Assessing the Impact of Proposed Marine Protected Areas on South Australian Rock Lobster Catches

R. McGarvey

SARDI
SOUTH AUSTRALIAN RESEARCH AND DEVELOPMENT INSTITUTE

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Non Technical Summary

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NON TECHNICAL SUMMARY:

A state and federal collaborative program (NRSMPAs) to establish marine protected areas (MPAs) is under way nationwide. This project examines no-take zones designated for state territorial waters which lie predominantly inside 3 nautical miles from shore.

In South Australia, the lobster industry peak bodies, in conjunction with state marine conservation NGO's, have endorsed the position that harvesting rights (pots owned with associated license to fish) should be bought back (and thus be permanently removed from the fishery) in order that the effort displaced out of newly created no-take zones did not increase levels of exploitation in the remaining still-fishable habitat. This alliance of fishing industry and conservation lobby recommended a policy in state government, now adopted, that effort displaced from no-take areas should be removed in a one-off state government purchase of those harvesting rights.

The principal output of this project is an estimate of the number of licensed lobster pots needing removal to balance the average net yearly catch loss due to MPAs established. To achieve this aim there are two stages, namely Objectives 1 and 2 of this project. The first stage is to estimate the average historical catches per year in each spatial sub-block. The second stage, is to account for catch benefits from established no-take areas that lessen the loss of long-term catch.

Objective 1. Estimate the historical average yearly catches in each of 30 state-waters sub-blocks. A spatially-resolved database of sampled South Australian commercial lobster catches has been compiled over the last decade. The contents and GPS latitude-longitude positions of approximately 80,000 commercial fishery pot lifts set over the last 8 fishing seasons (since 1993/94) were recorded. The legal weight of lobsters captured in each sampled pot lift was used to estimate the average historical legal-size lobster catch per unit area per year. This is the amount of rock lobster that has been captured per average km^2 of no-take area in each of the 30 sub-blocks examined, thereby covering all South Australian state territorial waters.

Objective 2 is to estimate the *net* catch loss with the establishment of an average marine reserve in each sub-block. Two ways that establishing the reserve can have a

spill-over effect of increasing long-term lobster catches outside the reserve were modelled and analysed statistically, namely by emigration of recruiting lobsters out of reserves into the fished zone where they can be captured (Chapter 2), and egg production from protected lobsters inside reserves (Chapter 3).

From recoveries in the surrounding fished zone of lobsters tagged and released inside Gleesons Landing Lobster Sanctuary, the emigration rate out of the reserve was estimated at 62%. This corroborated previous study of this data (Prescott et al., FRDC Project 93/086) which found high rates of emigration from this no-take zone.

With displaced effort removed, egg production from within no-take areas is likely to rise. The absence of exploitation means larger lobsters, and possibly also more dense numbers of mature adults. In Chapter 3, the evidence is examined for increased fishery recruitment due to higher egg production from inside reserves. In analysis of South Australian rock lobster, no correlation was found between estimated yearly egg production and recruitment of those eggs 6 years later. This (i) absence of a stock-recruitment signal, together with (ii) density dependence in recruitment implying lower than proportional increases in recruitment for any given percent increase in state-wide egg production, rendered the net effect of MPAs on overall lobster fishery recruitment essentially impossible to quantify. Increased egg production was therefore not included in the estimates of net catch losses to the fishery overall.

OUTCOMES ACHIEVED

The principal outcome from this small low-cost extension project was an estimate of the average net lobster catch loss per km^2 from each of 30 sub-blocks in South Australian state waters. These estimates will be needed to (1) buy out displaced effort, and thus (2) to compensate fishers for reduced long-term catches. Removing displaced effort achieves the objective of marine reserves, of providing unexploited habitat for biodiversity conservation in the benthic ecosystem, while having a beneficial or neutral effect on continued sustainability of lobster exploitation in the rest of the still-fished marine benthic habitat. The SA state government has now formally declared its intent to remove displaced effort through buy-back. These net catch loss estimates will, if approved, be used to calculate the levels of pot buy-back needed. In this way, they assist in removing a major obstacle for the current program of National Representative System of MPAs in South Australia to the satisfaction of all stakeholders.

Two new estimation methods were developed for assessing the impact of MPAs on fisheries. (1) An overarching method using GIS inputs and integrated binomial and emigration likelihoods generated an estimate of net catch loss per unit area of no-take zone in all sub-blocks, given data for (i) catch and effort logbook totals by statistical block, and (ii) latitude-longitude specific (i.e. point-location) sample catches. (2) A model integrated into (1) above was derived to estimate emigration rate from protected areas using fishery tag-recovery data. An analytic formula as well as a numerical likelihood estimator were developed, and these yielded close agreement. This permits estimation of emigration rate from no-take areas where individuals were tagged and released by researchers but where, being protected, only tag recoveries from the surrounding fished areas are returned.

KEYWORDS: Marine Protected Areas, lobster fishery, catch loss, displaced effort, buy-out, emigration, stock-recruitment, density dependence

Acknowledgments

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André Punt (CSIRO Hobart) reviewed Chapters 1 and 2. Hugh Possingham (University of Queensland) reviewed the entire report. Their reviews, with responses to their comments by the author, are included as Appendices 3.1 and 3.2.

Background

Federal and South Australian state governments have endorsed the establishment of the National Representative System of Marine Protected Areas, notably in South Australian state waters. Currently, proposed areas for coastal waters are being drawn up by the South Australian Department for Environment and Heritage, Environment Protection Agency (DEH/EPA), and boundaries will become available for comment. Discussions about where these parks should be located has begun with various sectors, including the fishing industry. Core high-protection ('no-take') areas from which fishing would be excluded will fall within MPA boundaries and make up a part, in some cases a small part, of the total managed MPA zone.

The South Australian rock lobster industry has taken a pro-active interest in participating in discussions with the DEH/EPA. Similarly, DEH has put in place an MPA task force to provide a forum for formal discussions about the optimal placement of MPA no-take boundaries. The goal of these negotiations will be to optimise the biodiversity protected while minimising the impact on marine resource production.

FRDC project 1999/162, "Evaluating the effectiveness of Marine Protected Areas as a fisheries management tool", is currently under way in Tasmania with Colin Buxton as Principal Investigator. Its objectives overlap those in South Australia, namely to assess the net impacts on predicted catches in the wake of MPAs being established. The computer simulation model by Malcolm Haddon explores potential impacts of lobster fishery effort displacement on stock sustainability in 56 Tasmanian fishing blocks. The project reported here is an extension of FRDC project 1999/162 for application to South Australia. This South Australian project differs from the Tasmanian project by undertaking not simulation, but estimation. In Tasmania, there is neither need nor data to undertake estimation of net catch loss: the government has no policy of fishery buy-back to remove displaced effort, and point-locations of lobster catches are not regularly sampled.

Spatial information on commercial lobster catches is available in South Australia. Since 1993, lobster fishers, sometimes with on-board researchers, have recorded the latitude-longitude of sample pot lift locations. All lobsters in each sampled pot are sexed and measured for length (see FRDC Final Reports 93/086 and 95/138). Approximately 10,000 pot lifts (about 0.1% to 1%) are sampled yearly.

MPAs permit lobster population enhancement that may compensate for some of the lost harvest from each area. The fishing industry has accepted that the amount of catch lost, for which pot buy-out would be needed, should be the *net* catch loss. That is, when historical catches are calculated inside no-take boundaries for buy-out, any 'give back' of this catch loss by the newly established no-take area, through (1) emigration out and subsequent capture in the fished zone, or (2) by enhanced egg production inside, would not require buy-out, thus reducing total compensation cost accordingly.

The original project proposal contracted to provide estimated net catch losses for 6 MPAs, when the locations and boundaries of 11 or 12 were thought to be near announcement. But this announcement was delayed. Thus to attain project objectives in the absence of specific no-take zone boundaries to analyse, the calculation of net catch loss , and thereby, pots needing removal, was done on a per-unit-area basis. The specific objective was to estimate net catch loss in landed weight (kg) per year per unit area (km^2) from each MFA 'sub-block', which is the portion of each MFA block lying in state waters.

This calculation of numbers of lobster pots requiring buy-out per km^2 of no-take area proceeded in five stages: First, the historical catches per year (in kg) were estimated for each of the 30 sub-blocks. Second, the proportion of lobsters emigrating from a no-take area in each year was estimated. Third, the potential effect of higher egg production (from higher lobster densities and/or size) in the now protected habitat was analysed. Fourth, these were all combined into a single overall (Bayesian MCMC) estimate of the net catch loss. Fifth, the overall MFA-block catch and effort totals were incorporated to derive the numbers of pots needing removal (per unit area) in each of the 30 sub-blocks covering all state territorial waters. Sixth, MCMC confidence intervals were estimated for pot buy-out per unit area in each sub-block.

Need

This project seeks to provide quantitative measures of the impact of proposed marine protected areas (MPAs) in South Australia on commercial landings of rock lobster. This will provide tools for the negotiation of specific MPA boundaries, to minimise the impact on rock lobster production, while still allowing protection of marine biodiversity.

Objectives

1. To provide a GIS tool that will show specific areas of rock lobster harvest, and allow computation of historical mean total catches from each MPA area proposed in South Australia.
2. To develop a model for estimating mean net losses of production of rock lobster as an impact of six proposed MPAs in South Australia.

CHAPTER 1. Estimating historical rock lobster catches inside state territorial waters from commercial pot lift monitoring

Introduction

As summarised in the Non Technical Summary, the objective of this project is to estimate the net catch loss of lobster from no-take zones lying inside state waters where MPAs are currently being proposed (Figure 1.1). In this chapter, the first stage of this estimation is described, namely to calculate historical catch totals of lobster inside state waters. Specifically, estimates are derived of yearly average catch (kg of landed lobster per km^2 of no-take area) for each of 30 'sub-blocks' lying inside state waters.

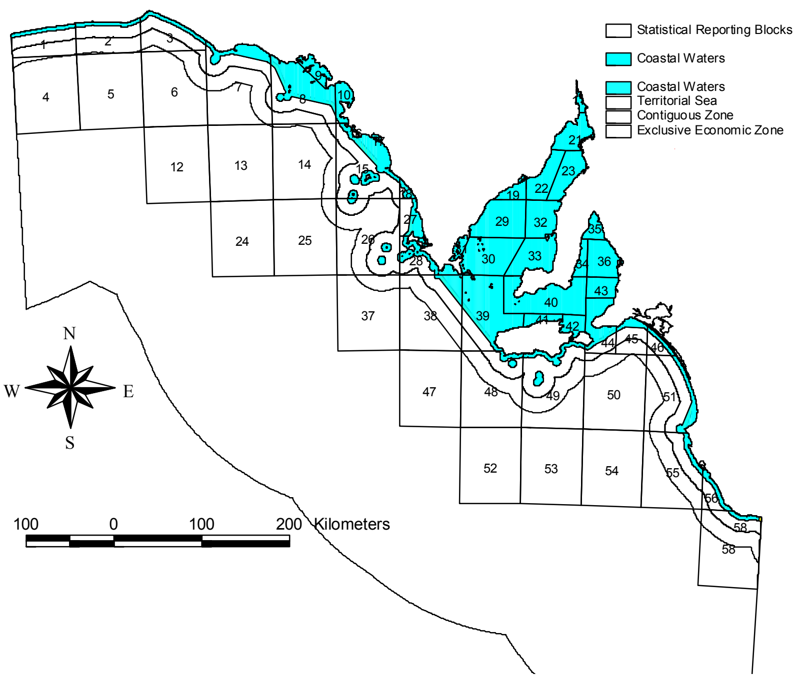


Figure 1.1. Management jurisdiction zones and statistical reporting blocks in the South Australian coastal zone. State territorial ('Coastal') waters are highlighted in blue.

The South Australian rock lobster fishery covers most of the coastal shelf waters where rocky habitat is found. Particularly high concentrations of catch occur in the Southeast, from shore to shelf edge south of Kingston, and off western and southern Kangaroo Island. Rock substrate is dense in these regions, and their westerly facing coastline permits the settlement of relatively high numbers of pueruli (lobster larvae). In addition, because of a narrower coastal shelf in these two areas, lobster larvae need to swim and be transported a shorter distance to inshore settlement from the open ocean where they pass much of their 18-24 months of larval pelagic phase. Lower but still significant catches occur along western Eyre Peninsula and along the cliffs and around rocky islands of the west coast, around Yorke Peninsula, along northern Kangaroo Island, and in rocky reef patches north and west from Kingston.

Thus there is high spatial variation in South Australian lobster catches. As a result, the levels of compensation needed for buy-out of displaced effort in different regions of the coastal marine habitat will vary accordingly.

For management purposes, the lobster fishery is divided into two zones, Northern and Southern, with the dividing boundary between the two zones extending south and west from the Murray Mouth. The Southern Zone has been managed by quota since 1993. The Northern Zone was managed by limits on the numbers of days fished yearly, but has adopted a quota system for the 2003/04 fishing season. In addition, both zones retain (1) limits on the numbers of pots that can be set each day, (2) restrict fishing to 7 months of each year, with no fishing in winter when females carry eggs, (3) require the returning to the sea of any egg-bearing females and all lobsters below a legal minimum size that come up in the pots, and (4) limit the total number of licenses, which has been declining over time.

Originally, in the project proposal, it was intended that specific no-take or MPA areas would be analysed. Deadlines for announcement of these candidate boundaries were moved back on a number of occasions. To date, no specific candidate MPA boundaries have been released, and discussions within government and between government and stakeholders (notably the fishing industry and environmental interest groups) are on-going. To facilitate these discussions, and in the absence of specific no-take boundaries to work with, an alternative method of advancing the goals of this project were adopted.

The state waters coastal zone was partitioned into 30 subregions and the average catches inside each were calculated. Yearly catch totals by South Australian lobster fishers are reported in one-degree square blocks, called "Marine Fishing Areas", or "MFA blocks". The 30 subregions analysed in this project will be formed from the portions of each MFA block that fall inside state waters, denoted 'MFA-state sub-blocks', or simply 'sub-blocks'.

Because the area of these sub-blocks will vary, and in order that the project outputs can be more easily applied by MPA planners and industry to calculate pots needing buy-back for any given size of no-take zone, these mean historical catches will be reported below as densities, that is, as yearly catches (in kg) per km^2 of no-take area inside state territorial waters.

This approach offers three advantages over the method originally proposed of considering 6 specific no-take areas: (1) It will allow the presentation of spatial variation in catches, by breaking down the estimates into the 30 sub-blocks. (2) This provides a complete coverage of the entire state coastal zone where no-take areas are under consideration. (3) By providing the pot buy-back estimates as per km^2 quantities, planners can calculate the compensation levels required for any size of no-take area proposed. Thus, a 30-sub-block coverage will provide substantially more information to industry and planners about impacts of MPAs on lobster catches.

The chapter will follow in four parts: (1) Data used in the calculation are summarised; (2) the Methods used to derive estimates of average yearly catches in each sub-block are described, (3) the Results, notably a map and table of these average catches are reported; lastly (4) a brief Discussion is included. Details of the calculation method are presented in two appendices.

Data

The data to be used for this estimation of historical catches are twofold: (1) catch and effort totals, reported in the daily catch logs of commercial lobster fishers, and (2) pot sampling, wherein commercial lobster fishers volunteer (or scientists go on board vessels) to measure the contents of a sample of individual pot lifts.

Commercial catch-log totals by month and MFA block

It is a legal requirement of license holders to report all commercial catch (in both kilograms and numbers landed) and effort (as pot lifts set) throughout each fishing season. These fisher-reported catch and effort totals, called 'catch log data', are the data used in all stock assessment for the total legal-size landed catch of rock lobsters in South Australia. These are available by month and 'MFA block'. MFA blocks are fishery catch-log reporting areas which cover the coastal zone (Figure 1.2), and are the smallest unit into which catch log data are spatially sub-divided.

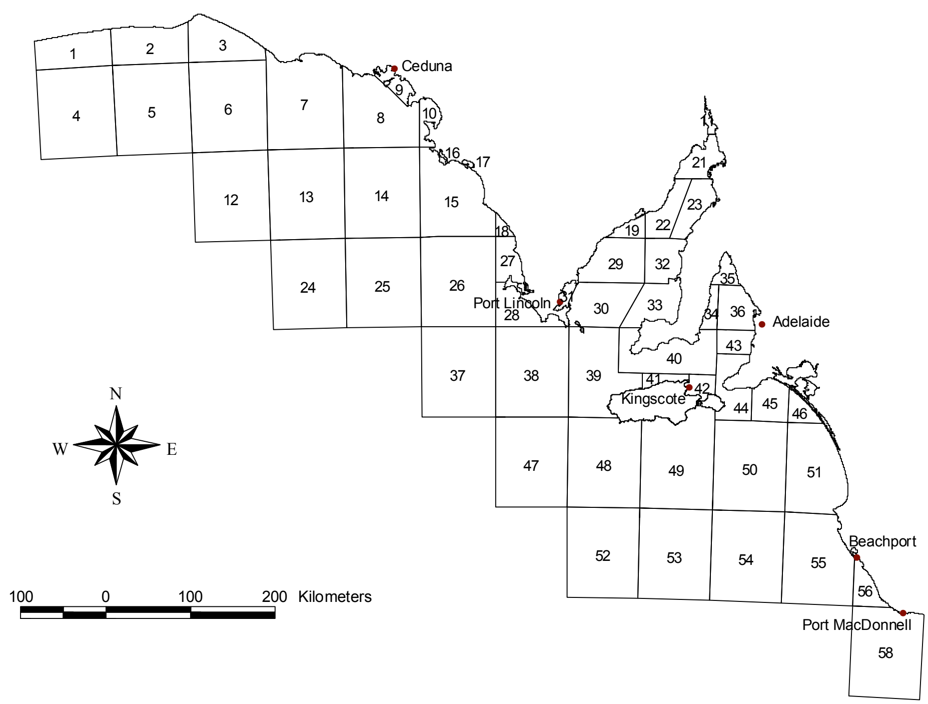


Figure 1.2. South Australian 'MFA' statistical reporting blocks for monthly catch and effort totals from commercial fishermen.

