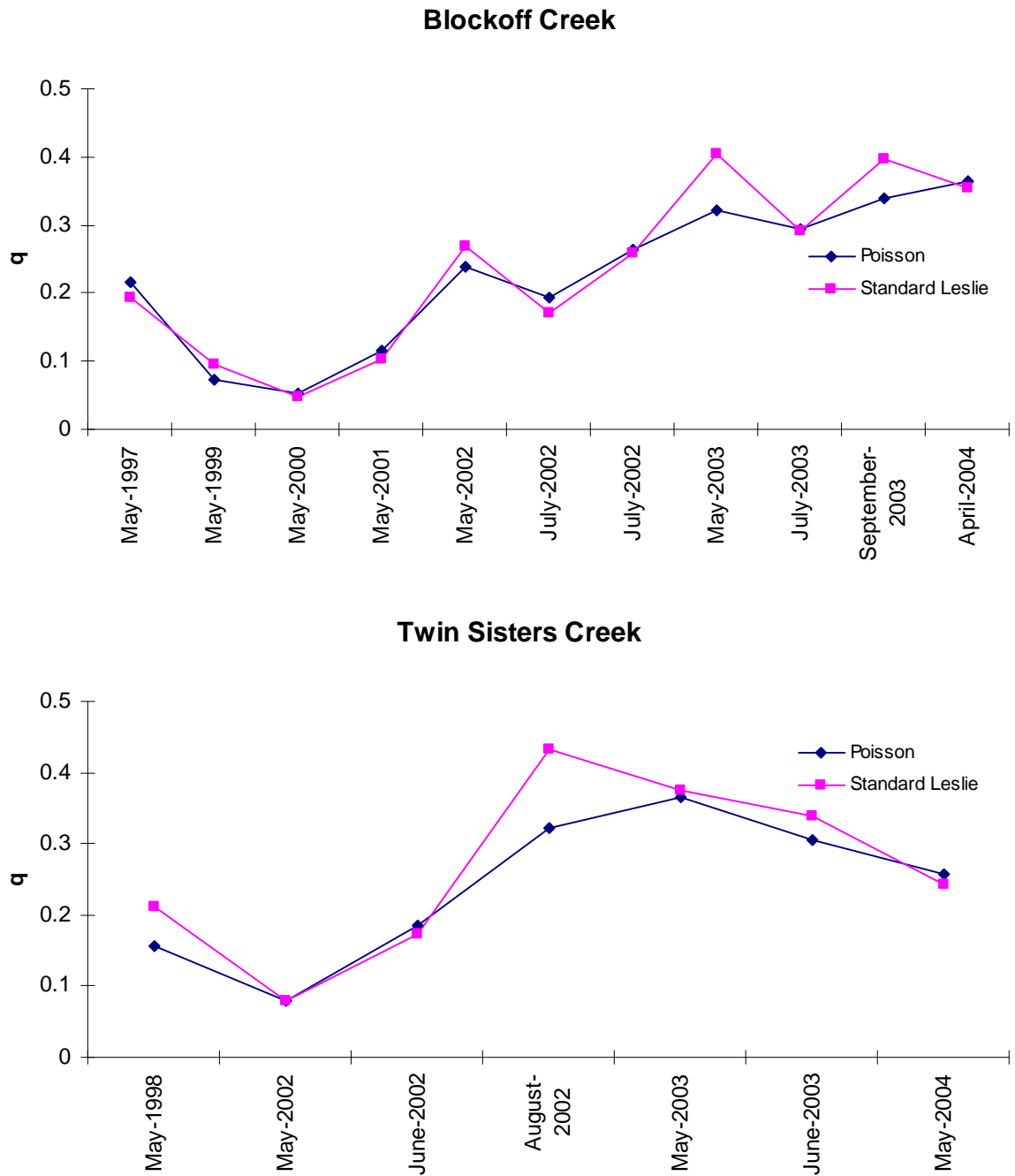


Figure 7-4. Proportion of mud crabs captured per day (q) within the depletion zone in Blockoff Creek and Twin Sisters Creek for each depletion experiment calculated using the standard Leslie depletion model and a maximum likelihood Poisson estimate.

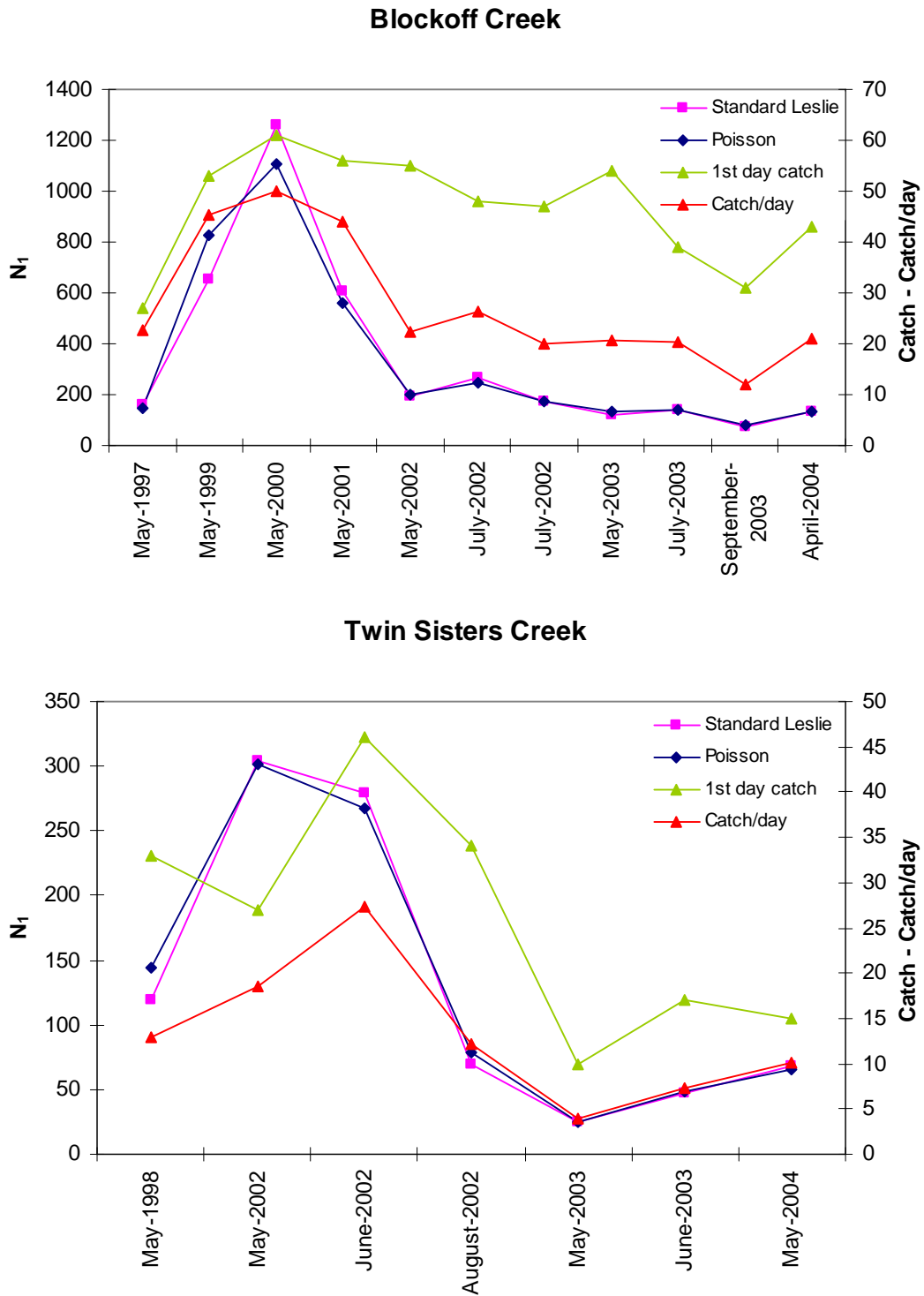


Figure 7-5. Comparison of initial abundance estimates from the Poisson and Leslie methods with the day 1 catch and catch per day for each depletion experiment in Blockoff Creek and Twin Sisters Creek.

