

The development and application of a length-based method to estimate the spawning potential ratio in data-poor fish stocks

Adrian Robert Hordyk

This thesis is presented for the degree of
Doctor of Philosophy of Murdoch University

2014



MURDOCH
UNIVERSITY
PERTH, WESTERN AUSTRALIA

Declaration

I declare that this thesis is my own account of my research and contains as its main content work which has not been submitted for a degree at any tertiary education institution.

.....

Adrian Robert Hordyk

Abstract

Although they support many millions of people, the vast majority of the world's fisheries are small-scale and data-poor, and without the resources or data systems needed for comprehensive stock assessments. There is strong evidence that unmanaged fisheries are a recipe for disaster, with over-exploitation of the stock almost inevitable. Additionally, it is increasingly recognised that the spatial scale of the stocks of many marine species is much smaller than previously thought, which adds another layer of cost to the stock assessment process, as the cost of collecting and analysing such fine-scale data is prohibitive. The overall aim of this thesis was to develop and test novel methods of stock assessment for data-poor and small-scale fisheries, based on the basic biological characteristics of the exploited species.

Knowledge of the basic biological parameters of fish stocks, such as the natural mortality rate (M), the growth parameters (commonly described by the von Bertalanffy equation, L_∞ and k), and the length at maturity (L_m), is important for many stock assessment methodologies. However, collecting such information is costly, and usually requires sophisticated ageing studies. I conducted a meta-analysis of over 120 marine species, from a range of taxa including teleosts, chondrichthyans, mammals and invertebrates, and examined the variation and patterns in the life-history ratios, and the relationships between size and spawning potential (Chapter 2). These patterns were examined by standardising the age and size of each species so that the relationship between size and spawning-per-recruit for a large range of diverse species could be compared on the same scale. This meta-analysis demonstrated that species that are often considered to be quite different, essentially have the same life-history strategy when viewed on the same relative scale. For example, tuna can be considered as 'larger, slower', anchovies, while prawns are 'smaller, faster' versions of fish. Additionally, and somewhat surprisingly, a number of teleosts with low $\frac{M}{k}$ values of ≤ 0.5 appear to have life-histories similar to marine mammals, and quite different from those expected of fish. The results of this study suggest that there is potential to establish a theoretical framework for 'borrowing' knowledge from well-studied species to apply to unstudied species and populations as an initial starting point for management.

The ratios of these parameters ($\frac{M}{k}$ and $\frac{L_m}{L_\infty}$) are less variable between individual stocks of the same species than the individual parameters, and certain values of these ratios ($\frac{M}{k} = 1.5$ and $\frac{L_m}{L_\infty} = 0.66$), known as the Beverton and Holt Life History Invariants (BH-LHI) have been used commonly to provide preliminary estimates of unknown parameters. However, many species have life-history ratios that vary considerably from the BH-LHI, and in this study I demonstrate the link between variation in the ratios ($\frac{M}{k}$ and $\frac{L_m}{L_\infty}$) and the life-history strategy of a species. For example, species with low $\frac{M}{k}$ (e.g., $\frac{M}{k} \leq 0.5$)

mature, and reach maximum size, early in life; i.e., have determinate growth and unfished populations dominated by large, mature, individuals. Conversely, species with higher $\frac{M}{k}$ (e.g., $\frac{M}{k} = 3.0$) mature at a smaller relative size, and have indeterminate growth. I developed analytical models to examine the relationship between these ratios and length structure, growth pattern, spawning-per-recruit, and the spawning potential ratio (SPR) for exploited stocks (Chapter 3). These analytical models were extended to include more realistic assumptions about maturity and selectivity-at-length, and a model that uses knowledge of the life-history ratios, and data on the length structure of the catch, was developed to calculate the SPR, an internationally recognised measure of stock status; the length-based SPR model (LB-SPR).