Table 1.1. Input totals by MFA block: area of whole MFA block, area of the portion ('sub-block') inside state territorial waters, and the whole-block average yearly total catch.

MFA block	Area whole block (' $A_w(b)$ ', km^2)	Area sub-block (' $A_{<3}(b)$ ', km^2)	Average yearly whole-block catch, 1990/91-2000/01, from logbooks (' $\bar{C}(b)$ ', kg)
55	9022.34	477.076	684537.2
56	1425.56	477.383	502770.3
39	7174.45	5517.08	160393.1
58	9563.94	281.195	395064
51	7339.78	1025.86	104023.5
28	2553.9	1229.16	169808.7
49	10368.4	749.324	95636.73
40	5200.16	5195.32	76948.27
48	9859.96	284.419	77317.91
15	7827.44	1911.08	135402.6
26	10161.2	25.5046	21712.18
27	1769.86	947.733	46946.64
3	3961.52	622.059	16922.45
7	10573.5	1337.12	29244.18
8	7213.92	3566.38	44204.27
38	10059.8	893.161	18149.73
30	4113.95	4094.91	5957.818
44	2689.78	1928.99	5684.364
18	407.438	284.164	11010.36
33	2938.07	2917.01	5151.091
10	1086.35	1061.41	9956.727
41	688.537	687.634	4667.182
46	1026.64	312.373	3284.727
9	968.757	960.749	1163.833
45	3357.7	458.165	1951.2
31	460.225	446.429	88
17	79.3582	76.4762	0
16	46.0673	44.9336	481.6667
2	4329.42	537.488	461.3333
42	976.201	974.294	1542.7

Point-location catches from pot sampling

Since 1991, a pot-sampling program has been carried out in the South Australian commercial lobster fishery. The number of lobsters in each pot lift, together with the carapace length and sex of each, are recorded. Since 1993 the records for most of these sample pot lifts, a total sample of about 80,000, include their GPS latitude-longitude positions. This spatially resolved database of catches, is undertaken primarily by South Australian rock lobster fishers and was developed in conjunction with FRDC projects 93/086-93/087 and 95/138. Using the GPS positions of these pot-lift catch samples, it will be possible to estimate the proportion of historical catches from each whole MFA block that was taken inside its corresponding sub-block, that is, inside state waters. Details of the data pre-processing of pot samples are given in Appendix 1.1.

The sample sizes, as numbers of pot lifts sampled, by whole MFA block and year (Table 1.2) show high variation, both spatially and from year to year. However, while there is variation, inevitable with all sampling, spatially the samples are largely representative of overall catches. This is illustrated in Figure 1.3, where the MFA blocks with greater overall catches (from catch log yearly averages, Table 1.1, column 3) are also those with greater amounts of sampling recorded.

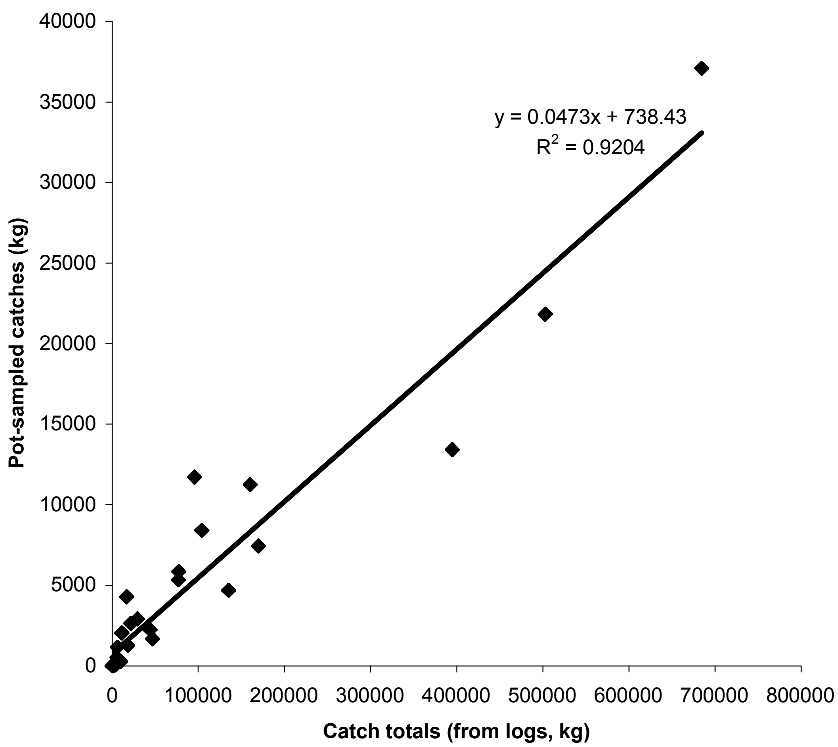


Figure 1.3. Scatterplot of pot-sampling catch totals (summed over 8 years) versus catch-log catch totals (averaged over 11 years), by whole MFA block.

Table 1.2. Sample size, as numbers of pot lifts sampled, by whole MFA block and fishing season. For MFA blocks with less than 100 sample pot lifts (for 'All seasons combined'), these sample pot-lift catch data were not used to calculate the spatial proportion of catch taken from state waters.

MFA block	South Australian rock lobster fishing season								All seasons combined
	1993/94	1994/95	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	
55	464	757	2160	2849	4747	2493	3351	2575	19396
56	553	305	1204	1102	1250	1099	1733	1264	8510
39	694	32	708	1601	1495	636	801	1408	7375
58	567	20	1492	1369	1570	506	796	631	6951
51	194	143	1029	797	1204	1258	780	513	5918
28	196	0	1375	835	685	531	497	1066	5185
49	243	290	821	588	514	1129	731	632	4948
40	196	0	707	445	460	422	553	471	3254
48	0	22	355	391	634	612	491	693	3198
15	0	0	688	558	718	189	130	448	2731
26	50	0	322	418	265	75	258	123	1511
27	0	0	303	327	361	59	62	255	1367
3	0	0	0	38	0	918	179	198	1333
7	0	0	3	91	135	452	330	290	1301
8	0	0	73	110	83	251	307	340	1164
38	55	0	112	164	178	70	109	256	944
30	15	0	198	55	8	34	70	116	496
44	0	0	174	74	56	30	30	34	398
18	0	0	69	134	31	4	21	38	297
33	0	0	114	31	40	16	37	20	258
10	0	0	98	6	0	15	12	56	187
41	0	0	8	0	0	12	20	18	58
46	0	0	0	0	0	0	11	0	11
9	0	0	0	0	0	0	2	6	8
45	0	0	2	2	1	2	1	0	8
31	0	0	0	2	0	0	0	2	4
17	0	0	0	0	0	0	0	2	2
16	0	0	0	0	0	0	0	1	1
2	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0

Methods

The method had three basic parts: First, the 11-year average of catch by whole MFA block was calculated from the catch-log data. Second, the proportion of catch taken in the state-waters sub-block of each whole MFA block was estimated from pot samples. Third, these were combined to estimate the yearly average catch inside state waters for all 30 sub-blocks.

Yearly catch-log totals by whole MFA block

The choice of estimation method adopted was based on the assumption that the absolute levels of average yearly catch in each MFA block should use, as their basis, the catch-log totals. Catch-log data are a 100% sample and are legally binding. The estimates of historical mean catch per unit area were therefore obtained under the assumption that the catch-log reported totals for catch by weight in each MFA block and year are given without error.

A second reason why an approach based on catch log totals yields a more accurate estimate than pot samples alone, is that an unbiased average of catch totals from this fishery should go back 11 years. This is because autocorrelation analysis of two recruitment time series over about 30 years, obtained from (1) the qR stock assessment model and (2) directly from reported counts of undersize lobsters brought up in commercial pots each year, provided evidence of an 11-year recruitment cycle (McGarvey and Matthews 2001). Time-series averages should be made through a complete cycle of temporal variation to give the best estimate of a long-term mean in yearly catches. The pot sampling time series (with GPS coordinates) is available only for 8 years, starting in the 1993/94 season. Thus to obtain an accurate mean yearly catch from logs in each block, an 11-year time-series average was taken over the past 11 lobster fishing seasons, 1990/91-2000/01.

These catch-log yearly totals are available only for whole MFA statistical reporting blocks. To achieve the chapter objective of estimating the yearly catch averages in the state-waters portion of each MFA block, the pot sampling data were used, as described in the subsection to follow.

Estimating the proportions of lobster catch taken in state waters

Two approaches, a ratio estimator and binomial likelihood, were considered for estimating the spatial proportion of catch taken inside each sub-block, that is, the proportion of catch taken in state waters where MPAs are being proposed. This proportion is needed for each MFA block.

A ratio estimator was first considered. The drawback of this approach is that the ratio estimator in its classic formulation (Cochran 1977, Chap 6) is designed for surveys where the two quantities whose proportion (i.e. ratio) is to be estimated are both measured simultaneously with every sample unit. In the more complicated situation of spatial distribution of rock lobster catches in each block, because the two quantities (catch by weight inside the sub-block and catch by weight in the whole MFA block overall) are not measured simultaneously, a ratio-estimator is not directly applicable.

Moreover, estimating the variance of a ratio estimate is known to be problematic (Cochran 1977).

Perhaps more critically for the inapplicability of the classic ratio estimator is that the sample sizes in the different 'samples', that is, yearly rock lobster fishing seasons, vary greatly among the 8 years of GPS-specific pot sampling, depending on the block. For all but 6 of 30 blocks, there were one or more of the 8 years when no pots were sampled in the block (Table 1.2). These 0-sample years must of course be excluded since a proportion we seek to estimate of 0 catch sampled inside state waters over 0 catch sampled in the whole block overall is not defined for those years.

This high variation in sample size by year (i.e. rock lobster season) is naturally accommodated by the binomial likelihood approach adopted in place of a ratio estimator, to estimate the proportion of pot sample catch taken inside each state sub-block. The binomial gives weighting to each year's data input in direct proportion to the sample size of catch taken in that year. A binomial likelihood thereby excludes years of zero sample catches automatically without creating bias.

Of the 30 MFA blocks that overlap with state territorial waters, in a minority (9), insufficient pot sampling had taken place (less than 100 total pots sampled over the 8 years) to allow the proportion of the catch taken in state waters to be reliably estimated. For these low-catch blocks, in place of the pot-sample catch proportion, we used the proportion of surface area of the block that falls in state waters. This is equivalent to assuming that catch per unit area is constant across these low-catch MFA block. Since the MFA blocks with low levels of pot sampling are, in general, those with low overall catch, the imprecision introduced by using area proportion rather than pot-sample-catch proportion will be relatively small. Additional details are given in Appendix 1.1.

A binomial likelihood estimator allows rigorous quantification of estimate uncertainty. The principal source of variance in the estimated proportion of commercial catch taken inside state territorial waters in each MFA block will be due largely to sample variation—that is, where the particular fishers doing sampling each survey year, happened to have set their pots on the days they volunteered to sample their catches. This variation is quantified using standard statistical procedures for likelihood estimates as outlined in Appendix 1.2. Since uncertainty in this proportion of catch taken in state waters predominantly reflects yearly variation, it is appropriate to treat each year's catch monitoring outcome as a repeated (iid) sample measure. In other words, the variance of the mean pot sampling proportion of catch taken inside the 3 nm limit as a fraction of overall catch in each MFA block was estimated by taking each year of survey as a repeated sample of that proportion.

In summary, the overall estimates of historical catch in each of the 30 blocks were obtained by multiplying the catch-log average over the past 11 years by the estimated mean proportion of catch taken inside each sub-block. These proportions were in turn obtained by either (1) the binomial likelihood estimate of that proportion, or (2) for the 9 blocks with less than 100 pots total sampled over the 8 years of sampling, taken as the proportion of surface area in the block falling inside state waters. Mathematical details of the binomial likelihood estimation are given in Appendix 1.2.

For estimating confidence intervals, only the sample variance for proportion in sub-block is explicit (namely the binomial likelihood variance over the 8 years of sampling); error in the catch-log totals from each whole block is not quantifiable.

Results

Lobster catches per km^2 show a high level of spatial variation. The calculated yearly historical catches in state waters (Table 1.4), notably per unit area, show spatial variation by sub-block spanning approximately three orders of magnitude. This variation spatially of historical catches per unit area inside state waters is mapped in Figure 1.4.

Differences in the lobster catch density generally follow the known trends in overall catches by MFA block. Thus, as with catch totals, the highest catches per km^2 in state waters (Table 1.4, third column) occurred in the Southeast, notably sub-block 58, yielding about 500 kg per km^2 and sub-block 56, yielding about 300 kg per km^2 per year). Southern Zone Block 55 also contributes high lobster catches overall, but a much smaller percentage of this, only 3%, was taken inside state waters (Table 1.3, '$\hat{p}_c$').

In the Northern Zone, there were several blocks which lie north of Kangaroo Island, that fell entirely in state waters (40, 33, 30, 41, 42) or largely so (39 and 44). The highest state-waters catch densities in the Northern Zone occurred in blocks 48 and 28 both of which have abundant hard substrate and a south-westerly exposure. A number of west coast blocks (3, 15, 18, 27) also yielded catches greater than 20 kg per km^2, being blocks where the highest lobster densities (apart from islands) are inshore, reflecting corresponding higher densities of rock bottom. The highest mean catch densities in the Northern Zone come from the coastal shelf west of Kangaroo Island, sub-blocks 48 and 39.

The binomial estimator yielded numerical estimates of the average proportion of lobster catch taken in state territorial waters for each MFA block that were identical to the raw catch proportions of pot-sampled catches from inside the sub-blocks divided by the total sampled catch in each whole block (4th and 6th columns of Table 1.3). This is expected, since the raw catch ratios are the maximum likelihood estimates. Formulating the estimation as a binomial likelihood permits rigorous quantification of uncertainty in these estimates, which will be carried forward to generate an overall estimate of uncertainty in the net catch loss from each MFA block, the final output of this project.

Table 1.3. Intermediate quantities and estimated (binomial-likelihood) outcomes, with blocks listed in order from largest to smallest by pot lift sample size, 'All seasons combined' in Table 1.2. For the last 9 blocks (below block 10), no estimation of catch proportion was possible due to insufficient (<100) sample pot lifts.

MFA Block	Sample size of pot lifts for whole MFA block (from Table 1.2)	Ratio of areas: sub-block over whole block	Raw pot sample catch ratio: sub-block over whole block	Number of years with > 0 sample pot lifts	Numerical maximum likelihood estimates of catch ratio: ('$\hat{p}_c$')	Standard error of $\hat{p}_c$ divided by the estimate of $\hat{p}_c$ ('$CV_{SE}\left[\hat{p}_c(b)\right]$')
55	19396	0.052877	0.033398	8	0.033398	2.794%
56	8510	0.334874	0.279586	8	0.279586	1.086%
39	7375	0.768989	0.969362	8	0.969362	0.168%
58	6951	0.029402	0.35758	8	0.35758	1.157%
51	5918	0.139767	0.15226	8	0.15226	2.573%
28	5185	0.481289	0.749354	7	0.749354	0.671%
49	4948	0.07227	0.11787	8	0.11787	2.527%
40	3254	0.99907	1	7	1	0%
48	3198	0.028846	0.609101	7	0.609101	1.048%
15	2731	0.244152	0.418485	6	0.418485	1.721%
26	1511	0.00251	0.021938	7	0.021938	13.010%
27	1367	0.535484	0.593546	6	0.593546	2.021%
3	1333	0.157025	0.910432	4	0.910432	0.479%
7	1301	0.126459	0.563773	6	0.563773	1.630%
8	1164	0.494374	0.562321	6	0.562321	1.861%
38	944	0.088785	0.507928	7	0.507928	2.767%
30	496	0.995372	0.982494	7	0.982494	0.393%
44	398	0.717154	0.879291	6	0.879291	1.614%
18	297	0.697441	0.984694	6	0.984694	0.276%
33	258	0.992831	1	6	1	0%
10	187	0.977039	1	5	1	0%
41		0.998688				
46		0.304267				
9		0.991734				
45		0.136452				
31		0.970024				
17		0.963684				
16		0.975391				
2		0.124148				
42		0.998046				

Table 1.4. Estimates of historical yearly 11-year average catch in state territorial waters (sub-block), by MFA block .