Table 7-2. Pearson correlation coefficients between each measure of depletion abundance at Blockoff Creek and Twin Sisters Creek

Blockoff Creek	Standard Leslie	Poisson	1st day catch	Catch/day
Standard Leslie	-			
Poisson	0.978899	-		
1st day catch	0.634527	0.638728	-	
Catch/day	0.926107	0.952751	0.667251	-

Twin Sisters Creek	Standard Leslie	Poisson	1st day catch	Catch/day
Standard Leslie	-			
Poisson	0.995354	-		
1st day catch	0.656108	0.68147	-	
Catch/day	0.898232	0.891047	0.868001	-

7.4 Discussion

The general similarity in the patterns of variation in the estimates of initial abundance, first day catch and catch per day suggest that all these measures provide some information about relative abundance. The high values recorded for each parameter in each location in May 2002 also reflect the high CPUE values recorded in the fishery during that period.

There is no evidence to suggest that the Leslie estimates of initial abundance are reliable estimate of absolute abundance. This is because a key assumption of Leslie depletion studies, i.e. that there is no immigration into the experimental area, was almost certainly violated in this study as researchers were unable to prevent crabs entering the depletion area. It is notable that Hay et al. (2005) concluded that there is little prospect of obtaining a robust estimate of total abundance across the entire NT Mud Crab Fishery because of the difficulties associated with estimating both mud crab abundance within habitat type and quantifying the types and areas of critical mud crab habitat using satellite imagery.

The relatively high correlations between estimates of q and N_1 suggest that when abundance is high, the proportion of mud crabs harvested is low. This suggests that immigration rates into the study area may be density dependent. That is, the proportion harvested may be under-estimated at higher densities because mud crabs move into the depletion zone more rapidly. Density-dependent movement would bias estimates of N_1 as catch rates would not decline as rapidly as they would have done if no new crabs had entered the depletion zone. This implies that in years of high density N_1 may be overestimated.

The relatively large variations in N_1 that are shown in Figure 7-3, e.g. Blockoff Creek in May 2000 and September 2003, could be over-estimates of actual variations in mud crab density. Certainly, the range of variation in N_1 is much greater than that the ranges of variation in either first day catches or mean catch per day. The greatest limitation to the use of first day catches as an estimate of abundance is the absence of temporal replication. The main problem with using mean catch per day estimated over the course of the depletion experiment as a measure of abundance is that each daily catch estimate is for a different level of actual abundance, due to the depletion effect of the experiment. If the objective was to obtain replicated measures of abundance, rather than conducting depletion experiments, this problem could be overcome by releasing crabs into the study area immediately after they were captured and tagged.

From a stock assessment perspective, the relevant question is whether (or not) the high costs associated with researchers conducting intensive depletion experiments are justified by the value of the data provided by these studies. As depletion experiments do not provide reliable estimates

of absolute mud crab abundance, the most critical issue is whether or not the estimates of relative abundance obtained by repeatedly sampling the same location over approximately eight days are significantly better than those that would be obtained by sampling over a shorter time period. The data available for the present study were not suitable for addressing this question directly, however this issue would need to be addressed if/when options for obtaining additional fishery-independent information on the relative abundance of mud crabs in the NT are being considered. The value of temporal replication of sampling will also need to be assessed in relation to the benefits associated with broad-scale, high resolution spatial coverage of the fishery. Sampling design will be a key determinant of the success of fishery-independent surveys that may be established to support future assessment of the NT Mud Crab Fishery.

Experience in other trap fisheries has shown that fishery-independent surveys in key areas can provide valuable information on stock abundance that can be used to inform the management of fisheries. For example, in South Australia, fishery-independent surveys of blue swimmer crabs (*Portunus pelagicus*) are routinely done using commercial vessels and crews under the direction of scientific observers, with the survey costs offset by the sale of the catch (e.g. Currie *et al.* 2007). In this and other South Australian fisheries, measurements of relative abundance from fishery-independent surveys are key biological performance indicators that underpin the harvest strategies. The main benefit of this approach is that by standardising the unit of effort, and for the effects of environmental factors (e.g. season, water temperature), the need to consider the effects of factors other than abundance on CPUE is minimised. In contrast, discussions of the other factors that affect CPUE tend to dominate consideration of stock assessment outputs that are based solely on commercial data, especially in situations when CPUE has declined and explanations other than a reduction in abundance are commonly muted.

Another benefit of conducting fishery-independent surveys is the positive relationships which are necessarily built among managers, fishers and scientists when this approach forms the basis of the research program to inform the harvest strategy. Our experience in South Australia suggests that information on stock status that is obtained from surveys conducted collaboratively by fishers and scientists tends to be accepted more readily than the outputs of stock assessments that involve less input from fishers. The main limitation to the use of fishery-independent surveys to support future assessment of the NT Mud Crab Fishery may be the high logistical costs, which are a direct result of the large size and isolation of the fishery. However, these problems could be at least partially offset by the using commercial vessels to undertake the surveys (with scientific observers onboard) and by selling the catch to pay for the survey costs.

The benefits of fishery-independent surveys for future management of the NT Mud Crab Fishery would be maximised if they were conducted in the key locations in the fishery and provided additional information on growth and mortality rates in these areas. One way to achieve this outcome would be to conduct a concurrent tagging program, e.g. inserting passive integrated transponder (PIT) tags into selected (e.g. large female) crabs collected in the surveys and release them at the point of capture. Screening for tags could be done as part of the existing market sampling program. This approach would yield vital information on the rates of growth and fishing mortality in key fishing areas.

8.0 GENERAL DISCUSSION

8.1 Available information and critical knowledge gaps

Considerable biological and fishery data are available for NT mud crabs, including catch and effort data from a logbook program (1983-present), sex-specific size information from a market monitoring program (1990-present), data from tagging studies (1997-2004), depletion studies (1999-2004) and an observer program (2006). Knuckey (1999) collated, analysed and interpreted biological and fishery data collected up to 1995. Stock assessments conducted in 1996 (Walters *et al.* 1997), 2000 and 2004 (Haddon *et al.* 2005) provided valuable information regarding changes in the status of the fishery over time. Hay *et al.* (2005) assessed fishery-independent methods for monitoring crab abundance and habitats in northern Australia.

Despite this wide range of information, there are several critical knowledge gaps that currently restrict assessment of the fishery. One of the most significant is the poor understanding of effort levels. Good correlations between logbook data and freight records suggest that catch may be estimated accurately, but there is a widespread perception that under-reporting of effort through the use of additional (unlicensed) pots is a major problem in the fishery. The recent changes in the prevalence of “double potting” (i.e. two potlifts per day) also has the potential to bias the estimates of nominal effort, especially if this activity is not uniformly undertaken or reported across the fishery. The present study and all previous assessments of the fishery have used CPUE as the primary indicator of crab abundance. Effort biases have significant implications for current knowledge and future assessment of the status of this fishery.

The FRDC-funded project that investigated the development of fishery-independent methods for measuring the abundance and habitats of mud crabs was only partially successful. It is not clear how the methods and measures developed in that study could be used for direct ongoing assessment of the fishery (Chapter 7). Certainly the final report provided no clear recommendations regarding the future application of this approach. Depletion studies do not appear to provide an effective method for estimating absolute abundance, even for the very small areas in which these studies were conducted, because of immigration of crabs into the study area. Importantly, the high cost of conducting the depletion studies does not appear to be commensurate with the quantity and quality of information provided about the stock. Repeatedly setting pots in one or two locations over the course of 8-10 days is likely to provide less information about the stock than would be obtained by setting the same amount of pots in more locations. A more cost effective and informative option for obtaining information about the stock may be to conduct less intensive surveys over a broader spatial scale with aim of obtaining unbiased estimates of relative abundance in critical parts of the fishery.