The key parameters of the LB-SPR model are: $\frac{M}{k}$, L_∞ , and the variation in length-at-age (CV_{L_∞}), as well as information on the size of maturity (L_m). The utility of the LB-SPR model, and its sensitivity to violations of the main assumptions, was examined using Monte Carlo simulations (Chapter 4). Length data were generated for four different species, reflecting different life-history strategies, and the variation of the estimated SPR was examined in a number of scenarios, including: misspecification in the input parameters, the number of fish measured, presence of dome-shaped selectivity, and recruitment variability. The results demonstrate that the model returns unbiased estimates of SPR, and performs well when the biological parameters are well known and the stock is at, or near, equilibrium. However, the model is sensitive to misspecification in the input parameters, particularly to L_∞ , where SPR can be significantly under- or over-estimated if L_∞ is not close to the true value. With high recruitment variability, the variation in estimates of SPR from the equilibrium-based LB-SPR model becomes greater, particularly when recruitment trends are auto-correlated. The results of the sensitivity tests indicate that the LB-SPR model has potential to provide a tool for rapid and cost-effective estimation of SPR for data-poor fisheries, which could be used for guiding management decisions and prioritising the direction of future research. Nevertheless, the results also showed that care must be taken to evaluate the validity of the assumptions of the LB-SPR model, and the precision of the biological parameters for the relevant stock, when interpreting the results of the model.

Fisheries managers usually make their decisions in response to estimates of the stock status. For example, if the stock is estimated to be below some target reference point, managers may choose to reduce catches or fishing effort to allow the stock to rebuild. The linking of the status of the stocks and the management decisions are often done by means of a harvest control rule (HCR), which defines a pre-determined agreed response to the estimated status of the stock. I developed a simulation model to perform a management strategy evaluation (MSE) to test a HCR that links the estimates of the SPR from the LB-SPR model to an appropriate management decision (Chapter 5). Three species, representing different life-history types, were investigated and the performance of the model was examined under a number of different scenarios, including: increased recruitment variability, dome-shaped selectivity, and time-varying natural mortality. The results indicate that

the LB–SPR HCR is capable of recovering an over-exploited stock within an acceptable time-frame. The results also demonstrate that care must be taken when setting SPR target reference points, especially when the biology of the species is not well known, and when recruitment is highly variable.

The developments of this thesis highlight the potential of applying a simple methodology to assessing and managing data-poor stocks, requiring only basic information on life-history and length composition of the catch. A framework was established for using knowledge from well-studied species to inform data-poor stocks, which allows initial estimates of the stock status to be made with only minimal data requirements. The methodology developed in this thesis thus provides a cost-effective, easily understood, and transparent method for estimating the SPR for data-poor and small-scale fisheries with only minimal data requirements, and thus allows managers and other stakeholders to begin making informed decisions without having to wait for the collection of additional data. In this respect, the LB–SPR model developed and demonstrated in this study provides a starting point for the assessment of data-poor and small-scale stocks, and assists in identifying important data gaps, prioritising research and collecting information to validate the unknown biological parameters, and beginning the process of gathering additional data to allow alternative assessment methods to be applied in the future (e.g., a time-series of total catches). Finally, this study has also identified areas for additional research, particularly further empirical testing of the LB–SPR model and the development of an integrated harvest strategy framework based on SPR reference points (Chapter 6).

Contents

Abstract	iii
List of Figures	ix
List of Tables	xiii
Acknowledgments	1
Dedication	3
Publications resulting from this study	4
1 General Introduction	5
1.1 Introduction	5
1.2 The status of the world's fisheries	6
1.3 Small-scale and data-poor fisheries	7
1.4 The need for alternative methods	8
1.5 Empirical methods and rules-of-thumb for data-poor fisheries	10
1.6 Life-history invariants	12
1.7 Research and structure of the thesis	13
2 Revisiting the concept of Beverton–Holt Life History Invariants with the aim of informing data-poor fisheries assessment	16
2.1 Introduction	16
2.2 Methods	18
2.2.1 Selection of parameter sets	18
2.2.2 Spawning potential ratio (SPR) model for the meta-analysis	20
2.2.3 Simulation of length composition	22
2.3 Results	22
2.4 Discussion	29
2.5 Conclusions	33
3 Some explorations of the life history ratios to describe length composition, spawning-per-recruit, and the spawning potential ratio of fished species	35
3.1 Introduction	35
3.2 Analytical models	37