MFA Block (b)	Average catch in state sub-block b (‘ $\hat{\bar{C}}_{<3}(b)$ ’, kg)	Average catch per unit area in state sub-block b (‘ $\hat{\bar{C}}_{<3}(b) \big/ A_{<3}(b)$ ’, $kg \cdot km^{-2}$)
55	22861.9	47.9209
56	140568	294.455
39	155479	28.1814
58	141267	502.382
51	15838.6	15.4394
28	127247	103.523
49	11272.7	15.0438
40	76948.3	14.8111
48	47094.4	165.581
15	56664	29.6502
26	476.318	18.6758
27	27865	29.4017
3	15406.7	24.7673
7	16487.1	12.3303
8	24857	6.96981
38	9218.76	10.3215
30	5853.52	1.42946
44	4998.21	2.5911
18	10841.8	38.1535
33	5151.09	1.76588
10	9956.72	9.38068
41	4661.06	6.7784
46	999.435	3.19949
9	1154.21	1.20137
45	266.245	0.581111
31	85.3621	0.191211
17	0	0
16	469.814	10.4557
2	57.2735	0.106558
42	1539.69	1.58031

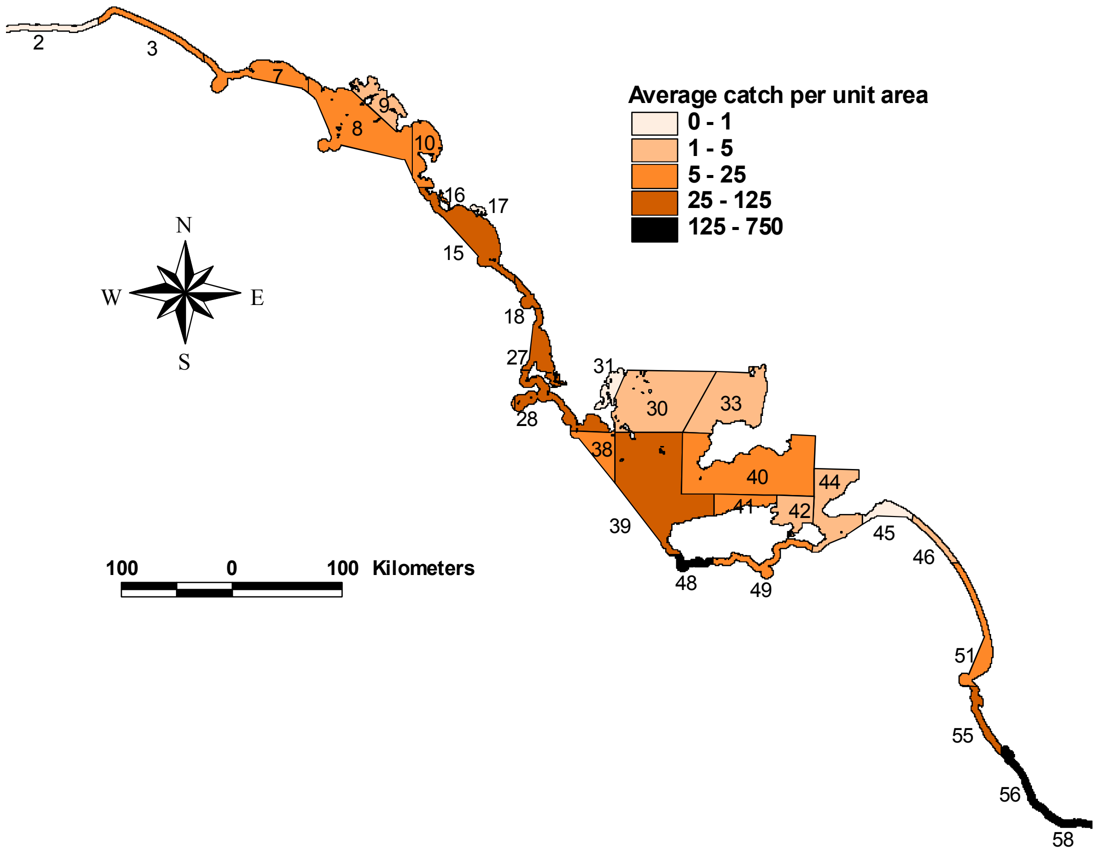


Figure 1.4. Average historical catches per unit area (kg · km^{-2}), by sub-block, from Table 1.4.

Discussion

The average rock lobster catch per unit area, the principal output from this chapter, is the basic quantity for calculating yearly catch losses in given MFA state coastal zones. The high variation in catch per unit area, implies that levels of compensation to buy out catch capacity from MPA no-take zones in some areas will be around 1000 times higher for some MFA blocks compared with others.

Because specific no-take areas have not been declared, net historical catches cannot be calculated for finer spatial resolution than sub-blocks. For the 9 of 30 lowest catch sub-blocks, the area proportions of the sub-block over the whole MFA block were used in place of the pot-sampling catch proportion.

This yearly mean historical catch will be reduced in subsequent chapters, to take into consideration contributions ('give-back') that prospective no-take zones will make to lobster catches outside of them, via lobster movement out of the no-take areas, and due to potential increases in egg production (per unit area) in the absence of exploitation.

References

Cochran, W.G. 1977. Sampling Techniques. John Wiley and Sons, New York.

McGarvey, R. and J.M. Matthews. 2001. Incorporating numbers harvested in dynamic estimation of yearly recruitment: onshore wind in inter-annual variation of South Australian rock lobster (*Jasus edwardsii*). ICES Journal of Marine Science 58: 1092-1099.

Prescott, J., McGarvey, R., Ferguson, G., and Lorkin, M. 1997. Population dynamics of southern rock lobster in South Australian waters. Final Report for Australian Fisheries Research and Development Corporation Project 93/086.

Rice, J.A. 1988. Mathematical Statistics and Data Analysis. Duxbury Press: Belmont, California. 594 pp.

Appendix 1.1. Pot sample data: database and GIS pre-processing

Queries were carried out from the rock lobster pot sampling (or 'catch monitoring') Oracle database. We excluded sample pot lifts (1) that were done by researchers chartering a vessel (where scientists direct the pot set to a location often chosen for biological investigation rather than being a pot lift set in the course of normal fishing operations), (2) where the GPS accuracy of the pot lift was reported by the fisher on the pot sampling form to be 'Poor', and (3) where the pot field indicator was "not catch sampling". This yielded a total of 79,890 sample pot lifts.

The legal catches at each sample pot lift, with GPS latitude-longitude coordinates were loaded as a point location layer into the ArcView 3.2 GIS ('geographic information system') spatial database software. Two polygon layers (i.e. maps) of (1) South Australian fisheries catch reporting ('MFA') blocks, and of (2) state territorial waters, were also obtained and loaded into ArcView.

Only sample catches were extracted from the 30 MFA blocks that intersected (in part or whole) the state territorial coastal zone. The state waters around the 402 islands were excluded. To include islands in the analysis would require deciding which combinations of islands to consider from a total of 402! (= 402*401*400*…*2*1) combinations. The exclusion of islands left 97.8% of the state waters' area included. Virtually no lobsters were harvested in the upper 2/3 of the two gulfs, and these blocks were also not included among the 30 blocks analysed (comparing Figure 1.2 with Figure 1.4). From the original total of 79,875 sample pot lifts extracted from the database, 76,814 or 96.2% fell into one of the 30 whole MFA-state blocks for which an average catch loss per unit area is to be calculated.

In each of the 30 blocks, a new polygon layer (of 'sub-blocks') was formed in ArcView as those portions of each of the 30 whole MFA blocks intersecting (lying inside) the state coastal jurisdiction. The totals of legal catch and sample pot lift numbers by yearly lobster season and by whole block and sub-block were summed and exported for use in the binomial estimator (Appendix 1.2). The surface areas of each MFA whole block (denoted '$A_w(b)$') and sub-block ('$A_{<3}(b)$') were also calculated. The state-water sub-blocks contributed 31,730 or 41.4% of the sample pot lifts and comprised 28.7% of the surface area in the 30 blocks.

As discussed in Methods, the 30 blocks were divided into two categories by the total number of pot lifts sampled. The 9 whole blocks (41, 46, 9, 45, 31, 17, 16, 2, 42) with less than 100 sample pot lifts over all 8 years were excluded from the catch-proportion-in-sub-block analysis. Assuming that fewer than 100 pots sampled provides an insufficient sample size to estimate the proportion of catch inside state waters, the proportion of surface area in these 9 blocks that fell in the sub-block, i.e. that intersected state waters was used in its place. Of whole blocks with less than 100 sample pot lifts, the highest was block 41 with a total of 58 pot lifts sampled over 8 years and the next was block 46 with 11 sample pot lifts.

One small but significant source of error remains in the latitude-longitude positions of sample pot lifts. The datums used by the GPS navigation coordinate system on each lobster boat were not recorded in the database. There are essentially two 'datum' standards in use, the Australian (AGD) datum and geocentric or 'world' (WGS and now GDA) datum. The datum specifies the overall coordinate system origin. Most fishers are probably unaware which datum they implicitly employ on their GPS's and this would generally create no error for their fishing operations since all previous marks would have been recorded and subsequently used with the single datum on their units. However between boats, a roughly 200 m SW-NE oriented difference in position is generated between the two commonly used datums. (Specifically, a latitude-longitude from a GDA-datum GPS unit will indicate a position 204 m to the SW of the same latitude-longitude read from an AGD-datum GPS.) Thus, pot lift positions have a minimum overall accuracy of 200 m due to the datum ambiguity. Introduced imprecision in the GPS satellite signal itself added another approximately 100 m of variation until 2000 when the USA government, who maintain the GPS satellite system, reduced its imprecision by an approximate order of magnitude.

Appendix 1.2. Sample catch proportion in sub-blocks: binomial likelihood

In this Appendix, the statistical algorithm of the binomial likelihood estimation is outlined. As outlined above, the objective was to estimate the proportion of catch that fell inside state territorial waters (in the 21 blocks with >100 pot lifts sampled). As noted in the Methods, uncertainty in this estimated proportion will be inferred from its reported yearly variation. The sample size of 8 fishing seasons of pot sampling data, 1993/94 to 2000/01 is 'small sample' by conventional definitions (Cochran 1977).

Let the estimate for the yearly average catch inside each MFA-state sub-block be denoted $\hat{\bar{C}}_{<3}$, where the "<3" subscript indicates the catch is inside the 3 nm limit of state waters. The 'hat' ($\hat{}$) indicates that the quantity is an estimate (not raw input data) and the bar that it is a yearly average. Upper case '*C*' will denote catch totals (either input data from catch logs, or the final estimates themselves) while lower case '*c*' will denote pot-sampled catches. This mean catch (by weight) in each sub-block will be estimated from (1) sampled catches inside each MFA-state sub-block ($c_{<3}(y,b)$), (2) sampled catches in each overall MFA block ($c(y,b)$), and (3) the catch-log-reported total catch in each year and MFA block ($C(y,b)$). The subscript "*b*" designates the MFA block under consideration, and "*y*" the year. An independent estimate of catch proportion is obtained for each MFA block. The bars over the catch symbols indicate averages over the years of sampling and catch-log history respectively, specifically

$$\begin{aligned}
\bar{c}_{<3}(b) &= \frac{1}{n_S}\sum_{y=1993}^{2000} c_{<3}(y,b) \\
\bar{c}(b) &= \frac{1}{n_S}\sum_{y=1993}^{2000} c(y,b) \\
\bar{C}(b) &= \frac{1}{n_C}\sum_{y=1990}^{2000} C(y,b)
\end{aligned} \qquad (1.1)$$

here n_C = 11, the number of fishing season years that catch-log catch totals (by weight) are averaged, from 1990/91 to the most recently completed fishing season, 2000/2001, and n_S = 8 years of pot sampling.

The standard ratio estimate is written

$$\hat{\bar{C}}_{<3}(b) = r(b)_c \cdot \bar{C}(b) \qquad (1.2)$$

where $r_c(b) = \bar{c}_{<3}(b) / \bar{c}(b)$ designates the 'raw catch ratio', a direct ratio of the mean yearly catches in sub-block over whole block. We seek a maximum likelihood estimate for this quantity. The analytic solution for the catch proportion of the binomial maximum likelihood estimator presented below has the exact solution given by Eq. 1.2.

We maximised a binomial likelihood to estimate the probability (call it 'p_c') that a unit of catch is taken from the sub-block. The probability $(1 - p_c)$ is the probability that an average unit of catch is harvested outside it in the rest of the whole block. The negative log of the binomial likelihood is written

$$-\log L_{p_C}(b) = \sum_{y[c[y,b]>0]=1993}^{2000} \left\{ -c_{<3}(y,b)\cdot\log\left[p_c(b)\right] - \left(c(y,b)-c_{<3}(y,b)\right)\cdot\log\left[1-p_c(b)\right] \right\}$$

.(1.3)

Note, this negative-log-likelihood sum will exclude years for each block when no pot samples were obtained. The parameters to be estimated are $\{p_c(b),\ b=1,21\}$, for the 21 blocks with 100 or more sample pot lifts. One parameter value of catch proportion in sub-block b ($\hat{p}_c(b)$) was estimated for each block, by numerically minimising $-\log L_{p_C}(b)$ using the AD Model Builder software.

The estimate of average historical yearly catch from each sub-block ($\hat{\bar{C}}_{<3}(b)$ in Table 1.4) was obtained as the product of the 11-year average of logbook catches in each whole block ($\bar{C}(b)$) times the estimated proportion of catch taken from inside each sub-block ($\hat{p}_c(b)$):

$$\hat{\bar{C}}_{<3}(b) \doteq \bar{C}(b)\cdot \hat{p}_c(b) \qquad (1.4)$$

since $\bar{C}(b)$ is assumed given without error.

The asymptotic approximation for the standard error of the estimate of $\hat{p}_c(b)$, denoted $SE\left[\hat{p}_c(b)\right]$, was obtained numerically as the inverse of the second derivative with respect to the parameter ($p_c(b)$) of the minus log likelihood at the maximum. This implicitly approximates the binomial by a normal in the neighbourhood of the likelihood maximum, generally a satisfactory approximation for estimating confidence intervals (Cochran 1977; Rice 1995). This gives the percentage error of the $\hat{p}_c(b)$ estimate, call it the CV_{SE}, $CV_{SE}\left[\hat{p}_c(b)\right] = SE\left[\hat{p}_c(b)\right] / \hat{p}_c(b)$. Thus the overall standard error of yearly average catch in each sub-block becomes

$$SE\left(\hat{\bar{C}}_{<3}(b)\right) \doteq \hat{\bar{C}}(b)\cdot CV_{SE}\left[\hat{p}_c(b)\right]. \qquad (1.5)$$

In the final estimate to incorporate movement and egg production as compensating factors for catch lost in potential MPAs, an MCMC integration will not make the asymptotic approximation insofar as it integrates the unapproximated binomial.

However, in this chapter for purposes of reporting standard errors of the estimates the asymptotic approximation was useful (Table 1.4).

It would have been possible to generate analytic formulas for the estimates of $\hat{\hat{C}}_{<3}$, by solving for the analytic maximum of the binomial log-likelihood. However, this would yield the same estimates we obtained numerically. Moreover, in subsequent stages of this analysis, notably when movement rate, estimated from tag-recoveries, is considered in the overall estimated net loss in long-term catch, a Bayesian analysis is foreseen. For this purpose a numerical likelihood is required. The AD Model Builder software allows both likelihood maximisation (used to obtain the numerical parameter estimates and their confidence intervals reported above) and integration of the Bayesian posterior, to be undertaken in Chapter 4.

CHAPTER 2. Yearly emigration rate of rock lobsters out of the Gleesons Landing Lobster Sanctuary

Introduction

The objective of this chapter is to obtain an estimate of net movement rate out of one lobster sanctuary in South Australia where lobsters were tagged and released. The proportion of lobsters that emigrate out of a lobster reserve yearly is estimated for the Gleesons Landing Lobster Sanctuary bordering the west coast of Yorke Peninsula. This estimate of movement rate will be used to account for catches from lobsters that settle as puerulus within reserves and subsequently move out, making them liable for capture in the commercial fishery. This emigration of lobsters out of no-take areas and subsequent capture represents a potentially important reduction in the long-term net catch loss from no-take areas established in MPAs along coastal zones inside state waters. It is the purpose of the calculation presented in this chapter to quantify that rate of emigration using the one tag-recovery data set that is available in South Australia.

Gleesons Landing Lobster Sanctuary is an area from where lobster fishing has been excluded. It lies along the Yorke Peninsula coast south of Corny Point in an area of medium to low lobster catches per unit area. In width, the sanctuary extends out 1-2 km from shore to seaward and runs about 7-8 km north-south along the coast.

Prescott et al. (1997, pp. 23-27) described a number of clear trends in the movements of South Australian *Jasus edwardsii* from the lobster tagging program: (1) Nearly all larger movements were directed offshore to deeper water and away from the coast. (2) In order of greater to lesser average distances moved, were (i) immature females, (ii) males, and (iii) mature or egg bearing females, for nearly all five South Australian regions analysed. (3) Movements were largely restricted to lobsters in a specific length range at time of tagging, roughly 100-140 mm CL for females, and 100-150 mm CL for males, with a noticeable shift to smaller sizes for both sexes in the Southeast where growth and thus size of maturity are known to be lower. (4) Overall, most lobsters in the fished areas did not move large distances, about 12% moving more than 5 km. (5) Two areas stood out as being habitats from where significant movement was observed, the coastal zone off the Coorong, and Yorke Peninsula. (6) In Yorke Peninsula, nearly all tagged lobsters that moved significant distances were tagged and released in Gleesons Sanctuary.