The sex-specific size information from the market sampling program is valuable and it is important that the collection of these data is continued. However, the utilisation of these size data in future assessments will be impeded by the lack of information available on growth patterns, particularly for crabs in the larger size classes. Improved descriptions of the growth patterns of crabs will require new methods for data collection as previous approaches have failed to provide sufficient information for crabs above the MLS. Future studies of growth patterns will also need to investigate alternative models that are characterised by assumptions that are consistent with the biological characteristics of mud crabs.

There is also a clear need to improve current knowledge of the rates of natural, fishing and discard mortality in the NT Mud Crab Fishery. Under the high rates of fishing mortality that have existed in the fishery over the last decade there is very significant potential for both localised depletion of key fishing areas and repeated capture of undersized crabs, with unknown and potentially cumulative effects on survivorship. Both of these issues could have significant implications for the long-term sustainability of the fishery. Establishing a monitoring program that uses modern tags (e.g. PIT tags) could provide valuable information on the patterns and rates of fishing mortality in the NT Mud Crab Fishery. Dedicated studies of discard mortality are also warranted given the fishery's strong reliance on MLSs as a management tool.

There is also a clear need for additional information on the general biology and ecology of mud crabs in the NT. For example, information on the relationship between size/age and fecundity is needed to assess the effects of current and previous size limits on levels of egg production. Similarly information on the behaviour of females in the period between mating and their offshore migration is needed to assess the potential for these mated crabs to be recaptured repeatedly, with potentially cumulative discard mortality, prior to their movement offshore.

Despite the significance of the knowledge gaps outlined above, the most pressing need for the NT Mud Crab Fishery is to develop a formal harvest strategy that outlines objectives, strategies, performance indicators, reference points and decision rules and that specifies a research and monitoring program to support future stock assessment. An integrated fishery assessment model would enhance the development and evaluation of a harvest strategy for the fishery. However, given the limitations to current data and knowledge (e.g. effort levels, growth patterns, mortality, fecundity, etc.) and the effects of these limitations on the reliability of model outputs, we recommend that both a formal harvest strategy and detailed research and assessment plan are established as soon as possible rather than waiting for a new model to be developed and applied. When and if an integrated fishery assessment model is developed for the NT Mud Crab Fishery it could then be used to support a quantitative evaluation of the existing harvest strategy.

8.2 Status of the resource and uncertainty

Information provided in this report provides insights into the status of the NT Mud Crab Fishery which are both internally consistent and reflective of the findings of recent assessments of the fishery (e.g. Haddon *et al.* 2005). Perhaps most importantly, data presented here provide clear support for the assertion by Haddon *et al.* (2005) that the fishery was under stress in 2004 and that the “*harvest rate and/or fishing mortality is too high, and Uncontrolled, the situation may not be sustainable*”. Insufficient time has elapsed to assess how effective the new management arrangements (i.e. 10 mm increases in MLSs) that were introduced in May 2006 have been in reducing fishing mortality rates to sustainable levels and improving the status of the fishery.

The rapid declines in catch and CPUE that followed the high catches and catch rates in 2000 and 2001, and which led to the concerning situation identified by Haddon *et al.* (2005), appear to have resulted from poor recruitment after 2003. Catch and CPUE in 2006 were at their lowest levels since 1995 and provide compelling evidence to support the statement by Haddon *et al.* (2005) that the level of fishing mortality in 2004 was not sustainable. The increase in the number of grids fished during each fishing year that was associated with this decline in CPUE suggests that the decline in crab abundance may have been greater than indicated by raw CPUE alone.

Haddon *et al.* (2005) noted that catches and CPUE in the Queensland and NT Gulf of Carpentaria fisheries increased concurrently in 2000 and 2001, and suggested that this provided evidence that the underpinning increases in recruitment were driven by broad-scale environmental factors. We agree with this conclusion but note that since 2003 CPUE in the Queensland Gulf of Carpentaria Mud Crab Fishery has recovered to levels similar to those prior to the decline, whereas CPUE in the NT has not increased (Figure 8-1). The different trajectories of CPUE in the two fisheries could result from spatial differences in the environmental-drivers of recruitment or could reflect differences in the effectiveness of the management arrangements in the two fisheries. In this regard it is notable that the Queensland Mud Crab Fishery has a prohibition on the taking of females and the MLS for males is 150 mm (c.f. MLSs of 130 mm for males 140 mm for females in the NT up until 2006).

The mean size of crabs in catches from the Gulf of Carpentaria component of the NT Mud Crab Fishery declined from approximately 156 mm to 146 mm for males and 161 mm to 152 mm for females between 1997 and 2004, before increasing in 2006 following the introduction of the 10 mm increases in the MLS to 140 mm for males and 150 mm for females. The declines in mean size during the high catch years of 2000 and 2001 presumably reflect both strong recruitment during this period and rising exploitation levels. The low mean sizes recorded as catches declined from 2002 onwards are likely to reflect the dependence of the fishery on new recruits and

increasingly “knife-edge” selection during this period (see Haddon *et al.* 2005). The high proportion of females in catches taken from the Gulf of Carpentaria in recent years may also be reflective of the recent high rates of fishing mortality.

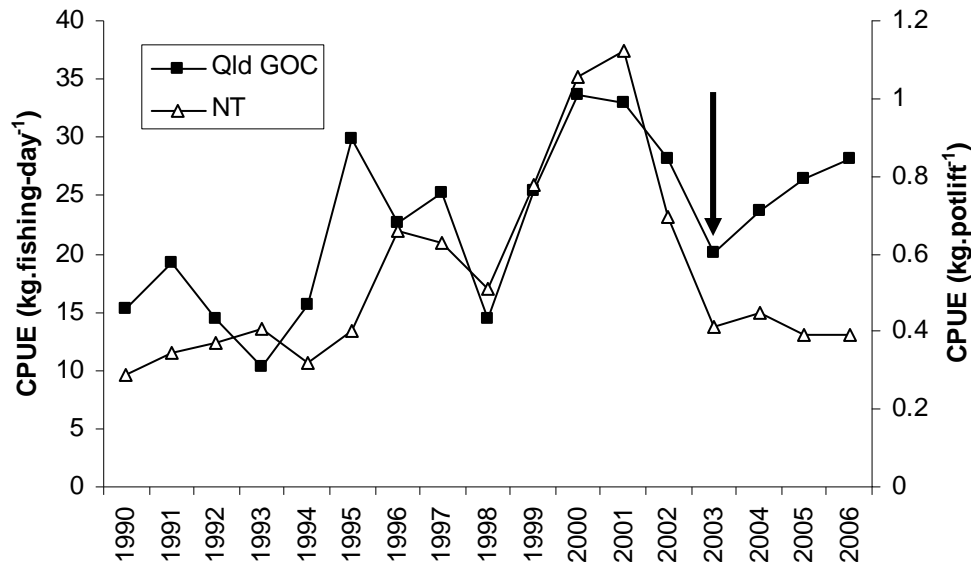


Figure 8-1. CPUE in the Queensland (kg.fishing-day⁻¹) and NT (kg.potlift⁻¹) Gulf of Carpentaria Mud Crab Fisheries from 1990 to 2006. Arrow indicates the last year of data available to Haddon *et al.* (2005).