3.2.1	Redefining the von Bertalanffy equation in terms of $\frac{M}{k}$	37
3.2.2	Number of animals at age in terms of $\frac{M}{k}$	39
3.2.3	Changing the scale of M and k	41
3.2.4	Relative biomass at age and length in terms of $\frac{M}{k}$	43
3.2.5	Estimating SPR from $\frac{M}{k}$, $\frac{F}{M}$ and $\frac{L_m}{L_\infty}$ with simple assumptions . . .	45
3.2.6	Estimating SPR from $\frac{M}{k}$, $\frac{F}{M}$ and $\frac{L_m}{L_\infty}$ with knife-edge selectivity . .	46
3.2.7	Fished length composition in terms of $\frac{M}{k}$ and $\frac{F}{M}$	47
3.2.8	Incorporating variation in length-at-age	48
3.2.9	Resolving the issue of non knife-edge selectivity	51
3.3	Conclusion	55
4	A novel length-based empirical estimation method of spawning potential ratio (SPR), and tests of its performance, for small-scale, data-poor fisheries	57
4.1	Introduction	58
4.2	Methods	59
4.2.1	Operating model	60
4.2.2	Estimation model	63
4.2.3	Simulation and evaluation	66
4.2.4	Preliminary empirical test	69
4.3	Results	71
4.4	Discussion	78
4.4.1	Influence of variation in parameters on estimating SPR	79
4.4.2	Representative length data	81
4.4.3	Dynamic effects on estimating SPR	82
5	An evaluation of a harvest strategy for data-poor fisheries using the length-based SPR assessment method	85
5.1	Introduction	85
5.2	Methods	87
5.2.1	Management Strategy Evaluation	87
5.3	Results	97
5.3.1	Comparison of the linear and logarithmic harvest control rules . .	97
5.3.2	Relative error in the parameters estimated by the LB-SPR method	101
5.3.3	Performance of the LB-SPR management strategy	101
5.4	Discussion	109
6	General Conclusion	118
6.1	Introduction	118
6.2	Significance of findings and implications for management	119
6.3	Avenues for further research	123

References	127
Appendix A Biological parameters of the 123 species used in the meta-analysis (Chapter 2)	144
Appendix B Extended derivations for Chapter 3	164
Appendix C Population dynamics model for Chapter 5	168
Appendix D Simulation model to estimate L_{∞} from length composition of the catch	172
D.1 Introduction	172
D.2 Methods	172
D.3 R Code	175
D.4 Use of the model	176

List of Figures

2.1	Observed relationships for 123 selected marine species between spawning potential ratio (SPR) and (a) standardised weight, (b) standardised length, (c) standardised age, and (d) weight standardized for size of maturity and maximum weight.	24
2.2	Simulated length frequency histograms illustrating how the size compositions of unfished populations are determined by the $\frac{M}{k}$ ratio for a species'. The range of $\frac{M}{k}$ ratios (0.1 to 4.0) chosen for simulating these histograms was based on the range of ratios observed in the meta-analysis of 123 species.	25
2.3	The relationship between relative length of maturity in (a) the 123 marine species selected for this meta-analysis; and (b) nine teleost families with more than three species plotted against the $\frac{M}{k}$ for each species.	28
2.4	Observed relationships between the spawning potential ratio (SPR) and (a) standardised weight, (b) standardised length, (c) standardised age for the three most numerous teleost families in the meta-analysis.	29
2.5	The relationship between asymptotic length and $\frac{M}{k}$ for a) 109 marine species in the database with $L_{\infty} \leq 200$ cm and b) nine teleost families with more than three species, for those species with asymptotic size ≤ 200 cm.	30
3.1	The standardised von Bertalanffy growth curves for fish at standardised length and standardised age from Equation 3.5 for $\frac{M}{k}$ ranging from 0.3 to 2.3.	39
3.2	The probability of a fish in the unfished state surviving to standardised length from Equation 3.10 for a range of $\frac{M}{k}$ (0.3–2.3).	41
3.3	The probability distribution of length for an unfished stock for four values of the ratio $\frac{M}{k}$: 0.6, 0.9, 1.5 & 3.0.	42
3.4	The relative biomass as a function of a) standardised age and, b) standardised length for a range of $\frac{M}{k}$ (0.3–2.3).	44
3.5	The spawning potential ratio (SPR) for a range of $\frac{F}{M}$ (0–3) and $\frac{M}{k}$ (0.3–2.3).	46
3.6	The expected standardised length composition for an unfished stock with variable length-at-age ($CV_{L_{\infty}} = 0.1$), and $\frac{M}{k}$ values of 0.6, 0.9, 1.5 & 3.0.	50
3.7	The expected standardised length composition for the catch for a fished stock with knife-edge selectivity at $L_c = 0.40$, and variable length-at-age.	52
3.8	The expected standardised length composition for the catch for a fished stock with logistic selectivity, and variable length-at-age.	55