Prescott et al. (1997, p. 26) concluded that "Within the Yorke Peninsula region, migrating lobsters originated from the lobster sanctuary. Lobsters emigrated to the north-western end of Kangaroo Island and to many of the scattered reefs and around islands in a southwest arc to the southern end of the Eyre Peninsula. Lobsters within a several kilometre radius [outside] of the sanctuary remained at or near their release sites. The extraordinary difference in migration behaviour between the two groups over such a small spatial scale suggests that high lobster density within the sanctuary induced lobsters to move out of this area." Thus, if the Gleesons Landing sanctuary is representative, higher rates of lobster movement are anticipated from no-take zones as densities rise. This hypothesis will be examined below.

The historical catches per unit area derived in Chapter 1 were yearly totals. Similarly, the overall net catch loss whose estimation is the principal objective of this project, will also be an annual rate, from which the number of pots needing buy-out will be estimated. Thus the goal of this chapter is to estimate the proportion of lobsters moving out of the sanctuary per year. This proportion will be applied in estimating overall net catch lost yearly from each MFA sub-block.

We define movement by a measured distance of greater than 3 km from point of tagging to point of recapture. This definition of lobster 'movement' is chosen for three reasons:

1. Most importantly, the mean width of MPA coastal zone to be protected in the current state representative system is assumed to be 5 km wide, that is, it is assumed that the no-take areas to be declared will extend from the shore outward to sea across the full 3 nm (which is about 5 km) of state territorial waters. Thus, a 3-km movement would represent the mean distance needed for lobsters to leave the state territorial waters of no-take zone, and enter fished waters. This assumption is further strengthened by the knowledge that most longer-range movements of the sort we seek to quantify here are in a uniformly offshore direction.

2. In this study, a 3-km movement seaward from any location in Gleesons Landing Sanctuary will place the tagged lobster well into the fished zone, i.e. it would constitute a movement out of the sanctuary whose proportion we seek to estimate. In fact, a movement over distances of approximately 1 km from the locations of tag-release inside the sanctuary would also put most lobsters outside of Gleesons, but few lobsters (4 of 33 recaptured in the first season after tagging) that emigrated from the reserve moved less than 3 km, the mean distance moved from the sanctuary being 37.4 km.

3. 3 km is a large enough distance to exceed normal tag-release and tag recovery GPS position measurement errors of about ±300 m.

The principal obstacle to successfully quantifying rate of movement out of this no-take reserve is the absence of any recaptures from inside the sanctuary where fishing is, of course, excluded. If this asymmetry in sampling (of recaptures coming only from lobsters that did, in fact, emigrate) were ignored, the yearly proportion emigrating out of the sanctuary would be overestimated. An estimation method was therefore developed and used which employs information about (1) the total numbers tagged inside and outside the reserve, and (2) the relative numbers recaptured in the fished zone, to infer the yearly proportion moving out of the sanctuary.

Methods

Data

The data used to estimate emigration rate from Gleesons Sanctuary are a tag-recovery data set of lobsters tagged and released both inside the sanctuary and in the fished zone surrounding the sanctuary. An extensive South Australian lobster tagging program was undertaken in 1993-1996 during FRDC project 93/087. In January

1994, Greg Ferguson, with fishers Lenny and Murray Williams, took a commercial lobster boat into the Gleesons Landing Lobster Sanctuary and over a week, captured, tagged and released 413 southern rock lobsters (*Jasus edwardsii*) into the no-take zone. Substantial numbers of lobsters were also tagged and released back into the fished coastal zone around the Yorke Peninsula surrounding Gleesons Sanctuary, namely into MFA blocks 33 and 40 (Figure 2.1).

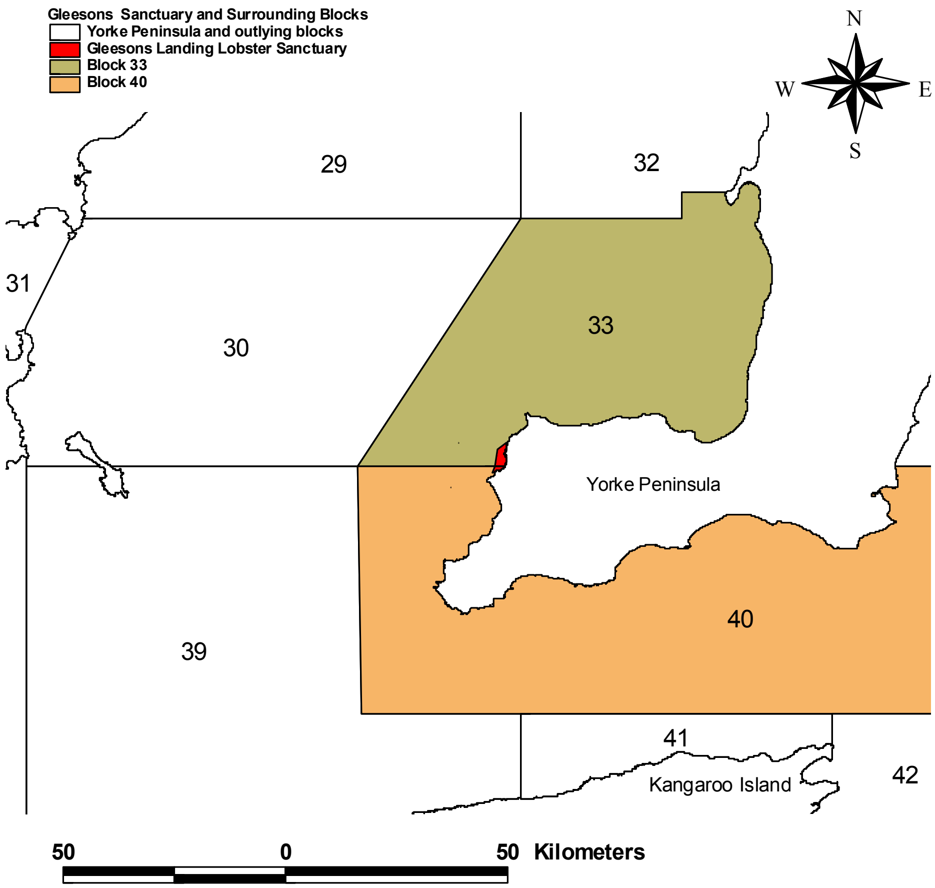


Figure 2.1. Location of Gleesons Landing Lobster Sanctuary (small red area on boundary of MFA blocks 33 and 40) along the west coast of the Yorke Peninsula.

Recoveries of tagged lobsters were nearly all reported by commercial fishers who noticed tagged lobsters in their catch in the course of day-to-day lobster fishing operations. GPS coordinates were recorded for all tagged and recaptured lobsters.

There are three principal limitations in using tag recoveries obtained from commercial fishing operations for estimating emigration rate of lobsters (or any exploited species) out of no-take areas:

1. The times-at-large are highly variable. The number of days from when each lobster is tagged and released to subsequent recapture in the fishery is not under scientific control.

2. The usual problem of tag non-reporting inheres: That is, some tagged lobsters are captured in commercial lobster pots but are not, for any reason, reported back to researchers maintaining the tag-recapture database.

3. There is an added potential bias with tagging into no-take areas: Tag recoveries cannot be obtained from inside no-take reserves for the simple reason that no fishing is allowed there. No subsequent research potting was undertaken, and thus no tag recoveries were obtained, from inside the sanctuary. Recaptures of tagged lobsters were therefore possible only in the fished zone outside the sanctuary.

If this asymmetry (of recoveries from the sanctuary only being obtainable from those lobsters that moved out) is not accounted for, then the rate of emigration out will be overestimated. A principal objective of the movement rate estimator presented in this chapter is to be unbiased for data sets from no-take areas using tag-releases into both the no-take area and surrounding fished zone, but where tag recoveries from emigrating individuals can only be obtained once they have moved out into the fished zone.

Some tagged and released lobsters were recaptured more than once. For these multiple recapture lobsters, only one of these recaptures is used. We sought to maximise the overall sample size by selecting the one of multiple recaptures that fell within the usable data set for this emigration estimate (namely those in the water for about a year). Therefore for lobsters recaptured more than once, the recapture used was the one for which the time-at-large was closest to one full year.

Exploratory Graphical Analysis

A graphical analysis of the tag and recovery data set was undertaken to assess its properties for movement analysis. Specifically, histogram distributions and scatterplots were graphed as numbers of recaptured lobsters from both sanctuary and fished zones in order to compare the movement behaviour of lobsters from no-take and exploited habitats.

Recapture lobster numbers were partitioned into histogram bins by (1) distance travelled, and (2) time-at-large, the latter defined as the time, in years, between when each lobster was tagged and released and when it was recaptured. Significant difference in distance travelled of lobsters from the fished zone versus those from the sanctuary could signal a different tendency to move from the sanctuary. We considered the distributions of distances moved over several spatial scales to examine potential features of movement behaviour as differences between fished and no-take. The lower rates of removal of recruiting adults inside the reserve (in the absence of fishing) may potentially give rise to a greater distance moved or a higher proportion moving away from their home reefs in the no-take area, as suggested by Prescott et al. (1997).

The recapture data include lobsters in the water for a wide range of times-at-large, many having been recaptured longer than one year subsequent to tag-release. However, to estimate emigration rate, we seek the proportion of lobsters emigrating out per year. Therefore, a principal objective of the graphical analysis is to select a subset of recaptures from both fished and protected areas that have a mean time at large of one year to quantify a yearly emigration rate.

Assumptions

In this subsection, the set of assumptions used to derive the emigration rate estimator formula (in the next subsection) are summarised. The first two assumptions were employed explicitly in Steps 1 and 2 below:

1. The two ways to define an estimate for proportion moved within the fished zone, namely as a proportion using only recaptured lobsters, and as a proportion over number originally tagged, can be set equal.

2. Catchabilities of lobsters that were tagged and released inside the sanctuary and moved equal those that were tagged and released outside and moved. In other words, we assume the recovery proportion of lobsters that moved from the sanctuary equals the recovery proportion of lobsters that moved (≥ 3 km) within the fished zone.

Also, implicit in Step 1, specifically in the first way to estimate proportion moved in the fished zone ($P_M^{F,1}$ in Eq. 2.2), is a third assumption:

3. Catchabilities of lobsters tagged and released in the fished zone that moved and those that did not move are equal.

In order to apply these results to estimating movement of lobsters out of no-take reserves throughout South Australia, two further assumptions are implied:

4. The rates of movement and non-movement of tagged lobsters is the same as that of the lobster population overall (as assumed for all stock assessment inference using tag-recovery data).

5. Estimates obtained here for Gleesons Landing are applicable to other lobster sanctuaries.

Emigration Rate: Estimate Formula Derivation

In this section, an analytic formula is derived, which provides a closed form solution for the estimate of yearly proportion emigrating out of the sanctuary. The estimate is given in terms of the following data inputs: the numbers tagged and released in (1) fished and (2) protected zones, and the numbers recovered that (3) moved (≥ 3 km) or (4) did not move from the fished zone over one year subsequent to tagging, and the (5) number that moved (≥ 3 km) from the sanctuary in one year. This closed form solution is one of two estimation methods for yearly emigration rate presented in this chapter. A second, likelihood method, is described in Appendix 2.2.

To carry out this derivation, we consider 4 possible outcomes for each tagged lobster: moved and recovered after one year (denoted M,R1), not moved and recovered after one year (NM,R1), moved and not recovered after one year (M,NR1), not moved and not recovered after one year (NM,NR1). These 4 possible outcomes must be considered separately for lobsters tagged inside, and for those tagged outside the sanctuary. The "1" in "R1" indicates recovery in the 1-year subsequent to tagging.

The derivation to follow will assume an ideal experiment where all tagged lobsters were recaptured exactly one year later. In practice, we do not control the times of recapture, being opportunistically carried out by commercial fishers in the course of daily fishing operations. As discussed further in the next subsection, the observed numbers of recaptures after one year at large will be approximated by the numbers recovered over a time-at-large interval of 0.5 to 1.5 years subsequent to tagging.

We define 'not recovered' to include both tagged lobsters that were not recaptured, as well as those that were recaptured by a commercial fisher but whose tag information was not reported back to researchers and therefore is not included in the tag-recovery database.

The tag-recovery data set provides direct measures for only 3 of these 8 possible inputs. From the releases into the fished zone (denoted by superscript '*F*') we use $N^F_{NM,R1}$ and $N^F_{M,R1}$, the numbers of lobsters that were recovered after a year and moved or that did not move. From lobsters tagged and released inside the sanctuary (superscript '*S*'), only the number that moved and were recovered ($N^S_{M,R1}$) is available as an unbiased measure.

In addition, we know the total number of lobsters originally tagged inside and outside the sanctuary, N^F_T and N^S_T. Data inputs from the tag-recovery data set will be denoted by a tilda (˜): $\{\tilde{N}^S_{M,R}, \tilde{N}^S_T, \tilde{N}^F_{NM,R1}, \tilde{N}^F_{M,R1}, \tilde{N}^F_T\}$.

For several of the proportions we estimate, two forms of definition are possible. One way proportions (notably proportions moved from both sanctuary and fished area) can be written is as a proportion of the total *number originally tagged* and released. The second definition calculates movement rate as a proportion of the total *number recaptured*. In the derivation to follow, this dual way to define the same quantities will be used to obtain an analytic formula in terms of the five data inputs. These two ways to define movement rate are denoted 'tag-conditioned' and 'recapture-conditioned'.

Step 1. The derivation begins by writing the estimate for proportion moved P^S_M in tag-conditioned fashion as a proportion of all tagged lobsters that move over one year, including both those recovered and those not recovered:

$$P^S_M = \frac{\tilde{N}^S_{M,R1} + N^S_{M,NR1}}{\tilde{N}^S_T}. \qquad (2.1)$$

We base the estimate on a tag-conditioned proportion moved from the sanctuary because, as noted, we have no recaptures for lobster not moving inside the sanctuary which the recapture-conditioned movement proportion would have required as input. We do, on the other hand, have information about the non-recovery of tagged lobsters that emigrate from the sanctuary into the fished zone, which the tag-conditioned proportion (2.1) above requires, assuming the rate of tag recovery is the same for fished- and sanctuary-tagged lobsters. Thus, two of these quantities ($\tilde{N}^S_{M,R1}$ and $\tilde{N}^S_T$) are available from the tag recovery data set and we now need only a way to infer $N^S_{M,NR1}$, the number of lobsters tagged in the sanctuary that moved out but were not recovered. This is carried out in Steps 2 and 3 below:

Step 2. In this step, Assumption 1 above is used. We write the movement proportion in the fished zone two ways, as tag- and recapture-conditioned proportions. We then set them equal.

For the fished zone, a recapture-conditioned measure of movement proportion (P^F_M) is written:

$$P^{F,R}_M = \tilde{N}^F_{M,R1} \ / \ (\tilde{N}^F_{NM,R1} + \tilde{N}^F_{M,R1}) \ . \qquad (2.2)$$

The superscript "R" on P^F_M refers to the proportion being recapture-conditioned. All three quantities on the right-hand side are given as data inputs. This way of estimating P^F_M, the first of two to be employed, used only lobster numbers recovered. It is, in this sense, conditional on recapture. Because recaptures comprise the data we have available, all quantities in this definition are provided by the tag-recovery data set, i.e. no unknowns appear on the right-hand side.

The proportion moving within the fished zone can be expressed a second way:

$$P^{F,T}_M = (\tilde{N}^F_{M,R1} + N^F_{M,NR1}) \ / \ \tilde{N}^F_T \ . \qquad (2.3)$$

This second form for P^F_M is conditional on tag-release—i.e. the proportion of lobsters moving over the one-year time interval is defined as a fraction of all lobsters tagged and released, not only of those recovered as in $P^{F,R}_M$.

The first assumption is written

$$P^{F,R}_M = P^{F,T}_M \ . \qquad (2.4)$$

Substituting Eqs. 2.2 and 2.3 into 2.4 and solving for $N^F_{M,NR1}$, the number that moved in the fished zone ≥ 3 km but were not recovered, yields:

$$N_{M,NR1}^{F} = \tilde{N}_{M,R1}^{F} \cdot \left\{ \frac{\tilde{N}_{T}^{F}}{\tilde{N}_{NM,R1}^{F} + \tilde{N}_{M,R1}^{F}} - 1 \right\}. \tag{2.5}$$

Step 3. The second assumption permits the derivation of a formula for $N_{M,NR1}^{S}$. We first define the recovery proportions of lobsters that moved in the fished zone (F)

$$f_{M}^{F} = \frac{\tilde{N}_{M,R1}^{F}}{\tilde{N}_{M,NR1}^{F} + \tilde{N}_{M,R1}^{F}} \tag{2.6}$$

and from the sanctuary (S)

$$f_{M}^{S} = \frac{\tilde{N}_{M,R1}^{S}}{N_{M,NR1}^{S} + \tilde{N}_{M,R1}^{S}}. \tag{2.7}$$

The second assumption is that the rates of recovery, *f*, of lobsters that moved were the same regardless of where they were originally tagged. That is, the recovery rate (necessarily in the fished zone) is the same for lobsters that were tagged in the sanctuary and moved into the fished zone as for those both tagged and recaptured in the fished zone:

$$f_{M}^{F} = f_{M}^{S}. \tag{2.8}$$

Substituting (2.6) and (2.7) into (2.8) and rearranging terms, we have

$$N_{M,NR1}^{S} = \frac{\tilde{N}_{M,R1}^{S} \cdot \left(N_{M,NR1}^{F} + \tilde{N}_{M,R1}^{F} \right)}{\tilde{N}_{M,R1}^{F}} - \tilde{N}_{M,R1}^{S}. \tag{2.9}$$

Step 4: Substituting (2.5) into (2.9) and that into (2.1) yields a closed-form estimation formula for the quantity we seek, the proportion moving from the sanctuary in one year:

$$P_{M}^{S} = \frac{\tilde{N}_{T}^{F} \cdot \tilde{N}_{M,R1}^{S}}{\tilde{N}_{T}^{S} \cdot (\tilde{N}_{NM,R1}^{F} + \tilde{N}_{M,R1}^{F})}. \tag{2.10}$$

Numbers Recaptured After One Year: Theory and Application

The derivation above assumes recapture data inputs (moved or not moved) are obtained under the ideal experiment where all recaptures are taken exactly one year subsequent to tag release. Because this was never technically (or financially) feasible, we relied on the reported tag returns by commercial fishers.