Our results suggest that total mortality rates for NT mud crabs are very high (>4.0) in comparison to accepted estimates of natural mortality (~1.2) and support previous assertions that the fishing mortality rates are very high (e.g. Haddon *et al.* 2005). Knuckey (1999) suggested that exploitation rates reached 50% in the developmental phase of the fishery leading up to 1995, and that most crabs were caught during their first year in the fishery. Similarly, Walters *et al.* (1997) suggested that exploitation rates in fished areas were probably over 70% of the available stock and that the fishery depended heavily on newly recruited crabs and was probably fully exploited. Haddon *et al.* (2005) suggested that rates of fishing mortality in the period leading up to their assessment in 2004 may not have been sustainable. Our findings suggest that rates of fishing mortality in recent years are very high by international standards (e.g. Fischer and Wolff, 2006) and clearly support the assertion by Haddon *et al.* (2005) that a reduction in fishing mortality was needed following their assessment.

The options for reducing fishing effort identified by Haddon *et al.* (2005) included a closed season, closed areas, an increase in the minimum legal size, a reduction in the number of licences or other input controls and the introduction of a quota system. Haddon *et al.* (2005) noted that: (i) the introduction of a closed season would need to be accompanied by measures to prevent an increase in effort outside the closed season; (ii) that closed areas would be difficult to enforce; (iii)

introducing input controls that limited efficiency could have safety implications; and (iv) that an increase in the MLS would have limited effects at the high levels of fishing mortality that were occurring in the fishery. We would add that a quota system would be difficult to enforce in this remotely located fishery.

A representation to the NT Government made on behalf of fishers by Dr Ian Knuckey following the report by Haddon *et al.* (2005) argued against the introduction of a closed season, mainly because of the impacts of supply interruptions on market access. The letter by Dr Knuckey argued that an increase in the MLS was the most appropriate option to address the sustainability concerns raised by Haddon *et al.* (2005). Our analyses support these arguments and show that the MLS that is needed to maximise yield-per-recruit increases as rate of fishing mortality increases. Hence, our results confirm the suitability of the management decision to increase the MLS to address sustainability concerns raised by Haddon *et al.* (2005).

During the course of the present study, we were requested by representatives of the NT Crab Fishermen's Association to assess the relative benefits of 5 mm increases in MLS compared to the 10 mm increases that were introduced in May 2006. Our analyses suggest that the 10 mm increase in the MLSs was warranted and that a 5 mm increase in MLS would have had significantly less effect. Specifically, our analyses show that the 10 mm increases in the MLSs for males and female crabs were more than four times as effective as 5 mm increases would have been in protecting small crabs. However, accurately evaluating the effectiveness of different MLSs on the sustainability of the fishery would require more detailed knowledge of the patterns of growth and mortality than are currently available. This evaluation would be assisted by the development of an integrated fishery assessment model.

The limitations in current knowledge of growth and mortality rates, and other critical parameters such as effective effort, reduce the certainty associated with this and previous assessments of the NT Mud Crab Fishery. However, there is little doubt that the rates of fishing mortality in 2004 were too high and that some management intervention was required to address the concerns regarding the sustainability of the fishery raised by Haddon *et al.* (2005). It is important to note that the introduction of the increased MLSs responded to industry concerns regarding the implications of other management interventions for the economic viability of the fishery. Data provided in the present report suggest that the quantum of the changes was also sufficiently large to provide a reasonable chance of reducing rates of fishing mortality to more sustainable levels. It should be noted, however, that in situations where rates of fishing mortality are high, most of the catch is comprised of new recruits and if recruitment is variable, minimum legal sizes alone may

not be sufficient to ensure sustainability (see Haddon *et al.* 2005). The main options for augmenting MLSs in these situations are seasonal closures and/or finer scale spatial management.

During the course of this study, several industry representatives repeatedly identified the need to develop an integrated fishery assessment model for the NT Mud Crab Fishery. While we acknowledge the scientific benefits that such a model could deliver to the assessment of this fishery, especially in identifying the gaps and weaknesses in current datasets (as we have done here), we would caution against both prioritising the development of a integrated fishery assessment model above the collection of additional (more useful) data and aiming to use the outputs from any new model to develop a harvest strategy for the fishery over the next few years. This is because the serious limitations in the data currently available on key parameters (e.g. effort, growth, fecundity and mortality) will limit the reliability of outputs from any model in the short term. The development, testing and refinement of an integrated fishery assessment model will also be costly and probably take several years. In the short to medium term, i.e. up to 3-5 years, we suggest that the focus for the NT Mud Crab Fishery should be on the establishment of a harvest strategy that is underpinned by a research and assessment program that provides reliable data to inform management decision-making. Potential components of a research and assessment program to underpin future management of the NT Mud Crab Fishery are identified in the last section of this chapter. When a research and assessment program is established that provides for the ongoing collection of data to support assessment of the fishery, then the benefits of developing an integrated assessment model to conduct a quantitative evaluation of the harvest strategy that has been established will warrant serious consideration.

8.3 Implications for future harvest levels and patterns.

The timing of this assessment was not suitable for assessing the effectiveness of the increases in MLS in supporting recovery of the spawning biomass and fishery. This is partly because some of the data required to assess the status of the NT Mud Crab Fishery following the introduction of the new management arrangements, e.g. the 2007 catch and effort data, were not available for this assessment. We recommend that the current assessment be updated as soon as the data for 2007 become available, i.e. in early 2008. In the absence of this information, it is not appropriate for this study to provide detailed recommendations regarding future harvest levels or the possible need to introduce additional specific management arrangements to ensure the future sustainability of the fishery. Further recommendations of this type should not be considered until after the data for the 2007 fishing season are analysed and reported.

8.4 Recommendations for the Development of a Harvest Strategy

The absence of a formalised harvest strategy for the NT Mud Crab Fishery should be addressed as soon as possible, ideally before or while the analysis of data for the 2007 fishing season is undertaken. A suite of integrated objectives, strategies, performance indicators, reference points and decision rules needs to be established for the NT Mud Crab Fishery as a matter of high priority. The harvest strategy will need to specifically refer to the indigenous, recreational and commercial components of the fishery and must be informed by broader government policies regarding the allocation and transfer of resource access to and among these stakeholders. This broad policy perspective will have significant implications for the specific objectives that are established for the fishery, including the prioritisation of issues such as traditional access and ownership, and the relative economic and social benefits of recreational and commercial fishing to the broader NT community.

Once the objectives for the fishery are established it will be possible to develop strategies to achieve these objectives. When this is done, it will be relatively straight-forward to develop and prioritise the social, economic and biological performance indicators. The analyses and recommendations presented in this report provide a sound basis for beginning to assess the potential biological performance indicators and reference points. Potential biological performance indicators (some of which are already used) could include: catch, CPUE, mean size, proportion of immature females in catches, proportion of second instar females in catches, measures of relative abundance from fishery-independent surveys and spatially explicit measurements of fishing mortality from a PIT tagging program. The target and limit reference points that should be established for the performance indicators will vary in response to the specific objectives of the fishery. For example, if the key objective is to maximise yield then the reference points will be different to those that would be needed if the key objective is to ensure that catches are stable and CPUE is high (to minimise costs). The development of a formalised harvest strategy for the NT Mud Crab Fishery must involve meaningful input and participation from all stakeholders, but will also require the provision of clear advice by the NT Government regarding its policies and approaches to the management of multi-sectorial fisheries.

The assessment by Walters *et al.* (1997) identified the value of incorporating finer-scale spatial management systems into the NT Mud Crab Fishery. In particular, that assessment noted the benefits of linking individual licences to particular areas. We agree that such a system would deliver many benefits in terms of custodianship of the resource, but note that the move to such a system would be difficult to achieve without strong support from the majority of the industry. Such support may be difficult to garner given the potential risks of such a system to individual licence holders, e.g. from a major decline in abundance (from whatever cause) in an individual or

group's fishing area. If the territorial system of spatial management proposed by Walter *et al.* (1997) is not adopted, it is not immediately clear to us how greater spatial management could be introduced into the NT Mud Crab Fishery. This is because quotas, especially spatially explicit quotas, would be difficult to enforce in the remote areas where most fishing occurs. Hence, whilst we acknowledge the potential benefits of incorporating a greater level of spatial management into the NT Mud Crab Fishery, we cannot provide clear recommendations about how this outcome could be achieved in the short term.