4.1	The five selectivity curves used to assess the sensitivity of the length-based SPR model to length data from a fishery with dome-shaped selectivity for Species I, II, III and IV.	70
4.2	The relative error (RE) in the estimated $\frac{F}{M}$ and resulting estimate of the spawning potential ratio (SPR) for the four simulated species for a) Test 1: misspecification of $\frac{M}{k}$, b) Test 2: misspecification of L_{∞} , c) Test 3: misspecification of $CV_{L_{\infty}}$, and d) resolution of the age-structured estimation model (X).	71
4.3	Boxplots showing the 5 th , 25 th , 50 th , and 95 th percentiles of the relative error (RE) in the estimated $\frac{F}{M}$, L_{S50} , L_{S95} and resulting estimate of the spawning potential ratio (SPR) for a range of sample sizes for a) Species I, b) Species II, c) Species III, and d) Species IV.	73
4.4	Boxplots showing the 5 th , 25 th , 50 th , and 95 th percentiles of the relative error (RE) in the estimated $\frac{F}{M}$, L_{S50} , L_{S95} and resulting estimate of the spawning potential ratio (SPR) with recruitment variability (Test 8) for a) Species I, b) Species II, c) Species III, and d) Species IV.	74
4.5	Boxplots showing the 5 th , 25 th , 50 th , and 95 th percentiles of the relative error (RE) in the estimated $\frac{F}{M}$, L_{S50} , L_{S95} and resulting estimate of the spawning potential ratio (SPR) with auto-correlated recruitment variability (Test 9) for a) Species I, b) Species II, c) Species III, and d) Species IV.	75
4.6	Boxplots showing the 5 th , 25 th , 50 th , and 95 th percentiles of the relative error in the estimated $\frac{F}{M}$ and the resulting estimates of the spawning potential ratio (SPR) for the 4 test species from 5,000 Monte Carlo simulations with simultaneous error in the three parameters of the length-based SPR method and recruitment variability ($\sigma_R = 0.6$).	76
4.7	Boxplots showing the 5 th , 25 th , 50 th , and 95 th percentiles of the relative error in the estimated spawning potential ratio (SPR) for the five different selectivity curves for Species I, II, III and IV.	77
4.8	The female length frequency distribution of <i>Sillago schomburgkii</i> (Coulson 2013, Murdoch University, unpublished data) with the fit from the length-based SPR (LB-SPR) model overlaid as a black solid line.	78
5.1	Flow chart describing the management strategy evaluation process used in this study to investigate the utility of the length-based spawning potential ratio assessment methodology (LB-SPR) as a suitable tool for the management of data-poor fisheries. SPR = Spawning Potential Ratio.	88
5.2	The two effort-based harvest control rules used in this management strategy evaluation: HCR 1 (solid black line, Equation 3) where the Effort Modifier is a linear relationship to the difference between the estimated and target SPR, and HCR 2 (dashed black line, Equation 4) which has a logarithmic relationship between the ratio of the estimated SPR and target SPR and the resulting value of the Effort Modifier.	91