Below (in section Results, Exploratory Graphical Analysis, Time at Large), we examine the temporal distribution of recaptures and conclude that the modes about 1 full year (recaptures between 0.5 and 1.5 years at large, Figure 2.2) would provide the best subset for estimating movement rate. It is unbiased in that these lobsters were in the water for about one year on average, and yields sufficient sample size.

Nevertheless, the underlying definition of numbers moved or not moved remains the same, namely it is the numbers of tagged lobsters that moved ≥ 3 km in one year after tag and release. The recapture numbers in the 1-year modes of Figure 2.2, from 0.5 to 1.5 years at large, represent approximations to the ideal numbers that would have been obtained had all recapture fishing occurred exactly one year subsequent to tag-release.

There is one additional assumption made in this approximation, namely the differences in mortality over that time and prior to it are neglected. That is, the presumably higher mortality of lobsters that are in the fished zone, and thus the corresponding difference in recovery rate between fished zone and sanctuary lobsters is neglected. However, the error (a second order effect, notably since these differences in mortality occur top and bottom in the movement proportions) is likely to be small, especially by comparison to Assumption 5 above.

Results

Exploratory Graphical Analysis

Time at Large

The most important objective of the exploratory graphical analysis is to select the subset of recaptures that were in the water, on average, for one year. That is, we seek a data set with a mean time at large of one year from both sanctuary and fished zone. The two histograms of all recaptures by time at large (Figure 2.2) show clear modes at yearly intervals of 1, 2, 3, etc. years at large. The largest mode of recaptures is between 0.5 and 1.5 years at liberty. These are the recaptures we seek. The mean times-at-large of recaptures between 0.5 and 1.5 years are, for the fished zone, 1.03 years plus or minus a standard error of 0.18, and for the sanctuary, 0.925 ± 0.017 years. The fished zone mean of 1.03 years is close to 1 (compared with its SE), but the mean time at large from sanctuary recaptures (at 0.925) is, on average, shorter by about a month than one full year.

However, it would make no sense to remove data points in order to raise the mean time-at-large in the sanctuary, since this would bias the estimate of emigration rate, lowering it. Recall that each recapture from the sanctuary is a vote for movement out—lobsters voting with their feet as it were. So the 0.5-1.5 year selection of data points chooses (i) for the sanctuary, all of the (33) recaptures in the visually distinct 1-year sanctuary mode (Figure 2.2) and (ii) all of the fished zone (366) recaptures that were at liberty for from 0.5 to 1.5 years. We shall refer to this subset of recaptures that were at large for from 0.5 to 1.5 years as the emigration yearly rate ‘estimate data subset’.

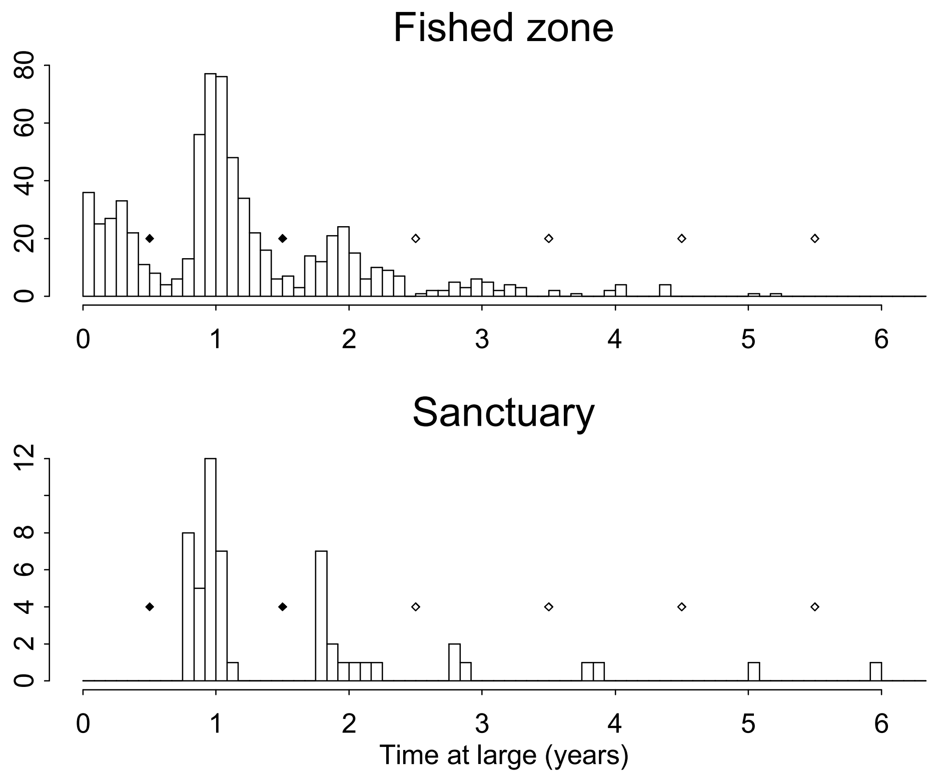


Figure 2.2. Histogram of times-at-large of recaptures from Gleesons Lobster Sanctuary and the fished zone of MFA blocks 33 and 40. The diamond points indicate bin separators at 0.5, 1.5. 2.5, etc. years-at-large. The black diamond points, those between 0.5 and 1.5 years at large, identify the sets of data from sanctuary and fished zone selected to estimate yearly emigration rate from the sanctuary.

Distance Moved

The rate at which southern rock lobsters move out of a no-take area is presumably strongly linked to its natural movement behaviour. In particular, it has been well shown in field studies (MacDiarmid et al. 1991; Booth 1997; Gardner et al. submitted), and those were confirmed for South Australian lobsters (Prescott et al. 1997), that most stay close to their home reefs of hard rock, preferably under rock shelfs or caves or other shelters from predators. They forage mostly at night within a few hundred meters of their home reef searching for food, and return back to that same home reef after foraging (MacDiarmid et al. 1991; Kelly 2001). It appears that the majority never leave their home reef. Other aspects of their behaviour is highly structured in a social sense, with hierarchies among males, and sometimes sexual spatial disaggregation. Thus their behaviour patterns are notably rich and complex.

Different characters of movement behaviour can be identified by examining qualitative patterns in the tag-recovery data. In this section, we seek to identify features of rock lobster movement behaviour by examining distributions of distances travelled by lobsters from fished zone and sanctuary. In particular, we seek evidence for or against the hypothesis suggested by Prescott et al. (1997) that movement rates from sanctuaries are higher than average, because of higher densities and/or other social forces. These density-dependent forces are presumably stronger inside the sanctuary due to the lower rates of removal of currently residing lobsters on these 'home reefs' in the absence of fishing. Lobster movement is higher at specific stages of their life history (notably for immature females and younger mature males, Prescott et al. 1997) further indicating a social dynamic of movement behaviour linked to reproduction. One hypothesis is that as juveniles approach the age of maturity (principally just before maturity for females, and just after for males), when home settlement reefs are crowded, lobsters emigrate, generally in an offshore direction, to seek new less crowded rocky reef habitat. These density dependent effects would constitute a likely cause of higher movement from MPA no-take areas if such higher rates were observed.

Scatterplots of Distance versus Time-at-Large

The broadest scale view of distance moved allows us to examine the possibility that distance away from home reef increases over time. If movement were a random walk (no home reef) or if the minority of lobsters that did move from their home reef adopted a nomadic existence or continued searching for a new home reef over time scales of a year or more, then the mean distance moved of recaptured lobsters should increase with time.

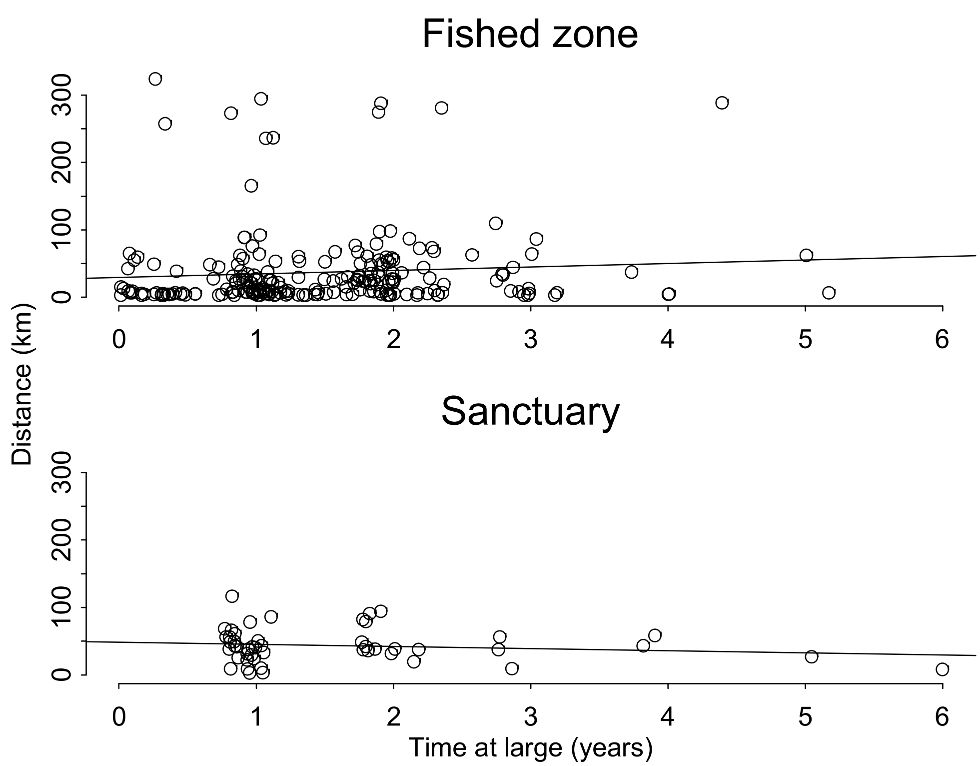


Figure 2.3. Scatterplots of distance moved versus time-at-large. Least squares regression lines are plotted.

The scatterplots of distance versus time-at-large (Figure 2.3) show (1) for the fished zone, only very slow increases in distance moved with increasing number of years at large, and (2) for the sanctuary, there is no evidence of increase in distance moved versus time. Overall, change in mean distance moved over the six years shown is small compared with the spread of individual distances moved. Thus, longer distance movement is, in most cases, a one-off event. The most likely hypothesis is that lobster movement over distances of more than a couple kilometres is something that happens only rarely and that when it does, the movement is not an ongoing process. The lobster leaves the home reef and then settles again somewhere else.

One feature is the presence of 11 recaptures from releases into the fished zone that moved relatively very large distances (the scatter of points along the top of the Fished Zone scatterplot in Figure 2.3), 10 of these over 200 km, much larger than the majority of those that did move in the fished zone. These 11 outliers constitute much longer distances travelled than in most of South Australia. Moreover, they appear essentially randomly distributed over time-at-large. Two of these recaptures that moved the farthest were at large for only about half a year, and five of them were among the estimate data set at large for about 1 year. No explanation is evident for these very long movements. Some (or even all) may represent recording errors, though we did check the original records.

<u>Histograms by Distance: Longer Distances</u>

The principal objective in comparing fished zone and sanctuary over longer scales of distance moved is to assess whether there is a significant difference in how far lobsters move from sanctuary habitat, compared with those in the fished zone, when they do move. Two questions are asked: (1) Do lobsters moving out of the sanctuary move far enough to exit the 5-km-wide state territorial waters proposed for no-take zones under current consideration? (2) Is there any tendency for lobsters from the sanctuary to move farther, on average, than those from the fished habitats of MFA blocks 33 and 40?

The histogram comparing distances moved by lobsters inside the sanctuary and those tagged in the fished zone (Figure 2.4) illustrate a difference in movement behaviour of lobsters tagged and released into the two habitats. These histograms include only the estimate data subset of recaptures in the water for a year on average (those between the black diamonds in Figure 2.2 used for the emigration rate estimate). Moreover, since no recaptures from the sanctuary were possible that moved less than about 1 km, in order to fairly (graphically or quantitatively) compare the range of distances moved from sanctuary and fished area, the lobsters that moved less than 1 km were left out of the fished area histogram. Also excluded were the five ‘outliers’ that moved > 130 km in the fished zone to allow the graphs to show more detail.

Thus, there is strong evidence from the histograms of (longer) distances moved (Figure 2.4) that lobsters from the sanctuary move greater distances when they move. One explanation may be that density-dependent processes, presumed to be acting more strongly in the sanctuary, affected not only the proportions moving, but also the distance moved when movement took place.

Possible exceptions to farther distances being moved by sanctuary lobsters are the five very long-distance moving (≥ 130 km) lobster recaptures from the fished zone. However, these were sufficiently rarely occurring in fished zone recaptures that it is unlikely we would have observed this infrequent outcome in the smaller sanctuary recapture sample. This is quantified statistically as follows: The proportion of these longer moving lobsters from the fished zone (5 of 366 from the estimate data subset), about 1.4%, is such that if this same probability of occurrence is assumed for sanctuary-released lobsters, the probability that we should expect to observe zero moving $\geq$ 130 km is 63.5% from the sample of 33 1-year sanctuary-recaptures (calculated as a binomial probability of $x = 0$ for $p = 5/366$, and $n = 33$.)

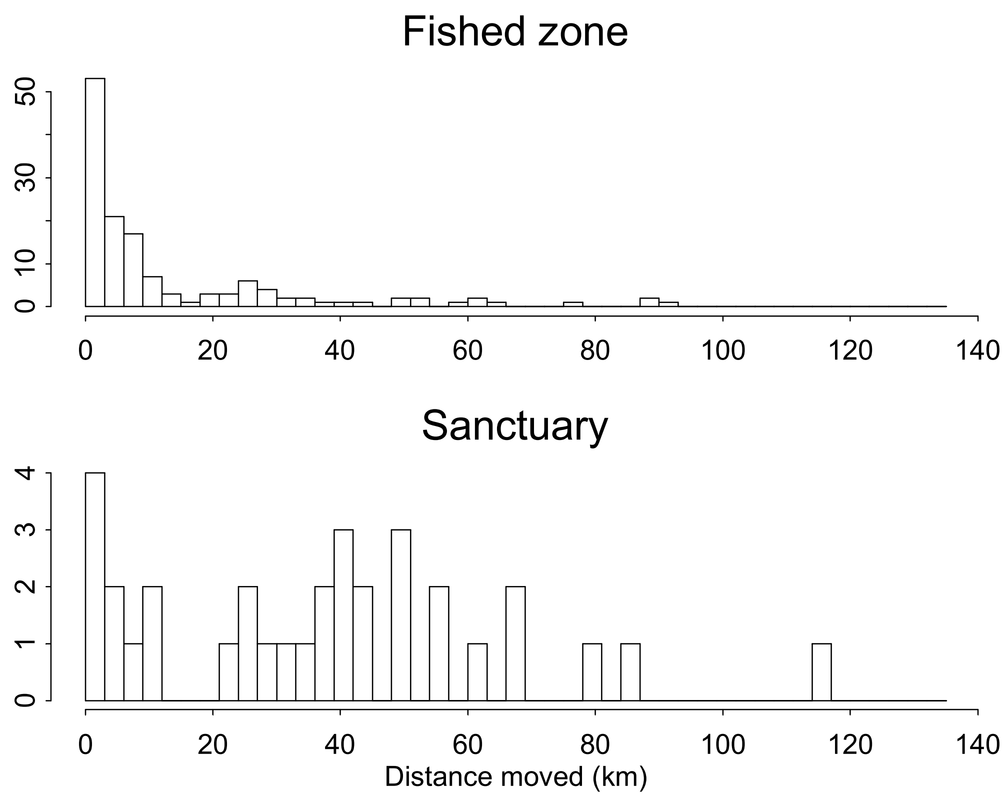


Figure 2.4. Numbers of recaptured lobsters moving various distances from tag to recapture (in 3-km bins) from sanctuary and fished areas. Recaptures were only included that (1) were at large for 0.5 to 1.5 years (between black diamonds of Figure 2.2), (2) moved > 1 km and (3) moved < 130 km.

Thus, over these distances which would result in emigration from proposed state-waters MPA no-take zones, there is strong evidence that lobsters from the sanctuary move greater distances (when they move > 1 km).

Histograms by Distance: Shorter Distances

A closer examination of the recaptures of lobsters that moved relatively shorter distances provides another opportunity to compare movement behaviour patterns. The question that we ask in this subsection is, ‘Of those that moved shorter distances, do lobsters from the sanctuary express different behaviour than those in the fished area?’