8.5 Research to enhance future stock assessment

The harvest strategy that is developed for the NT Mud Crab Fishery must outline a research and monitoring program to address future stock assessment needs. This report provides a starting point for identifying components of the future research and monitoring program. The report shows that, as is the case in many fisheries, one of the main limitations to assessment of this fishery is the absence of unbiased estimates of relative/absolute abundance. Currently, the CPUE trend from the commercial sector provides the main insight regarding interannual changes in relative abundance, but the interpretation of this trend is impeded by uncertainties regarding both nominal and effective effort. One option for addressing the lack of information regarding interannual changes in relative abundance would be to instigate a program of fishery-independent surveys in key parts of the fishery. These surveys could be conducted by fishers on commercial vessels with scientific observers aboard with the proceeds from survey catches used to offset survey costs. This approach has proven to be very useful in several South Australian fisheries (e.g. Currie *et al.* 2007). As well as providing valuable information on the relative abundance of crabs in key parts of the fishery, this approach has the additional advantage of strengthening relationships between fishers, scientists and fisheries managers. For fishery-independent surveys to succeed in improving future assessment and management of the NT Mud Crab Fishery, this approach would need to be strongly supported by industry and be established as part of an integrated research and assessment program for the fishery.

Another key priority for future research and assessment of the NT Mud Crab Fishery is the collection of additional information on the patterns and rates of growth and mortality. To succeed, growth studies must involve the collection of data from large crabs. One option for obtaining data from large crabs would be to establish one or more research areas where commercial and recreational fishing are prohibited. However, this approach may not be attractive to fishers and may be difficult to enforce in this remote fishery. Another option would be to establish a monitoring program that utilises passive integrated transponder (PIT) tags. This approach could be integrated with the (potential) program of fishery-independent surveys with some of the captured crabs (e.g. large females) being PIT tagged and released by scientific

observers. Similarly, the (existing) market sampling program for NT mud crabs could be expanded to include screening for PIT tags. A major scientific benefit of this approach would be the acquisition of spatially explicit measurements of fishing mortality which would significantly enhance future stock assessments of this heavily exploited resource. Funding could potentially be sought from the Fisheries Research and Development Corporation to assist in the development of a stock assessment system that integrates fishery-independent surveys and a PIT tagging program to provide spatially explicit measures of relative abundance, size and fishing mortality.

Information on the reproductive biology and ecology of NT mud crabs (e.g. relationship between size/age and fecundity; behaviour of females between mating and their offshore migration) is needed to assess the suitability of various management options (e.g. increases in MLS, seasonal closures) that have and could be established in the NT Mud Crab Fishery. A cost effective way of obtaining this reproductive information and developing a population model would be to instigate a Ph.D. study of the ecology and population dynamics of mud crabs in the NT. This study could develop a population model for mud crabs that would assist the development of an integrated stock assessment model for the NT Mud Crab Fishery.

One of the main short-term objectives for the NT Mud Crab Fishery should be to establish a coherent and effective program for ongoing stock assessment to underpin future management of the fishery. The establishment of such a program will not be done most effectively by periodically appointing external consultants to conduct one-off stock assessments over a short period of time using whatever data are available. Rather, an ongoing program for the collection, analysis and reporting of data should be established to explicitly underpin the harvest strategy. Such a program would ideally be conducted by scientists located in the NT who work closely with fisheries managers and industry. If scientists from outside the NT are contracted to support local scientists, then this support would ideally be provided at a low level over a period of several (3-5) years, rather than more intensively during the few months required to complete an individual assessment. The ongoing involvement of local (and potentially remote) scientists is recommended because it would reduce the proportion of time spent by individual scientists developing their knowledge of the species, fishery and data and enable these scientists to focus their efforts on refining (rather than reinventing) the approach to stock assessment. The most appropriate role for scientists from outside the NT is to support local staff to refine approaches to monitoring and stock assessment. This approach would be enhanced by periodic independent review of stock assessment reports.

Establishing a coherent and effective program for ongoing stock assessment of the NT Mud Crab Fishery will require the acquisition and allocation of adequate funds to support this process.

Significant funding is needed because the NT Mud Crab Fishery is fully developed with high rates of fishing mortality and significant potential for over-exploitation. Where this funding should come from is a key question for all stakeholders in the fishery. Currently, stock assessment is funded solely by the NT Government. However, in most Australian jurisdictions, industry (through licence fees) usually contributes significantly to the costs of undertaking stock assessments of fully developed fisheries. The absence of a coherent and effective ongoing program for stock assessment of the NT Mud Crab Fishery can be directly related to the combined effects of limited government funding and the absence of a system for recovering research costs from industry. Future management arrangements for the fishery should reflect the accuracy and precision of information on stock status, which will be largely determined by the level of investment in research, monitoring and assessment. If the quality of information available to assess stock status remains low, then future management arrangements should be precautionary. Conversely, if stock status is monitored carefully and assessed regularly, a less conservative harvest strategy could be established.

Members of the NT Mud Crab Fishery should play a significant role in determining the future direction of the fishery. Identifying management objectives for inclusion in the management plan will be a critical element of this process. If a key objective of the fishery is to maximise yield, there will be a need to establish a significant ongoing research, monitoring and assessment program to manage the risks of overfishing that are associated with high exploitation rates. If the key management objective is to achieve stability and minimise fishing costs by establishing lower exploitation rates and minimising the risks of overfishing, then the need for investment in research, monitoring and assessment would be considerably lower.

REFERENCES

- Currie, D.R., Hooper, G.E. and Ward, T.M. (2007). Blue Crab (*Portunus pelagicus*) Fishery 2005/06. Stock Assessment Report to PIRSA Fisheries. South Australian Research and Development Institute (Aquatic Sciences). RD 03/0274-4, Adelaide.
- Fischer, S., Wolff, M., 2006. Fisheries assessment of *Callinectes arcuatus* (Brachyura, Portunidae) in the Gulf of Nicoya, Costa Rica. Fisheries Research (Amsterdam) 77, 301-311.
- Gopurenko, D., Hughes, J.M., 2002. Regional patterns of genetic structure among Australian populations of the mud crab, *Scylla serrata* (Crustacea:Decapoda): Evidence from mitochondrial DNA. Marine and Freshwater Research 53, 849-857.
- Haddon, M., Frusher, S., Hay, T., Hearnden, M., Gribble, N., Brown, I., 2005. Mud Crab (*Scylla serrata*) Assessment Workshop. Fisheries Group, Department of Business, Industry and Resource Development, Darwin, p. 30.
- Hay, T., Gribble, N., de Vries, C., Danaher, K., Dunning, M., Hearnden, M., Caley, P., Wright, C., Brown, I., Bailey, S., Phelan, M., 2005. Methods for monitoring the abundance and habitat of the northern Australian mud crab *Scylla serrata*. Fisheries Research and Development Corporation, p. 112.
- Henry, G.W., Lyle, J.M., 2003. The National Recreational and Indigenous Fishing Survey. . p. 190
- Hilborn, R., Walters C. J., 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. Chapman and Hall, New York. 570 p.
- Imai, H., Cheng, J.H., Hamasaki, K., Numachi, K., 2004. Identification of four mud crab species (genus *Scylla*) using ITS-1 and 16S rDNA markers. Aquat. Living Resources. 17, 31-34.
- Keenan, C.P., Davie, P.J.F., Mann, D.L., 1998. A revision of the genus *Scylla* de Haan, 1833 (Crustacea : Decapoda : Brachyura : Portunidae). Raffles Bull. Zool. 46, 217-245.
- Knuckey, I.A., 1999. Mud Crab, *Scylla serrata*, Population Dynamics in the Northern Territory, Australia and their Relationship to the Commercial Fishery.
- Knuckey, I.A., Davie, P.J.F., Cannon, L.R.G., 1995. *Loxothylacus iblei* Boschma, (Rhizocephala) and its effects on the mud crab, *Scylla serrata* (Forsk.) in northern Australia. Journal of Fish Diseases 18, 389-395.
- Ong, K.S., 1966. Observations on the post larval life-history of *Scylla serrata* Forskal, reared in the laboratory. Malaysian Agric. J., 45(4) : 429-433.
- Walters, C., Buckworth, R., Calogeras, C., Hay, T., Knuckey, I., Ramm, D., 1997. Status and Future Development Potential of the Mud Crab Fishery. In: Ramm, D. (Ed.), Towards the Sustainable Use of Northern Territory Fishery Resources: Review Workshops Led by Carl J. Walters. Northern Territory Department of Primary Industry and Fisheries, Darwin, p. 33.