5.3	The maturity (solid lines), and the logistic (dashed lines) and dome-shaped selectivity-at-length (dotted lines) curves for the three test species used in the management strategy evaluation: a) Species I; Pacific mackerel (<i>Scomber japonicus</i>), b) Species II; silver warehou (<i>Serirolella punctata</i>), and c) Species III; crimson snapper (<i>Lutjanus erythropterus</i>).	92
5.4	Boxplots (central line: median; box: 25% and 75% quantiles; whiskers: greatest observation less than 1.5 times the interquartile range from the median) showing the distribution of relative error in the outputs of the LB-SPR model in the final year of the projection period: the length at 50% and 95% selectivity ($S_{L_{50}}$ and $S_{L_{95}}$), the relative fishing mortality ($\frac{F}{M}$) ratio, and the spawning potential ratio (SPR) for Species I (a-d), Species II (e-h), and Species III (i-l).	102
5.5	The trajectories of the relative spawning stock biomass (Rel. SSB) for Scenarios 1-5 (left to right; median solid line and 5th and 95th percentiles light grey) and Scenarios 6-10 (left to right; median dash line and 5th and 95th percentiles dark grey) for Species I <i>Scomber japonicus</i> ($\frac{M}{k} = 1.5$, a-e), Species II <i>Serirolella punctata</i> ($\frac{M}{k} = 0.97$, f-j), and Species III <i>Lutjanus erythropterus</i> ($\frac{M}{k} = 0.36$, k-o) projected for 60 years.	105
5.6	The trajectories of the relative catch (Rel. Catch) for Scenarios 1-5 (left to right; median solid line and 5th and 95th percentiles light grey) and Scenarios 6-10 (left to right; median dash line and 5th and 95th percentiles dark grey) for Species I <i>Scomber japonicus</i> ($\frac{M}{k} = 1.5$, a-e), Species II <i>Serirolella punctata</i> ($\frac{M}{k} = 0.97$, f-j), and Species III <i>Lutjanus erythropterus</i> ($\frac{M}{k} = 0.36$, k-o) projected for 60 years.	106
5.7	The trajectories of the estimated SPR (Est. SPR) for Scenarios 1-5 (left to right; median solid line and 5th and 95th percentiles light grey) and Scenarios 6-10 (left to right; median dash line and 5th and 95th percentiles dark grey) for Species I <i>Scomber japonicus</i> ($\frac{M}{k} = 1.5$, a-e), Species II <i>Serirolella punctata</i> ($\frac{M}{k} = 0.97$, f-j), and Species III <i>Lutjanus erythropterus</i> ($\frac{M}{k} = 0.36$, k-o) projected for 60 years.	107
5.8	The trajectories of the static SPR (equilibrium SPR of the operating model) for Scenarios 1-5 (left to right; median solid line and 5th and 95th percentiles light grey) and Scenarios 6-10 (left to right; median dash line and 5th and 95th percentiles dark grey) for Species I <i>Scomber japonicus</i> ($\frac{M}{k} = 1.5$, a-e), Species II <i>Serirolella punctata</i> ($\frac{M}{k} = 0.97$, f-j), and Species III <i>Lutjanus erythropterus</i> ($\frac{M}{k} = 0.36$, k-o) projected for 60 years.	108

5.9 Boxplots (central line: median; box: 25% and 75% quantiles; whiskers: greatest observation less than 1.5 times the interquartile range from the median) showing the distribution of relative error in the estimated L_∞ in each year for Species I, II and III in Scenario 5 ($SPR_{\text{targ}} = SPR_{\text{MSY}}$; a, c, and e respectively) and in Scenario 10 ($SPR_{\text{targ}} = 0.60$; b, d, and f respectively). 110