The histograms of all recaptures that moved 5 km or less (Figure 2.5), indicate qualitatively different distributions of distances travelled. The fished zone lobsters are exponentially distributed with declining numbers recaptured at successively farther distances from the home reef. The sanctuary lobsters, show no evident pattern and constitute what must differ non-significantly from a uniform distribution. The differences in the two distributions are sufficiently evident graphically that no statistical analysis should be needed to convince the reader.

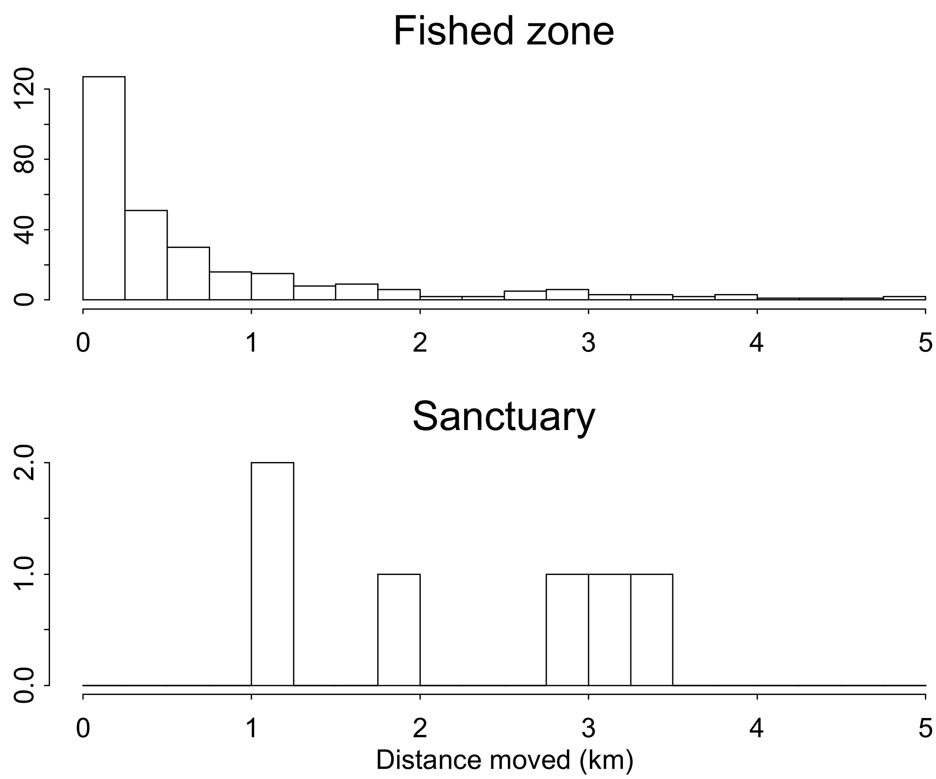


Figure 2.5. Histograms (0.25 km bins) from the estimate data subset (in water for a year) of distances moved up to 5 km for all lobster recaptures from fished zone and sanctuary.

A second set of histograms, over 1-20 km was also plotted where, as in Figures 2.4, we exclude all lobsters from the fished zone that moved less than 1 km to prevent them biasing the comparison between sanctuary and fished area. The outcome is the same as for Figure 2.5, namely that the fished zone recapture distances are exponentially distributed, and the sanctuary distances are more nearly random (i.e. uniform).

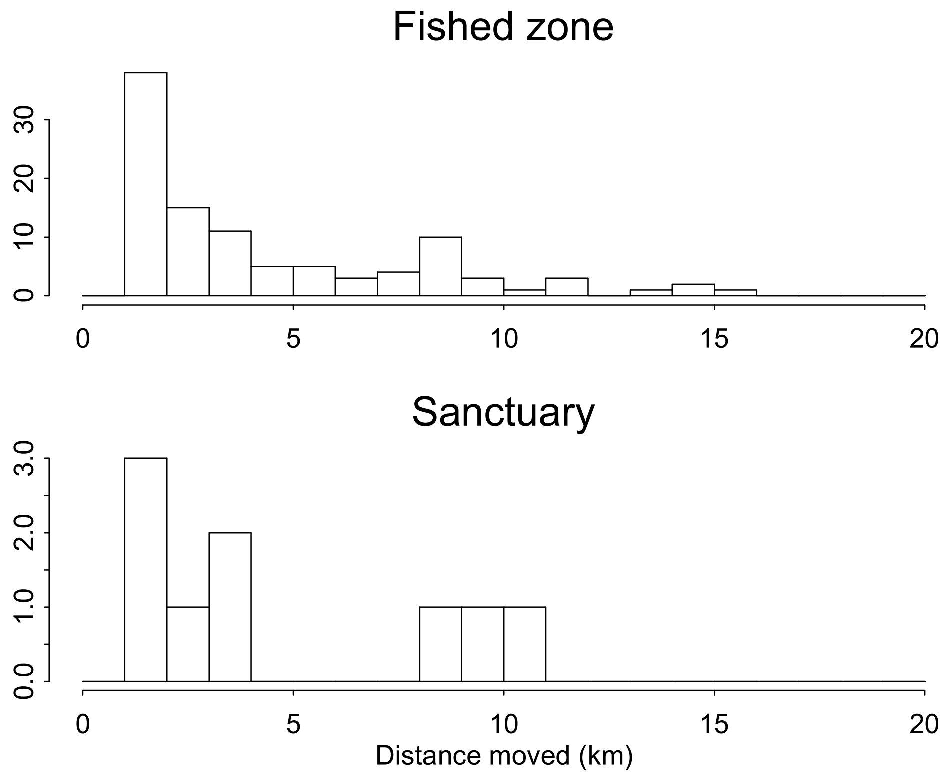


Figure 2.6. Histograms (1 km bins) from the estimate data subset (in water for a year) of distances moved up to 20 km from fished zone and sanctuary (excluding recaptures that moved < 1 km).

Thus, the outcome is consistent over several spatial scales: Lobsters tagged and released in the fished zone appear to demonstrat a stronger tendency, as exponentially distributed distances, to stay close to their home reefs (1) for all recaptures (Figure 2.5), and (2) for those that did move > 1 km (Figure 2.6). Thus, distances moved again show a qualitative difference between movement behaviour of lobsters from the sanctuary and those in the fished zone.

Input data for movement rate estimation

The principal objective of this Chapter 2 is to estimate the proportion emigrating out of the sanctuary yearly. This emigration rate will be inferred from the estimate data subset, restricted to recaptures in the water about a year, specifically recaptures at large from 0.5 to 1.5 years. In this section, we specify the 5 tag and recapture numbers which will be taken as data inputs to the emigration rate estimate.

Details of the database query and pre-processing are summarised in Appendix 2.1. This includes the first two data inputs of numbers tagged and released in (i) sanctuary and (ii) fished zone, N_T^S and N_T^F. From the 1-year modes (recaptures between 0.5 and 1.5 years at large, Figure 2.2), of 366 1-year recaptures from the fished zone, (iii) ($\tilde{N}_{M,R1}^F$=) 89 moved and (iv) ($\tilde{N}_{NM,R1}^F$=) 277 did not move 3 km.

From the sanctuary, only 4 of 33 1-year time-at-large recaptured lobsters had moved < 3 km. These were essentially discarded (not used in the emigration rate estimate) since they likely constitute a vast underestimate of the total numbers that would have been recovered from the sanctuary that moved 3 km or less. The remaining data input is (v) the number that moved (≥ 3 km) from the sanctuary (in one year ($\tilde{N}^S_{M,R1}$=29). These results are summarised in Table 2.1.

Table 2.1. Data inputs: the numbers of lobsters tagged and released $\{\tilde{N}^S_T, \tilde{N}^F_T\}$, and numbers that were recovered and had moved greater than 3 km either out of the sanctuary $\{\tilde{N}^S_{M,R1}\}$ or in the fished zone $\{\tilde{N}^F_{M,R1}\}$, and the numbers recovered that had moved less than 3 km within the fished zone $\{\tilde{N}^F_{NM,R1}\}$.

Data input variable	Observed number tagged and released or recovered
$\tilde{N}^S_T$	413
$\tilde{N}^S_{M,R1}$	29
$\tilde{N}^F_T$	3235
$\tilde{N}^F_{M,R1}$	89
$\tilde{N}^F_{NM,R1}$	277

Estimate of Yearly Movement Proportion

The closed-form estimator derived above gives an estimate for proportion moved from the sanctuary (P^S_M) of 0.6206. Thus about 62% of the lobsters tagged in Gleesons Sanctuary moved out. The maximum-likelihood estimated value, carried out numerically using the double-hypergeometric likelihood described in Appendix 2.2, yielded a value of 0.6212.

The two estimates agree closely. The small difference (0.09%) between them is presumably due to the use of the numerical approximation for the log-gamma function by the expansion of Eq. (2.A.5). The close agreement suggests that the numerical likelihood is properly formulated and that the error introduced by that approximation is small.

The numerical estimation of emigration rate will be integrated into the overall likelihood for net catch loss per unit area in each MFA sub-block, which contains the additional likelihood components for net historical catches. Uncertainty in this emigration rate estimate, quantified in the movement likelihood, is thereby included in the overall estimate uncertainty for numbers of pots needing removal.

Table 2.2. Intermediate calculated quantities: The proportions of lobsters tagged in the fished zone that moved greater than 1 km using both a tag-conditioned ($P^{F,1}_M$) or

recaptured conditioned ($P_M^{F,1}$) definition for that proportion; the inferred numbers that moved but were not recovered in the fished zone ($N_{M,NR}^F$) and in the sanctuary ($N_{M,NR}^S$); the inferred numbers that did not move and would have been recovered had there been equivalent levels of harvesting in the sanctuary ($N_{NM,R}^S$), and the recovery proportions (necessarily in the fished area), assumed equal, for lobsters that moved inside the fished zone f_M^F or from the sanctuary (f_M^S). These are intermediate outputs from the numerical (A D Model Builder) estimation. The equalities of $P_M^{F,1} = P_M^{F,2}$ and $f_M^F = f_M^S$ were used as the basis for constraints 1 and 2.

Intermediate variable	Estimate
$P_M^{F,1} = P_M^{F,2}$	0.243
$N_{M,NR}^F$	697.7
$N_{M,NR}^S$	227.3
$N_{NM,R}^S$	17.7
$f_M^F = f_M^S$	0.113

Standard errors for the emigration rate estimate were obtained numerically from the hypergeometric likelihood using both 1. the asymptotic approximation (derived from the inverse hessian) and 2. as exact profile likelihood. These gave 95% errors of 21.2% and 21.5% of the estimated mean rate respectively. The normal asymptotic pdf and the profile likelihood pdf were also plotted (Figure 1), yielding qualitatively close agreement. Asymptotic confidence intervals therefore appear satisfactory for emigration proportion estimates not lying near the bounds of 0 and 1.

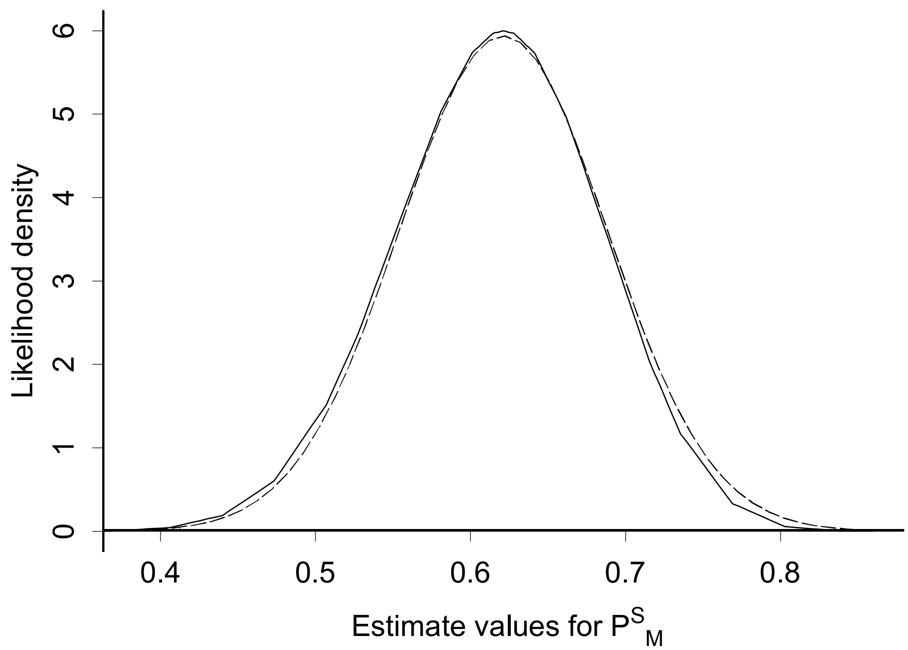


Figure 2.7. Spread of likely estimates for proportion of tagged lobsters emigrating over 1 year from Gleesons Landing Lobster Sanctuary. The dashed line is the asymptotic normal approximation (dashed) for the likelihood pdf confidence range about the estimate of P_M^S. The profile likelihood is shown as a solid line.

It is intuitively informative to do a qualitative check on the estimate of 62% emigrating per year. The estimate formula (Eq. 2.10) has two basic components. It can be written as $P_M^S = \dfrac{\dfrac{\tilde{N}_{M,R1}^S}{\tilde{N}_T^S}}{\dfrac{\tilde{N}_{NM,R1}^F + \tilde{N}_{M,R1}^F}{\tilde{N}_T^F}}$. The top ratio, $\dfrac{\tilde{N}_{M,R1}^S}{\tilde{N}_T^S}$ = 7.0%, is the raw tag-conditioned proportion of number that moved from the sanctuary in one year and were recaptured divided by the number originally tagged in the sanctuary. This ratio formula would estimate movement proportion as written if all lobsters that moved were recovered. But since not all recaptured lobsters were recovered, we must correct for a less-than-100% recovery rate by dividing the top ratio through by the recovery rate in the designated time interval (0.5 to 1.5 years) of lobsters that moved. This recovery rate estimate from fished zone tag recoveries, $\dfrac{\tilde{N}_{NM,R1}^F + \tilde{N}_{M,R1}^F}{\tilde{N}_T^F}$, equals 11.3% (given as $f_M^F = f_M^S$ in Table 2.2). The top ratio is raw information and no intuitive guess about what it should have been is possible. It simply gives the proportion that moved of the total tagged, the 'raw' information on movement rate.

But we can further consider the value of 11% recovery rate to assess whether it is reasonable. In particular, the estimated yearly exploitation rate for that 1995 Northern Zone rock lobster season is 26% (estimated by the current South Australian 'qR' stock assessment model, Ward et al. 2002). So approximately 26% of the legal-sized lobsters in the Northern Zone were harvested that year. An estimated tag-recovery rate of 11% means that of all the tagged legal-sized lobsters on the bottom, 11% were captured *and their tags reported*. Thus this 11% recovery rate implies a tag reporting rate of $0.113/0.26 = 43.5\%$. This is within the range of approximate tag reporting rates that fishers have suggested should be reasonable, though this quantity cannot be established with certainty. If we accept a 43% tag reporting rate as not unlikely, the overall estimate of 62% is plausible.

Discussion

The rate of emigration (in numbers) of 62% is substantial. The implication is that density dependence on those unexploited habitats is such that a majority of the lobsters recruiting each year (reaching age of maturity, around 100 mm CL) are obliged to move out. New space for more adults on unfished home reefs is created only by natural mortality. On fished habitats, an instantaneous natural mortality rate of 10% per year is assumed by most *Jasus edwardsii* stock assessments in Australia and New Zealand. Under this model of 1-to-1 replacement, 62% is not unlikely.

Under this 1-to-1 replacement model of emigration behaviour, the critical quantities that would determine the yearly movement rate out of a no-take area would be the balance of input supply of lobsters (recruitment as growth of juveniles in those home reefs where pueruli presumably settle) against the removal by all causes, these being, (primarily or entirely) mortality and movement. Under this hypothesis, once lobster densities stabilise after a habitat is protected from harvesting, as observed in the Maria Island reserve in Tasmania (Edgar and Barrett 1999) and at Leigh Reserve in New Zealand (MacDiarmid and Breen 1993), any 'spill over', that is, yearly recruitment of juveniles and newly matures that exceeds the natural mortality on the reef ($N_R - N_M > 0$) would be obliged to emigrate.

It is likely that this yearly movement proportion would rise and fall. In years of low recruitment, or high mortality (due to heavy fishing, for example) proportion emigrating would, by this hypothesis, be lower. In some areas (in some years) of lower density, there will be a net immigration of lobsters from other areas of high spill over. This movement hypothesis would predict a 'spreading out' of (primarily juveniles and newly mature) lobsters among reefs. In this way, the relative balance of spill-over movements should tend to result in more uniform levels of crowding on reefs in a given area spanning a scale of about tens of kilometres over which these longer-distance movements are observed to occur in tag-recovery studies.

In addition, movement appears to be related to reproduction. All studies reported highest rates of movement by immature females, followed by males, with generally higher movement rates by younger males (Annala and Bycroft 1993; McKoy 1983; Annala 1981). In South Australia, nearly all movement was directed from inshore to offshore areas and this was observed for lobsters moving out of the Gleesons Landing Sanctuary, that moved in a consistent southward direction towards the shelf edge. Correlations with season in the lobsters undergoing directed migrations around the southern end of the South Island of New Zealand (Annala and Bycroft 1993; McKoy 1983) is consistent with the conclusions of Kelly (2001) and MacDiarmid (1991) that *Jasus edwardsii* movements are closely linked to reproductive, moulting and feeding cycles. Thus while the large disparity between lobsters tagged inside Gleesons compared with those immediately outside in proportions moving and mean distances moved implies a density-dependent motive, an association with reproduction and moulting would, at least in part, explain the much farther distances moved from Gleesons than would have been necessary merely to find lower density lobster habitat.