APPENDIX 1

Draft

Analysis of length data from the Northern Territory's Mud Crab fishery

N. G. Hall
June 5, 2007

Summary

Two new methods of analysis were applied to the length composition data, both of which assumed equilibrium conditions and that growth followed a von Bertalanffy curve. Another new approach, which was intended to estimate natural mortality from the data resulting from the change in minimum size that was introduced for female crabs in 1996, proved to be of little value as few crabs within the size range affected by the size limits are represented in the catches from the fishery. Estimates of total mortality derived from the analyses of data from Roper River using both methods produced very high estimates of total mortality. There was a suggestion that total mortality had increased slightly in more recent years and that the average size at which crabs enter the exploited stock had declined. Please note, however, that these results have not yet been subjected to scrutiny and criticism by scientists familiar with both the data and the species and, until endorsed by those scientists, should be viewed with caution. However, the methods of length composition analysis described in this brief note appear to show considerable promise for use in future assessment of the Mud Crab fishery.

Details of analysis

Size composition data from the Northern Territory Mud Crab fishery were kindly provided by DPIFM. These data comprised 57,504 observations of the carapace width of individual crabs measured between 1990 and 2006 from sites at Joseph Bonaparte Gulf, Van Diemen Gulf, Gulf of Carpentaria, Beagle Gulf, Arnhem Land and other locations. C-AID Consultants (2001) report that the minimum carapace width (CW) for female Mud Crabs was increased from 130 mm to 140 mm in 1996. They note that, in 2001, the minimum size for male crabs remained set at 130 mm CW and that experimental work had indicated that crabs would attain this size in approximately 12 months. The minimum sizes for males and females retained by commercial fishers subsequently increased to 140 and 150 mm CW in 2006, but remained at 130 and 140 mm CW for recreational fishers (Northern Territory of Australia, 2006). The values of the parameters L_{∞} and K of the von Bertalanffy growth curve estimated by Knuckey (1999) were 193.6 mm carapace width (CW) and 1.14 year^{-1} , respectively. The data for females from Adelaide and Roper Rivers were selected for more detailed analysis.

It rapidly became apparent when attempting to apply the model that estimated growth from data reflecting a change in minimum size that the data for the Northern Territory Mud Crabs were not representative of the full size distribution of the stock. For example, only 24 of the 2,728 crabs measured at Adelaide River following the change in minimum size fell within the size class from 130 to 139 mm (Figure 1). Thus, it appears that the samples that were collected are those of the retained catch rather than being representative of the individuals in the stock. Moreover, the crabs do not become fully vulnerable to capture until they attain a carapace width of 140 to 160 mm. Clearly, the assumptions of the method that employs the changes in the size composition between the old and new minimum sizes to estimate natural

mortality were not satisfied for these data. Accordingly, further exploration was undertaken to determine whether information on total mortality might be derived from the data.

A Wetherall plot of the mean carapace width of female crabs greater than specified widths at first capture and those widths at first capture for crabs collected in samples of catches from the Adelaide River, Joseph Bonaparte Gulf, between 1990 and 1995 and 1996 and 2006 revealed a linear trend until the width at first capture was approximately 150 mm, followed by an apparently exponential decline as the crabs approach the maximum recorded width (Figure 2) (Wetherall *et al.*, 1987). The initial linear trend is, however, an artefact of the model (arising from the fact that the mean length of crabs greater than a specified size does not change until the specified size reaches the length at which the crabs become vulnerable to the fishery). The curve that becomes evident at about 140 to 150 mm CW suggests that the Mud Crabs enter the exploited stock at about this size. The subsequent linear trend provides information that allows estimation of the ratio Z/K and L_∞ , or, if L_∞ and K are known, an estimate of Z . To avoid the subjective nature of analyses using the Wetherall approach, i.e. determining where to apply the length cut-offs for the data to be analysed, a model was developed to fit a curve derived from the mean length of fish above a specified length, allowing for a logistic function describing the increasing vulnerability of fish as they become exposed to the fishery. A re-sampling method was developed to provide approximate estimates of the 95% confidence limits for the parameter estimates.

For years where adequate data were collected, there is a reasonably good fit to the observed data, e.g. Fig 3. Estimates of total mortality are, however, extremely high (e.g. 5.52 (95% C.I. 5.12 to 6.09) for Roper River Sex 1 Mud Crabs in 2005) and appear consistent with the view that appears to be held by DPIFM scientists that the fishery is heavily exploited. The data suggest that total mortality has increased slightly in more recent years (Figure 4). A disturbing sign of recent years is the decrease in recent years in the average size at which the Mud Crabs of sex 1 at Roper River become vulnerable to capture by the fishery (Fig 5) and the prospect that the legal minimum size that was applied is likely to have been of limited effectiveness in protecting crabs.

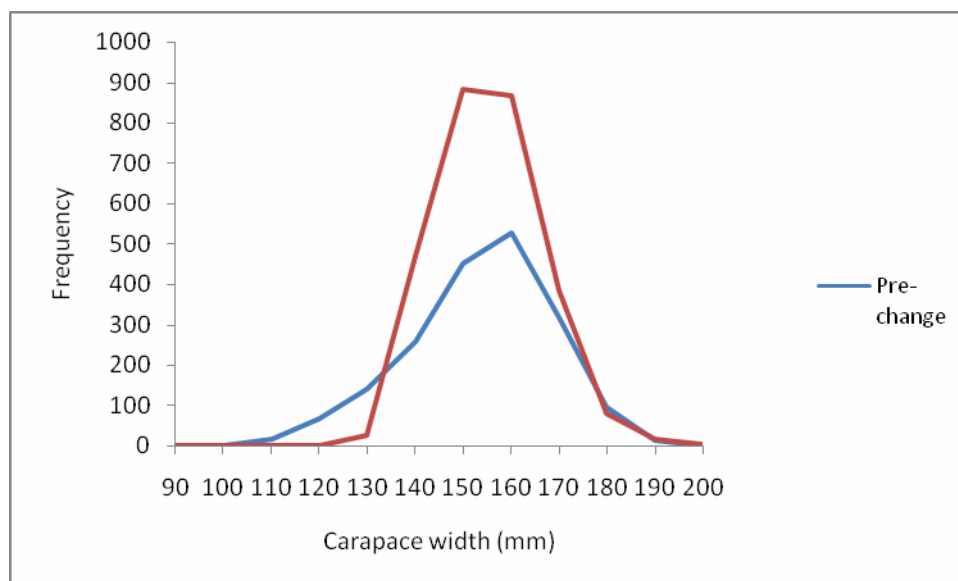


Figure 1. Size composition of female Mud Crabs sampled from catches taken at Adelaide River, Joseph Bonaparte Gulf, between 1990 to 1995 and 1996 to 2006, i.e. prior to and following the change in minimum size from 130 to 140 mm CW.