List of Tables

2.1	A synopsis of the taxa and species in this meta-analysis summarizing the range of parameters used for each species group. Appendix A contains a table listing the parameters used for each species and supporting sources.	27
4.1	The biological and selectivity parameters for the four test species used in the robustness tests of the length-based SPR model.	66
4.2	Description of the 12 tests to understand the robustness and sensitivity of the length-based SPR (LB-SPR) model to a range of parameter misspecification and assumption violations for the four test species of Table 4.1. .	67
4.3	The estimated spawning potential ratio (SPR) from the length-based SPR model (LB-SPR) model for the <i>Sillago schomburgkii</i> data (Coulson et al., 2005) for the combination of three different values for the L_{∞} and $\frac{M}{k}$ parameters.	78
5.1	The biological and selectivity parameters for the three test species used in the management strategy evaluation of the length-based spawning potential ratio assessment methodology.	93
5.2	The ten scenarios used in the management strategy evaluation of the length-based spawning potential ratio assessment methodology for three test species with different life history strategies. Scenarios 1–5 had a SPR target of SPR_{MSY} , and the tests were repeated with a more precautionary SPR target of $SPR_{0.60}$ in Scenarios 6–10.	96
5.3	The summary statistics comparing the performance of the LB-SPR assessment method with two different effort-based harvest control rules for Species I (Pacific mackerel <i>Scomber japonicus</i>), showing the median and 5th and 95th percentiles of the spawning stock biomass (SSB), the static SPR, and the relative catch in the final year of the projection period (Year 60), as well as the time to first reach the target SSB, the relative catch in the first 10 years of the projection period, and the absolute average variation (%AAV) in fishing effort for a) Scenarios 1 – 5 and b) Scenarios 6 – 10. .	98

5.4	The summary statistics comparing the performance of the LB-SPR assessment method with two different effort-based harvest control rules for Species II (Silver warehou <i>Seriolella punctata</i>), showing the median and 5th and 95th percentiles of the spawning stock biomass (SSB), the static SPR, and the relative catch in the final year of the projection period (Year 60), as well as the time to first reach the target SSB, the relative catch in the first 10 years of the projection period, and the absolute average variation (%AAV) in fishing effort for a) Scenarios 1 – 5 and b) Scenarios 6 – 10. .	99
5.5	The summary statistics comparing the performance of the LB-SPR assessment method with two different effort-based harvest control rules for Species III (Crimson snapper <i>Lutjanus erythropterus</i>), showing the median and 5th and 95th percentiles of the spawning stock biomass (SSB), the static SPR, and the relative catch in the final year of the projection period (Year 60), as well as the time to first reach the target SSB, the relative catch in the first 10 years of the projection period, and the absolute average variation (%AAV) in fishing effort for a) Scenarios 1 – 5 and b) Scenarios 6 – 10.	100

Acknowledgments

Working on my doctoral studies has been an incredible, but often overwhelming and challenging, experience, and it would not have been possible to complete this thesis without the help and support of many kind and generous people.

I was very fortunate to have had two wonderful supervisors for my PhD, Professors Neil Loneragan and Jeremy Prince. I am extremely grateful for their guidance and advice over the last four years. Jeremy never wavered in his belief of the significance of this work, and I'm thankful for his continued encouragement and patience, especially during the (many) times where I was lost confidence. Neil was tireless in his efforts to edit and improve my writing, always had time available for meetings and catch-ups, and provided much useful and appreciated advice throughout my entire time at Murdoch University. Thanks to you both for your training, advice, and encouragement throughout my PhD, especially for continuing to remind me of the bigger context of my work.

Funding for this project was provided by means of a research scholarship from Murdoch University. Thanks also to the Marine Stewardship Council and the David and Lucille Packard Foundation, who provided significant additional funding which allowed me to complete the final stages of this research. Thanks to David Agnew and Nicolas (Nico) Gutierrez, from the MSC, whose support, comments, and discussions were very helpful and much appreciated. Also thanks to Keith Sainsbury for his advice and assistance, especially with the theoretical development of my length-based model, and Tony Smith, who also provided useful advice and suggestions.

A big thank you to all the members of the Centre for Fish, Fisheries and Aquatic Ecosystems Research at Murdoch University. It's great to have such a fantastic group of people to work with, and such a wonderful research centre to be a part of.