The negative log likelihood estimate of emigration rate in Appendix 2.2 was integrated with that of Chapter 1. To make movement out of the sanctuary explicit, in Chapter 4, the historical catches by weight in each MFA sub-block are multiplied by the estimated value of the proportion remaining inside, $1 - P_M^S$, to obtain the estimated annual net catch loss.

A further compensating factor will be the egg contributions by the higher densities and longer lifespan anticipated for lobsters that remain in the reserve. This is problematic due to a paucity of direct information and will be addressed in Chapter 3.

Catch by Weight of Lobsters that Emigrate from the Sanctuary

Because most emigration occurs in the size ranges of about 100-150 mm CL for males and 100-140 mm CL for females, in effect, they can be considered recruits, but late recruits, coming into the legally harvestable stock at a size near to or larger than lobsters that settled and grew into legal size (of around 100 mm CL) from within the fished zone. Thus, the establishment of a no-take reserve means that about 38% of the recruits from that protected zone that formerly recruited to legal sizes are lost from the fishery. The remaining 62% eventually emigrate out of the no-take area into the remaining fished zone and thus recruit. The principal difference between this recruitment due to emigration out of the no-take area and regular growing to legal size in fished habitat is that recruitment as emigration from a no-take area happens at a generally larger size, from 100 to 140 or 100 to 150 mm CL versus the legal minimum length of about 100 mm CL.

The estimate obtained in this chapter is the proportion emigrating yearly by numbers (not biomass). For males, using South Australian lobster growth parameters from fished habitats, it is known (Prescott et al. 1997, Figures 41-42) that average yield per recruit is enhanced with increasing size of recruitment from sizes legal minimum length (100 mm) and above. Thus, if growth rates were the same inside the reserve as currently estimated for outside, each male recruiting to the fishable stock from the sanctuary would contribute a greater weight of capture per individual because he would be larger, in the range of 2-20% higher yield per recruit (Prescott et al. 1997, Figures 41-42). However, growth has been shown to be density dependent, i.e. slower in areas of higher density (McGarvey et al. 1999), thus this yield-per-recruit benefit is mitigated. Moreover, it is plausible to assume that natural mortality on juveniles and younger adults is also higher, at least marginally, in no-take habitats. And recently, larger lobsters have brought a significantly lower price. All these factors would reduce the 2-20% higher capture weight per emigrating recruit by amounts that cannot be quantified.

The method adopted was therefore to neglect the potential increases in weight that larger size of recruitment might imply (for males only) in exploited habitats. Within these balancing information constraints of higher known yield per recruit for fished habitat lobsters versus our limited knowledge of compensatory density-dependent processes of growth and natural mortality in the sanctuary, the most reasonable assumption is to take the estimate of 62% of lobsters emigrating to imply that 62% of what were previously recruits from these no-take areas would eventually migrate out and contribute the same weight of harvested biomass. Thus, the 62% of numbers migrating out of no-take zones translates into the same 62% in subsequent weight captured.

The use of commercially harvested tag-recovery data is appropriate for the current application. Because only tagged lobsters that do get harvested are included as input data, both movement and subsequent recapture in the commercial fishery are implicit in the emigration rate estimate above. To quantify compensation for net catch loss, it is this combined rate of both movement out and subsequent recapture as commercial catch that we seek to quantify.

Lobster Movement at Gleesons Landing and Elsewhere

To apply these results requires the assumption that the rate of movement observed in Gleesons Landing is representative of all the MFA coastal sub-blocks. We must make this assumption because there is only one available data set from which to infer proportion moving out of no-take zones by comparison to surrounding fished habitat, namely tag recoveries from Gleesons Landing and the surrounding Yorke Peninsula coastal lobster grounds.

Tagging studies of large scale movements of *Jasus edwardsii* in New Zealand (Annala and Bycroft 1993; McKoy 1983; Annala 1981), Tasmania (Gardner et al., submitted), and previous work here in South Australia (Prescott et al. 1997) all quantify generally low overall movement rates for this species. Most lobsters (85-97%% in the studies cited above) were recaptured close to the site of tag-release, defined as either within 1 km (Prescott et al. 1997; Gardner et al., submitted) or 5 km (Annala and Bycroft 1993; McKoy 1983; Annala 1981; Booth 1997). *Jasus edwardsii* are predominantly nocturnal and all studies of daily movements conclude that they typically forage within a few tens or hundreds of meters from their shelters in the rock habitat (MacDiarmid et al. 1991; Kelly 2001). The work of MacDiarmid and Kelly examined daily movements for foraging and mating in and around the home reef. MacDiarmid et al. (1991) also reported near-exponential distribution of distances, in their study, over much shorter distances up to 100 m, representing daily movements.

However, among studies of longer-scale movements that would constitute permanent emigration away from a home reef (Annala and Bycroft 1993; McKoy 1983; Annala 1981; Booth 1997, Gardner et al., submitted) none have been of lobsters tagged and released into reserves.

Thus, this is the first study that has quantified longer-distance movement rates inside and outside an established lobster no-take area. The first outcome was that (1) a higher proportion of lobsters were estimated to move (≥ 3 km) from the sanctuary (62%), compared with those tagged and released into the fished areas (24%). (2) There were also qualitative differences in the patterns of movement of lobsters from the sanctuary, namely sanctuary lobsters moved farther distances, and (3) the distribution over distance moved was exponential in the fished area and more nearly uniform for sanctuary lobsters. Thus both qualitatively and quantitatively, the lobsters from Gleesons sanctuary expressed movement behaviour with higher tendency for emigration from their home reef than in the neighbouring fished areas.

In a comprehensive study of movements using a huge database of *Jasus edwardsii* tag recoveries in Tasmania, Gardner et al. (submitted) observed that the areas of least movement on the southern coast were the areas of highest density. They argued that this provides contrary evidence to the speculation of Edgar and Barrett (1999) which I also propose in this Discussion, that emigration rate from reserve areas should be higher (as it has been estimated to be for Gleesons in this study). Under a 1-to-1 replacement model of relative movement rate, spatial variation in puerulus settlement must also play a role in spatial variation of emigration rates from home reef.

More generally, the study of Gardner et al. (submitted) and other previous studies in New Zealand (Annala 1981; McKoy 1983; Annala and Bycroft 1993) and South Australia (Prescott et al. 1997) all quantify considerable spatial variation in relative movement rates.

Thus, one qualifying factor in making inference about movement behaviour state-wide is that the lobsters in this region of the southern Yorke Peninsula exhibit higher mean rates of long-term movement than in most other South Australian habitats. Gleesons lies near the habitable range of southern rock lobster. North of Corny Point (about 10 km north of the Gleesons Sanctuary) into the Spencer Gulf, few lobsters are harvested in commercial numbers. The salinity and temperatures in more northerly regions of Spencer Gulf rise, especially in summer, to levels that are above tolerance for this marine crustacean. This probably explains the higher overall movement rate per year (≥ 3 km) of 24% (Table 2.2) from the fished areas (of MFA blocks 33 and 40).

One way to further investigate this alternative hypothesis, of the Gulf environment causing higher rates of movement, is to look at Fished Zone recaptures from lobsters that were tagged and released in MFA block 33 on its own, rather than the combination of blocks 33 and 40 which was used as the fished zone throughout this chapter's analysis. Block 33 is the one which lies farther north, fully inside the southern Spencer Gulf (Figure 2.1) and since Gleesons Sanctuary lies on the southern boundary of this block, all releases into 33 would have been equally far north or more northerly into the Gulf than those from Gleesons. Thus if Gulf habitat were engendering this higher rate of movement observed from Sanctuary releases, movement rate should be as high or higher in block 33 since lobsters released into the fished zone of 33 would, on average, be experiencing more gulf-like environmental conditions. The outcome of re-calculating movement rate from block-33 fished zone releases was that 22.6% (19 of 84 recaptures) moved greater than 3 km in one year. The result for the combined fished zone releases into 33 and 40 was 24.3% (Table 2.2). Thus, the movement rate of lobsters from block 33 is effectively the same (or a bit less than) that of lobsters released into the combined fished zone of 33 and 40 surrounding Gleesons. This evidence runs counter to this alternative hypothesis of high movement rates from Gleesons than the surrounding fished zone being due to its location in the northern part of the combined 33 and 40 fished area.

A second factor that might imply higher than average rates of movement out of Gleesons Landing is that this location was originally chosen for protection, as requested by Northern Zone fishers, because it was thought to be an area of higher than average rates of puerulus settlement. This was thought to be the case based on the relatively larger numbers of undersize lobsters regularly captured on those now-protected reefs. Thus if settlement rates are higher inside Gleesons Lobster Sanctuary, by this density-dependent hypothesis for spatial differences in movement rate, higher rates of emigration by lobsters recruiting to mature sizes should also be higher.

However, two countering factors in assessing the relative movement rate of this reserve compared to others in South Australian state waters also inhere:

South Australian no-take reserves currently being proposed will lie inshore along the coast within 3 nm. The state-wide trend of net lobster movement from inshore to offshore throughout South Australia identified by Prescott et al. (1997), would therefore imply generally higher than average rates of movement out of these reserves even without density-dependent effects.

Moreover, the puerulus settlement rates and thus density of recruiting juveniles is relatively low in the Yorke Peninsula region overall, notably compared to the Southeast where about two-thirds of the lobster catches state-wide are taken. Along the Southeast coast of South Australia, from Kingston to the Victorian border, measured rates of puerulus settlement inshore are much higher than in the Northern Zone. Collectors from the Southeast generally yield puerulus settlement rates about 10-100 times greater than the Northern Zone collectors, though none have been placed at Gleesons specifically. Thus, if the balance of recruitment versus natural mortality (mediated via a fixed number of shelters in the rock substrate) determines yearly movement, then assuming similar levels of natural mortality in the two regions, no-take emigration rates could potentially be higher in the Southeast, due to yearly recruitment of juveniles per unit area being higher, and in some locations, very much higher.

Implications of Diver Transect Visual Surveys in Gleesons and Margaret Brock

Subsequent to the review and approval of this final report (April 2003), diver surveys were completed to estimate density inside and outside of two lobster sanctuaries, Gleesons and Margaret Brock. These results are summarised in Appendix 4 of this report.

The principal outcome of this field work is that lobster density, within fairly wide confidence intervals, appears to be nearly the same inside and outside of both no-take sanctuaries.

This provides an important independent confirmation of the general conclusions presented in this chapter and the next, namely that density-dependent regulation acts relatively strongly in South Australian lobster populations, at least at these two locations. In effect, some process is acting to even out lobsters densities across spatial scales of a few kilometres (specifically the distance between inside and outside reef sites surveyed in this field study). The most likely density regulating mechanism is that of movement. The results in Chapter 2 above give strong evidence that movement rate, distance moved, and tendency to remain near the home reef are considerably different for lobsters from inside the Gleesons sanctuary. Greater and farther movements of lobsters in the unexploited population would provide a likely and effective process to regulate and even out spatial variations in density of the sort that a no-take area of a few km in width would otherwise induce. Thus, the field work substantiates the density dependent movement hypothesis supported above with tag-recovery data from Gleesons sanctuary.

Also informative is that this observation of similar densities inside and outside is observed in a second no-take area, namely Margaret Brock. The tag-recovery movement results presented in this chapter apply only to the Gleesons Sanctuary because only there were tagged lobsters released. The extension of evidence for strong density dependent effects from one to two sanctuaries, with those being in very different habitats and degrees of exposure to the open sea, greatly strengthens the probability that this effect, shown for Gleesons in this chapter, applies more widely in South Australia. Thus, it seems likely that lobster movement over spatial scales similar to those of the NRSMPA no-take area dimensions proposed is a principal process giving rise to the small differences in density observed inside and outside of these two currently existing sanctuaries.

References

Abramowitz, M., and I.R. Stegun. 1965. Handbook of Mathematical Functions. Dover Publications, New York.

Annala, J.H. 1981. Movements of rock lobsters (*Jasus edwardsii*) tagged near Gisborne, New Zealand. New Zealand Journal of Marine and Freshwater Research 15: 437-443.

Annala, J.H., and Bycroft, B.L. 1993. Movements of rock lobsters (*Jasus edwardsii*) tagged in Fiordland, New Zealand. New Zealand Journal of Marine and Freshwater Research 27: 183-190.

Edgar, G.J., and Barrett, N.S. 1999. Effects of the declaration of marine reserves on Tasmanian reef fishes, invertebrates and plants. Journal of Experimental Marine Biology and Ecology 242: 107-144.

Gardner, C., Frusher, S, Buxton, C., and Haddon, M. Movements of the southern rock lobster *Jasus edwardsii* in Tasmania, Australia. Bulletin of Marine Science, submitted.

Kelly, S. 2001. Temporal variation in the movement of the spiny lobster *Jasus edwardsii*. Marine and Freshwater Research 53(3): 323-331.

MacDiarmid 1991. Seasonal changes in depth distribution, sex-ratio and size frequency of spiny lobster *Jasus edwardsii* on a coastal reef in northern New Zealand. Marine Ecology Progress Series 70: 129-141.

MacDiarmid, A.B., and Breen, P.A. 1993. Spiny lobster population change in a marine reserve. *In*: C.N. Battershill, D.R. Schiel, G.P. Jones, R.G, Creese, and A.B. MacDiarmid [eds.], Proceedings of the 2nd International Temperate Reef Symposium. NIWA Marine, Wellington.

MacDiarmid, A.B., Hickey, B., and Maller, R.A. 1991. Daily movement patterns of the spiny lobster *Jasus edwardsii* (Hutton) on a shallow reef in northern New Zealand. Journal of Experimental Marine Biology and Ecology 147: 185-205.

McGarvey, R., Ferguson, G.J., and J.H. Prescott. 1999. Spatial variation in mean growth rates at size of southern rock lobster, *Jasus edwardsii*, in South Australian waters. Marine and Freshwater Research 50: 333-342.

McKoy, J.L. 1983. Movements of rock lobsters *Jasus edwardsii* (Decapoda: Palinuridae) tagged near Stewart Island, New Zealand. New Zealand Journal of Marine and Freshwater Research 17: 357-366.

Prescott, J., McGarvey, R., Ferguson, G., and Lorkin, M. 1997. Population dynamics of southern rock lobster in South Australian waters. Final Report for Australian Fisheries Research and Development Corporation Project 93/086.

Rice, J.A. 1995. Mathematical Statistics and Data Analysis. Duxbury Press, Belmont, California.

Seber, G.A.F. 1982. The Estimation of Animal Abundance and Related Parameters, second edition. Griffin, London.

Ward, T.M., R. McGarvey, Y. Xiao, and D.J. Brock. 2002. Northern Zone Rock Lobster (*Jasus edwardsii*) Fishery. South Australian Fisheries Assessment Series 2002/04b. SARDI Aquatic Sciences, Adelaide. 109 pp.

Appendix 2.1. Tag-recovery data: database and GIS pre-processing

Two data files were queried from the South Australian rock lobster tag-recovery database. One included all the recaptured lobsters in the recapture data set regardless of recapture location in South Australia. The second query was of lobsters tagged and released, whether recaptured or not. Only lobsters tagged and released either (1) inside Gleesons Sanctuary, or (2) in the two MFA blocks surrounding the lobster sanctuary, 33 and 40 were considered.

A total of 33,821 recaptures and 3689 tag releases into (1) and (2) were queried from the database. Of the 3689 tag releases, 749 were recaptured. A substantial number of lobsters (182 of 749) were recaptured more than once. For these, only the recapture was used whose time-at-large was closest to 1 year. Of the 749 recaptures, 53 had been released into the sanctuary, and 696 were from the fished zone. These yielded the data inputs of tag numbers in the sanctuary and the fished zone (N_T^S and N_T^F) used in the emigration rate estimator.

ArcView GIS polygon layers were imported which delineated the MFA statistical reporting blocks (Figure 1.2) and of the Gleesons Sanctuary (Figure 2.1). The tag polygons, namely inside the sanctuary or outside it in blocks 33 or 40, where each lobster was tagged and released was determined for each recapture using an ArcView spatial join.

The tag-release and recapture GPS latitude-longitude locations for all recaptured lobsters tagged in MFA blocks 33 or 40 or in the sanctuary were exported to Excel. Summary statistics were calculated using the Visual Basic for Applications (VBA) programming language in Excel. The distance across the surface of (an assumed spherical) earth was calculated between the sites of tag-release and recapture.

Appendix 2.2. Movement proportion: double-hypergeometric likelihood

In Methods, a closed form solution was presented for estimating the proportion of tagged lobsters that moved from the reserve. As in Chapter 1, in order to rigorously estimate confidence bounds, we constructed a likelihood formulation of this estimate. In this appendix, the details of a full likelihood formulation of the estimator are presented.

The likelihood describing a single tag-recapture experiment is hypergeometric (Seber 1982) because sampling is without replacement. This can be formulated as a 2 x 2 contingency table (Rice 1995), where the two outcomes are moved or not moved, and the lobsters originally tagged (the total experimental population in this contingency table) are partitioned into those tagged lobsters that were recovered and those that were not. This yields the four possible outcomes listed in Methods.