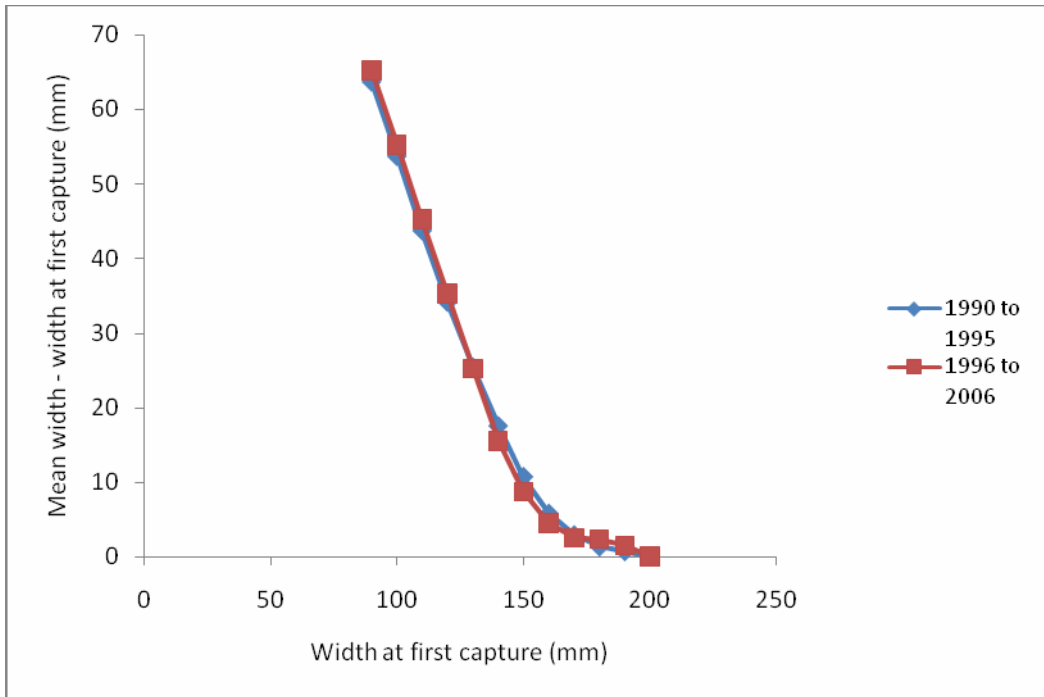


Figure 2. The relationships between the mean carapace width of crabs greater than the specified width at first capture and the width at first capture from female crabs collected in samples of catches from the Adelaide River, Joseph Bonaparte Gulf between 1990 and 1995 and 1996 and 2006.

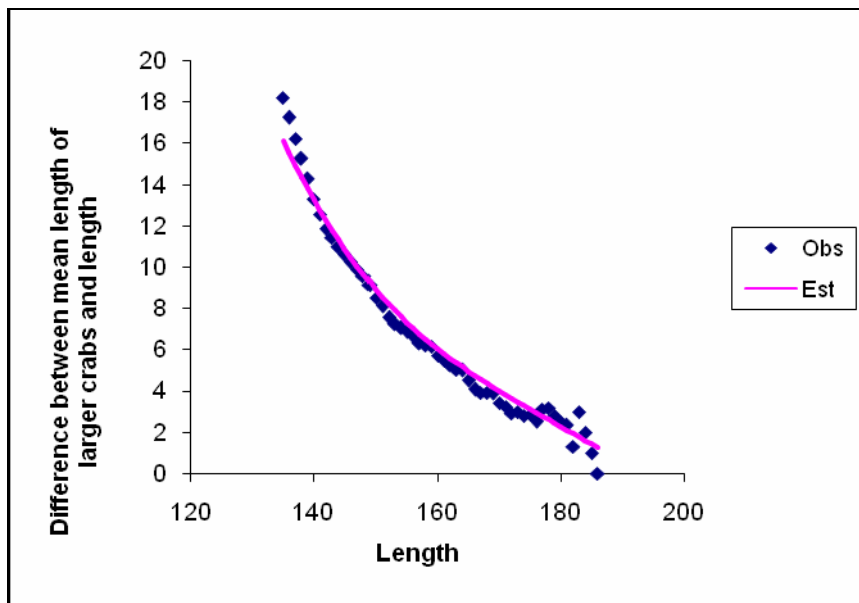


Figure 3. Wetherall plot for Mud Crabs (with a sex code of 1) from the Roper River in 2005 with curve predicted using the new model.

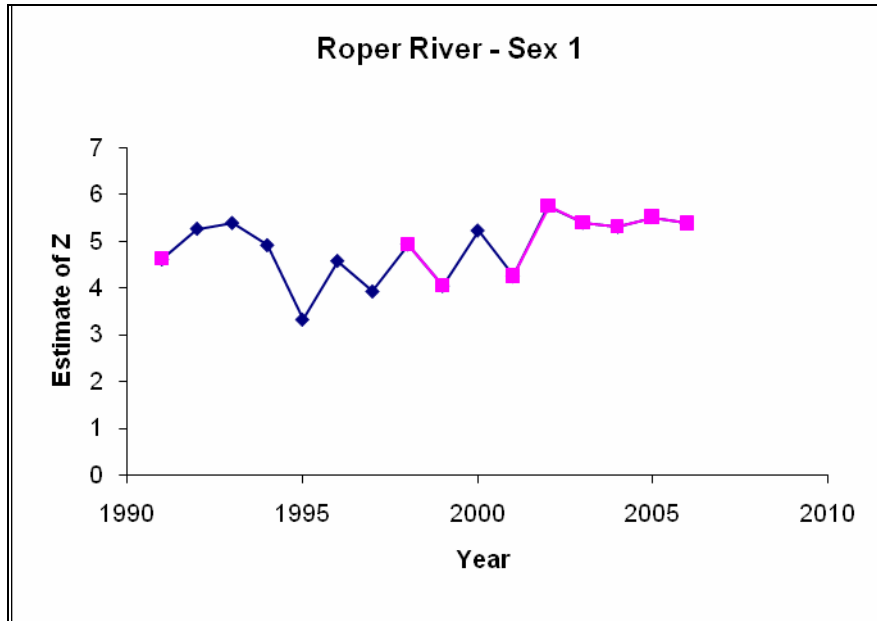


Figure 4. Estimates of total mortality derived for Mud Crabs with sex code 1 from the Roper River using the enhanced Wetherall analysis. Values shaded in pink are derived from samples in excess of 350 crabs.