My PhD study has been quite an adventure, and included two extended trips to the University of Washington in Seattle, USA. I am grateful to Professors Ray Hilborn and André Punt for allowing me to audit their classes at the School of Aquatic and Fisheries Science, and also for providing me with space and resources in their labs. I am especially thankful for the time both Ray and André made to meet with me and discuss my work. I thoroughly enjoyed my time at SAFS and in Seattle. The coursework was challenging but extremely rewarding, and I would not have been able to complete my PhD without the training and advice I received there. Thank you to all the members of Ray's lab for your kindness and generous hospitality. I will never forget my time there. Trudging around the Alaskan tundra on the lookout for sockeye salmon and grizzly bears was a special highlight!

One of the other highlights of spending time at SAFS was meeting Kotaro Ono: a fine

officemate, a great co-author, and a fantastic friend. Thanks to you and Marine for being such great friends. I miss sharing offices with you in Seattle, and am grateful for your discussions and help regarding my work. I'll never cease to be amazed at your ability to spend a couple of seconds checking my equations that took me, quite literally, a week to work out!

Thanks also to Sarah Valencia, another great friend whom I met in the USA. I've very much enjoyed working together over the last few years, and look forward to continuing to work together into the future.

Also thanks to our other great friends from Seattle: Heather and Luke Rogers who were very generous and kind landlords during our first trip in 2011/2012, and Ryan and Alicia Hemphill with whom we stayed for 3 months in late 2012. Your kindness and hospitality are greatly appreciated.

During the course of my PhD I've had the fortune of traveling to a number of national and international conferences and workshops. Thanks to all the wonderful people I've met at these meetings and during my travels. In particular, I'd like to thank Pablo Pita, as well as Diana and their daughter, Ada, who showed me such generous hospitality during my recent trip to beautiful Galicia, Spain. What a fantastic way to celebrate the (almost) completion of my PhD!

I am especially thankful for all the support and encouragement from my family and friends. In particular, I am deeply indebted to my parents, Harry and Arly, for all that they have done for me throughout my life, and their support, advice and encouragement over the years, especially during my time of study. Dad, a special thanks for proof-reading my thesis, this was very much appreciated.

Life has a habit of presenting new and unexpected challenges, and the recent year was no exception. The news of Mum's illness, and her passing several months later, was a difficult experience for us all, and I thank God that I have such a close and loving family and a network of friends that remained so supportive during this difficult time. Thank you all for your thoughts, words, prayers, and support during my entire PhD, but especially in this last year.

Finally, my thanks to my darling wife Candice. Candy, thanks so much for your patience and love. I am incredibly grateful and amazed at your patience and understanding, especially when I decided so many years ago to quit my perfectly good job, and chase my dream of becoming a marine scientist! Thank you. For everything. You know that this would have been impossible without you. Now it is your turn. I am so proud of you in your studies, and know that you are going to make an exceptionally wonderful nurse!

Dedication

*In loving memory of my mother, Arly Hordyk (1953–2013)
for believing in me, and teaching me to believe*

Publications resulting from this study

The following chapters of this thesis have been peer reviewed and accepted for publication:

- Chapter 2 Prince, J. D., Hordyk, A. R., Valencia, S., Loneragan, N. R. & Sainsbury, K. 2014. Revisiting the concept of Beverton–Holt Life History Invariants with the aim of informing data-poor fisheries assessment. *ICES Journal of Marine Science*. fsu011.
- Chapter 3 Hordyk, A. R., Ono, K., Sainsbury, K., Loneragan, N. R. & Prince, J. D. 2014. Some explorations of the life history ratios to describe length composition, spawning-per-recruit, and the spawning potential ratio. *ICES Journal of Marine Science*. fst235.
- Chapter 4 Hordyk, A. R., Ono, K., Valencia, S., Loneragan, N. R. & Prince, J. D. 2014. A novel length-based empirical estimation method of spawning potential ratio (SPR), and tests of its performance, for small-scale, data-poor fisheries. *ICES Journal of Marine Science*. fsu004.
- Chapter 5 has been accepted for publication in the journal *Fisheries Research*. Hordyk, A.R., Loneragan, N. R., & Prince, J.D. An evaluation of a harvest strategy for data-poor fisheries using the length-based SPR assessment method. Submitted February 2014 to *Fisheries Research*.