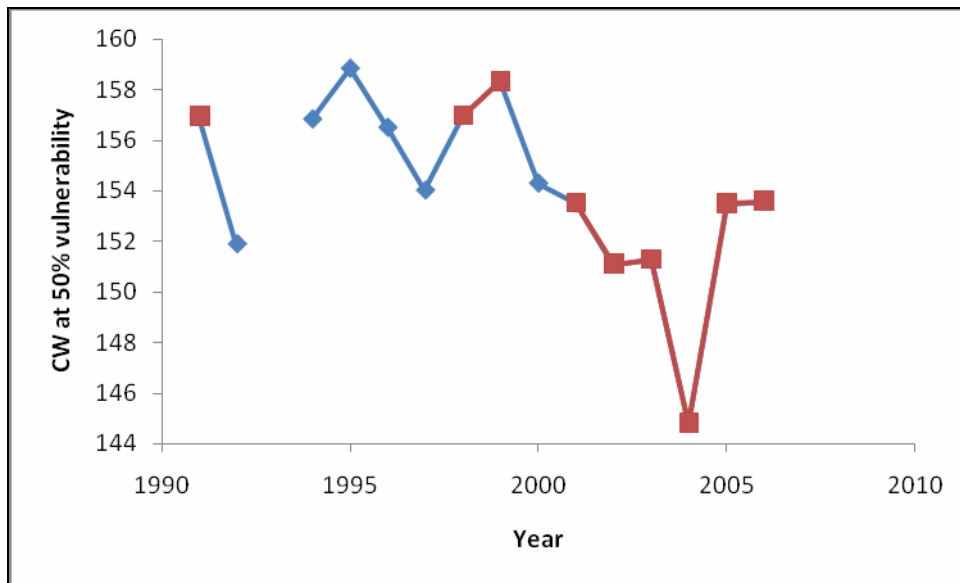


Figure 5. Estimates of the carapace width at which 50% of the crabs of sex 1 at Roper River are vulnerable to capture. Points shaded in red are derived from samples in excess of 350 crabs.

The enhanced Wetherall model, however, does not take the natural variability around the expected values predicted by the von Bertalanffy growth curve into account. Accordingly, a new model was developed to produce an estimate of the length distribution of the catch. In this model, the expected length at age t is assumed to be described by a von Bertalanffy growth curve, with parameters L_{∞} , K , and t_0

$$E_t = L_{\infty} \{1 - \exp[-K(t - t_0)]\}$$

The value of the normal pdf for the observed length, L , given that the fish is of age t , under the assumption that observed lengths have a normal distribution (with common standard deviation s) about the von Bertalanffy growth curve is

$$\phi_t = \frac{1}{\sqrt{2\pi s^2}} \exp\left[-\frac{(L - L_t)^2}{2s^2}\right]$$

The probability of capture of a fish of the given observed length is calculated as

$$S = \frac{1}{1 + \exp\left[-\ln(19) \frac{L - L_{50}}{L_{95} - L_{50}}\right]}$$

The probability that a fish is of age t , under the assumption of constant and continuous recruitment and constant total mortality Z is $Z \exp(-Zt)$, where t is assumed to range from 0 years to (say) 100 years. Note that this is equivalent to an assumption of constant annual recruitment and total mortality, where sampling intensity is constant throughout the year. Thus, the probability that a fish is of length L and of age t is $Z \phi_t \exp(-Zt)$. The relative probability of collecting a fish of length L , which is assumed to be the probability of catching and observing a fish of length L given that the fish is of any age between 0 and 100 years, is therefore

$$P(L) = Z S_L \int_0^{100} \phi_t \exp(-Zt) dt$$

The observed lengths are classified into length classes, L_k , where k is the number of the length class and $1 \leq k \leq n$, L_k is the midpoint of the length class and n_k is the number of fish lying within the length class. Accordingly, the probability that a fish lies within length class k may be calculated as

$$p_k = \frac{P(L_k)}{\sum_{j=1}^n P(L_j)}$$

The log-likelihood is calculated with the assumption that the frequency distribution represents a sample from a multinomial distribution, i.e.

$$\lambda = \sum_{k=1}^n n_k \ln(p_k)$$

Estimates of the parameters L_{∞} , K , t_0 , Z , L_{50} , L_{95} , and s may be obtained by maximising the value of the log-likelihood. The model is further simplified by setting $t_0 = 0$ years.

Note: Alternative growth curves may be substituted for the von Bertalanffy growth curve. A routine to estimate the approximate 95% confidence limits for Z was implemented by calculating the likelihood profile for this parameter.

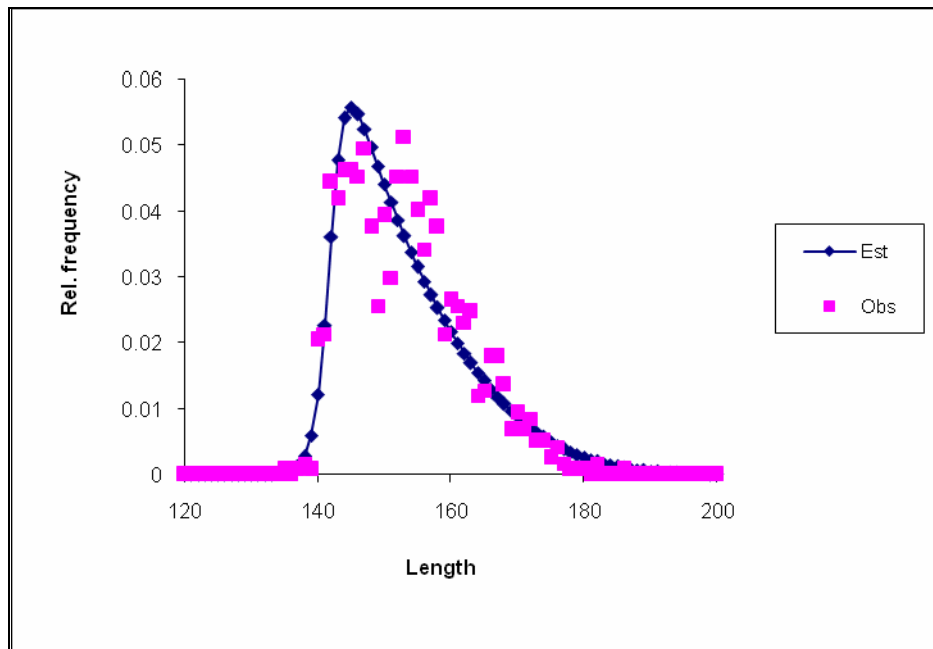


Figure 6. Observed and predicted relative length distribution of Mud Crabs of sex 1 from Roper River in 2005, in which Z is estimated to be 4.5 year^{-1} .

The new Length distribution method appears to show considerable promise for size composition data such as that which have been collected for the Northern Territory Mud Crabs, e.g. Figure 6. The resulting estimates of Z are consistent with those obtained from the Wetherall method, however. For example, an estimate of 5.20 year^{-1} was obtained by fitting the length distribution for the data for individuals of sex=1 from Roper River in 2006 compared with an estimate of 5.39 year^{-1} using the enhanced Wetherall approach. It should be noted that, if, as assumed in the 2004 Mud Crab assessment workshop, natural mortality is of the order of 1.2 year^{-1} (Fisheries Group, 2004), the mortality associated with fishing is extremely high.

The approaches that have been used to analyse the length composition data for the Northern Territory's Mud Crab fishery appear to hold considerable promise for future assessment and management of this resource.

References

- C-AID Consultants. 2001. Assessing the ecological sustainability of the Northern Territory Mud Crab fishery. A report prepared for Environment Australia as required for assessment under guidelines for Schedule 4 listings under the Wildlife Protection (Regulation of Exports and Imports) Act 1982.
- Fisheries Group. 2004. Mud Crab (*Scylla serrata*) Assessment Workshop. Department of Business, Industry and Resource Development, Darwin Northern Territory. Fisheries Report No. 79.
- Knuckey, I. A. 1999. Mud Crab, *Scylla serrata*, Population Dynamics in the Northern Territory, Australia and their Relationship to the Commercial fishery, Ph.D. thesis.
- Northern Territory of Australia. 2006. Mud Crab Fishery Management Plan Northern Territory Government Gazette, Darwin, Northern Territory of Australia.
- Wetherall, J.A., J.J. Polovina and S. Ralston. 1987. Estimating growth and mortality in steady-state fish stocks from length-frequency data, p. 53-74. In D. Pauly and G.R. Morgan (eds.) Length-based methods in fisheries research. ICLARM Conference Proceedings 13, 468 p. International Center for Living Aquatic Resources Management, Manila, Philippines, and Kuwait Institute for Scientific Research, Safat, Kuwait.