As described in Methods, there are two interacting tag-recovery experiments needed to generate an estimate, namely of lobsters tagged in the sanctuary, and of lobsters tagged in the fished zone. Thus a pair of linked hypergeometric likelihoods, each corresponding to a 2-way contingency table, is the form of the likelihood estimator for P_M^S.

The derivation of a closed-form solution in Methods required two assumptions which applied in a likelihood estimation act to constrain the range of values the eight elements in the contingency tables can take. In the likelihood formulation of this estimator, a third constraint will be needed which is analogous to the first assumption explicit in Methods.

The derivation for constructing this likelihood from a pair of linked hypergeometric probability functions will proceed by (1) writing out the 'raw' contingency tables, in terms of the eight *N*-values, as denoted in Methods, (2) algebraically re-expressing the eight elements of the tables so that the parameter to be estimated is explicit, (3) imposing the three constraints, and (4) writing out the linked double-hypergeometric likelihood, using the standard hypergeometric likelihood form for contingency tables.

For the lobsters tagged inside the sanctuary, the raw contingency table is:

Sanctuary-tagged	Recovered	Not Recovered	Totals
Moved	$\tilde{N}_{M,R}^S$	$N_{M,NR}^S$	$\tilde{N}_{M,R}^S + N_{M,NR}^S$
Not moved	$N_{NM,R}^S$	$N_{NM,NR}^S$	$\tilde{N}_T^S$ - $(\tilde{N}_{M,R}^S + N_{M,NR}^S)$
Totals	$\tilde{N}_{M,R}^S + N_{NM,R}^S$	$\tilde{N}_T^S$ - $(\tilde{N}_{M,R}^S + N_{NM,R}^S)$	$\tilde{N}_T^S$

For the lobsters tagged in the fished zone:

Fished-zone-tagged	Recovered	Not Recovered	Totals

Moved	$\tilde{N}^F_{M,R}$	$N^F_{M,NR}$	$\tilde{N}^F_{M,R} + N^F_{M,NR}$
Not moved	$\tilde{N}^F_{NM,R}$	$N^F_{NM,NR}$	$\tilde{N}^F_T$ - $(\tilde{N}^F_{M,R} + N^F_{M,NR})$
Totals	$\tilde{N}^F_{M,R} + \tilde{N}^F_{NM,R}$	$\tilde{N}^F_T$ - $(\tilde{N}^F_{M,R} + \tilde{N}^F_{NM,R})$	$\tilde{N}^F_T$

As in Methods, we have denoted the five values for which data are directly available from the tag-recovery data set by a tilda (˜).

The two hypergeometric probability mass functions of predicted numbers moved and recovered corresponding to the two contingency tables above are written:

$$P(\tilde{N}^S_{M,R}) = \left(\frac{\binom{\tilde{N}^S_{M,R} + N^S_{M,NR}}{\tilde{N}^S_{M,R}} \binom{\tilde{N}^S_T - (\tilde{N}^S_{M,R} + N^S_{M,NR})}{N^S_{NM,R}}}{\binom{\tilde{N}^S_T}{\tilde{N}^S_{M,R} + \tilde{N}^S_{NM,R}}} \right) \tag{2.A.1}$$

$$P(\tilde{N}^F_{M,R}) = \left(\frac{\binom{\tilde{N}^F_{M,R} + N^F_{M,NR}}{\tilde{N}^F_{M,R}} \binom{\tilde{N}^F_T - (\tilde{N}^F_{M,R} + N^F_{M,NR})}{\tilde{N}^F_{NM,R}}}{\binom{\tilde{N}^F_T}{\tilde{N}^F_{M,R} + \tilde{N}^F_{NM,R}}} \right). \tag{2.A.2}$$

Because the goal is to estimate the movement proportion, P^S_M, (rather than any specific value of N), it will need to be made explicit in the likelihood as the sole freely varying parameter. Substituting from the definition of P^S_M in Methods Eq. (2.1), we have

$$N^S_{M,NR} = P^S_M \cdot \tilde{N}^S_T - \tilde{N}^S_{M,R}. \tag{2.A.3}$$

Substituting for all occurrences of $N^S_{M,NR}$, (2.A.1) becomes:

$$P(\tilde{N}^S_{M,R}) = \left(\frac{\binom{P^S_M \cdot \tilde{N}^S_T}{\tilde{N}^S_{M,R}} \binom{\tilde{N}^S_T \cdot \left(1 - P^S_M\right)}{N^S_{NM,R}}}{\binom{\tilde{N}^S_T}{\tilde{N}^S_{M,R} + N^S_{NM,R}}} \right). \tag{2.A.4}$$

The two constraints employed in the closed-form derivation of Methods, Eqs. (2.5) and (2.9), are imposed here unchanged on (numerical) minimisations of the likelihood.

The factorial terms in the binomial coefficients of (2.A.4) and (2.A.2) are defined only for natural numbers. However, in numerical application, factorials (in terms of which the binomial coefficients are defined) must be replaced with continuously varying approximations because the objective function is minimised using numerical derivatives. We therefore generalised the factorial z! using its well-known continuous generalisation, the gamma function, Γ(z+1). Abramowitz and Stegun (1965, p. 257) give an asymptotic approximation formula for the natural log Γ(z):

$$\log\,\Gamma(z) \;=\; \left(z-\frac{1}{2}\right)\log(z)-z+\frac{1}{2}\cdot\log(2\pi)+\frac{1}{12z} -\frac{1}{360z^3}+\frac{1}{1260z^5}-\frac{1}{1680z^7}+\frac{1}{1188z^9}-\frac{691}{360360z^{11}}+\frac{1}{156z^{13}} \qquad (2.A.5)$$

A binomial coefficient expressed in terms of gamma functions is written:

$$\binom{z}{w}=\frac{z!}{w!(z-w)!}=\frac{\Gamma(z+1)}{\Gamma(w+1)\,\Gamma(z-w+1)}\,. \qquad (2.A.6)$$

The formulas of (2.A.5) and (2.A.6) permitted the approximation of the hypergeometric in terms of continuously varying quantities.

Writing the full joint likelihood formed by the product of the two hypergeometrics we have

$$L=\left(\frac{\binom{\tilde N^F_{M,R}+N^F_{M,NR}}{\tilde N^F_{M,R}}\binom{\tilde N^F_T-(\tilde N^F_{M,R}+N^F_{M,NR})}{\tilde N^F_{NM,R}}}{\binom{\tilde N^F_T}{\tilde N^F_{M,R}+\tilde N^F_{NM,R}}}\right)\cdot\left(\frac{\binom{P^S_M\cdot\tilde N^S_T}{\tilde N^S_{M,R}}\binom{\tilde N^S_T\cdot\left(1-P^S_M\right)}{N^S_{NM,R}}}{\binom{\tilde N^S_T}{\tilde N^S_{M,R}+N^S_{NM,R}}}\right).(2.A.7)$$

Taking the negative log and writing term by term this becomes

$$-\log L=-\log\binom{\tilde N^F_{M,R}+N^F_{M,NR}}{\tilde N^F_{M,R}}-\log\binom{\tilde N^F_T-(\tilde N^F_{M,R}+N^F_{M,NR})}{\tilde N^F_{NM,R}}+\log\binom{\tilde N^F_T}{\tilde N^F_{M,R}+\tilde N^F_{NM,R}} -\log\binom{P^S_M\cdot\tilde N^S_T}{\tilde N^S_{M,R}}-\log\binom{\tilde N^S_T\cdot\left(1-P^S_M\right)}{N^S_{NM,R}}+\log\binom{\tilde N^S_T}{\tilde N^S_{M,R}+N^S_{NM,R}}.$$

Expressing each log binomial coefficient $\log\binom{a}{b}$ in terms of the gamma, we have

$$\log\binom{a}{b}=\log\left[\frac{a!}{b!(a-b)!}\right]=\log\left[\frac{\Gamma(a+1)}{\Gamma(b+1)\Gamma(a-b+1)}\right]=\log\Gamma(a+1)-\log\Gamma(b+1)-\log\Gamma(a-b+1)$$

.

As formulated, the value of $N^S_{NM,R}$ remains undetermined by data or constraint. A third constraint is therefore required to formulate the solution in terms of a double-hypergeometric likelihood. Analogous to constraint 1 for the fished zone (2.4), namely assuming that the two ways to define number moved from the sanctuary can be set equal:

$$P^{S,1}_M = \tilde{N}^S_{M,R} \ / \ (N^S_{NM,R} \ + \ \tilde{N}^S_{M,R}) = P^{S,2}_M = (\tilde{N}^S_{M,R} \ + \ N^S_{M,NR}) \ / \ \tilde{N}^S_T . \quad (2.A.8)$$

This implies that the proportion moved out of the sanctuary of those recaptured equals the total proportion that moved out of the sanctuary, recaptured and otherwise, of the total tagged. In this application, $N^S_{NM,R}$ is understood as the number that would have been taken if fishing had not been excluded from the sanctuary. Solving for $N^S_{NM,R}$, we have the third constraint:

$$N^S_{NM,R} = (\ \tilde{N}^S_{M,R} \cdot \tilde{N}^S_T) \ /(\tilde{N}^S_{M,R} \ + \ N^S_{M,NR}) \ - \ \tilde{N}^S_{M,R} . \quad (2.A.9)$$

The numerical estimator did not converge without Constraint 3.

That this numerical double-hypergeometric likelihood formulation gives an estimate for P^S_M similar to that of the closed form solution summarised in Methods is verified in Results.

CHAPTER 3. Evidence to date for higher egg production yielding subsequent higher recruitment in the South Australian rock lobster population

Introduction

Because lobster densities and life spans are expected to rise in areas protected from fishing, higher levels of egg production per unit area are expected in no-take zones (Tuck and Possingham 2000). Gardner et al. (2000) simulated the expected changes in overall Tasmanian lobster fishery egg production (under quota) for a range of assumed conditions, notably for no-take areas in regions of (1) low and high growth, and (2) relatively low and high fishing pressure. They found that for some placements of no-take areas, overall egg production can actually decline if effort is displaced from areas of relatively low growth or areas where protection of egg production is already sufficient, notably in southern Tasmania, where many females do not reach fishable size, and thus are already protected. Haddon (pers. comm., FRDC Project 1999/162) has developed a detailed simulation of the displacement of effort among 56 reporting areas in Tasmania.

In South Australia, the state government has given notice of its intention to buy out fishing capacity sufficient to compensate for net losses in long-term average fishery catch that occur once MPAs with no-take zones are established. Thus, with the excess lobster pots removed, there will not be effort displacement in the South Australian lobster fishery. To the extent that the calculation of net catch loss is accurate, no change in egg production is expected in the remaining open fishery areas because the total level of fishing mortality in these areas will not change. Therefore effort displacement does not figure in the calculations to follow. The goal, therefore in this chapter is to try and quantify the expected rise in recruitment, and thus in long-term fishery yields, due to higher egg production from no-take protected lobster habitats.

Egg production within no-take zones will almost certainly rise because each lobster will on average live longer in the absence of harvesting and therefore be larger, and older/bigger females produce more eggs in each spawning year. Moreover, lobster densities are also likely to rise, implying more female lobsters spawning per m^2. The evidence in the published literature for these changes of lobster density and size in existing no-take areas is examined below.

The effect on recruitment and thus catch overall will, however, involve consideration of other relationships, notably of how recruitment would be expected to change with increases in egg production. The task in this chapter would be to quantify approximately what this concomitant rise in catch would be. The principal result is that this is not possible given the data and absence of a stock-recruitment relationship.

A rigorous calculation of net increase in egg production would require several components: (1) An estimate is needed of percentage increase in lobster population density when limited only by carrying capacity in an unfished habitat. This should also consider the movement out of no-take areas. (2) The change in lobster age/size structure would need to be inferred. (3) Density dependence in growth was shown to be significant and strong in South Australian rock lobster (McGarvey et al. 1999). This implies that the growth of lobsters would be slower in unfished no-take habitat. From these three inputs, an estimate of the increase in egg production could theoretically be obtained.

However, to estimate the impact as higher catches in the rest of the zone due to eggs produced in each no-take area, (4) an estimate of the number of new recruits arriving in the population approximately six years later as a function of a given number of additional eggs being released inshore is needed, in order to estimate the increase in overall catch due to this higher no-take egg production. (5) One additional factor is the location of the protection zones under consideration. Being inshore, primarily inside 3 nm of the coast, there is reason to think the survival of lobster eggs is lower than from females who have moved or originally settled offshore closer to or on the shelf edge. Rock lobster larvae live most of their 18-24 month free-floating pelagic phase drifting in the open ocean. The level of predation on these eggs/larvae is undoubtedly higher as eggs drift above the coastal shelf where most ovigerous fish live, and so average survival may be higher for eggs released near the open ocean, i.e. near the shelf edge, than from females inshore along the coast where protected zones are currently proposed.

The principal quantity sought is the proportion coefficient relating percentage increases in recruitment to percentage increases in egg production. This would be used in step (4) above. In all populations, this coefficient will drop below 1, meaning, on average, less than 1 surviving recruit for every additional egg, as population density rises from a low level. It is this coefficient, presumed to lie between 0 and 1, that we shall examine evidence for in this chapter, in estimating the slope of the stock-recruitment relationship for South Australian rock lobster.

It is the principal of compensating density dependence that allows all populations to be stable, and thus sustainable, rather than to rise (or fall) exponentially through time. Density dependence in recruitment is also the process which permits all fisheries to persist under long-term reductions in adult abundance and thus lifetime female egg production. This flexibility of recruitment to remain nearly steady when adult egg production is strongly affected (as it is in all fisheries) is what allows them to persist under exploitation. Thus, decreases in total egg production have a relatively small effect on decreasing recruitment.

Nevertheless, in years of relatively poor recruit survival, or when the population is pushed to excessively low levels, where recruitment overfishing does become a factor, higher egg production should be expected to have a greater effect as more recruitment. And in any given year, more eggs cannot yield fewer recruits; some of the additional eggs survive to adulthood. In general, however, for stable populations, this increase may be small.

As elaborated in Discussion, lobster populations are particularly prone to showing no evidence of a stock-recruitment relationship. Corroborating this outcome, lobster populations are also exceptionally stable, catches remaining roughly constant (or even rising as in New England lobster) under a wide range of levels of high exploitation. Thus, lobster populations usually show little or no dependence of recruitment on changes in levels of egg production.

In this chapter we shall first review evidence from the literature for (1) and (2) above, namely higher densities and larger size inside protected populations of *Jasus edwardsii* (southern rock lobster). Second, we present the results of the attempt to detect (4), a stock-recruitment relationship in the South Australian population.

Evidence for Higher Lobster Densities and Larger Size in Marine Protected Areas

The Cape Rodney to Okakari Point Marine Reserve near Leigh in north-eastern New Zealand (henceforth denoted the 'Leigh reserve') has been the subject of several studies comparing *Jasus edwardsii* densities and mean size both temporally, before and after establishing the protected area (MacDiarmid and Breen 1993), and spatially, comparing densities on lobster reefs inside and outside the reserve (MacDiarmid and Breen 1993; Babcock et al. 1999; Cole et al. 1990).

The Leigh reserve studies all showed increases in density and in mean size inside the reserve. MacDiarmid and Breen (1993), using diver transects, observed an increase in density of about 4.5 times that measured by Ayling (1978) prior to the establishment of the reserve after 5 years. Lobster number densities subsequently levelled off, and then declined slightly (MacDiarmid and Breen 1993). Mean size also increased significantly, with much higher numbers of larger (fishable size) lobsters. MacDiarmid and Breen also observed larger numbers of undersize lobsters which implied substantially higher rates of settlement in the protected zone.

Spatial comparisons yielded similar outcomes. MacDiarmid and Breen (1993) reported lobster number densities 3-12 times higher than in neighbouring unprotected reef habitat, and because of larger mean size, this translated into biomass densities some 20 times greater. Babcock et al. (1999) found densities 1.6 to 3.7 times greater inside the Leigh reserve. Cole et al. (1990) located no lobsters at all in diver transect sites outside the reserve, but reported densities (0.0525 m^{-2}) similar to though lower than MacDiarmid and Breen (0.0608 and 0.1007 m^{-2}) inside Leigh reserve.

Edgar and Barrett (1997) using visual diver survey in a BACI design measured changes in *Jasus edwardsii* density in four marine reserves declared in southeast Tasmania in September 1991. Surveys were conducted from March-May 1992 to August-October 1993. They found a 61% increase in lobster density inside the reserve over this roughly 1.5 year period. This was not statistically significant, but is nevertheless plausible and is not inconsistent with the New Zealand studies, notably the factor of 4 increase in density over 5 years reported by MacDiarmid and Breen (1993).

Methods

The estimation model used to generate stock assessment indices of recruitment and egg production in South Australian rock lobster is called the qR model and has been described in detail previously (McGarvey et al. 1997; McGarvey and Matthews 2001). It fits to the two available yearly time series of catch, namely by weight (Cw, in kg) and numbers (Cn, in numbers of lobsters landed). Effort (E, as numbers of pot lifts) is taken as given, a standard Schaefer catch relationship (Cn=qEN) is assumed, and the likelihood is written as a modified normal. The catchability (q) and each year's recruitment are estimated numerically as free parameters. Previous models (delay-difference, biomass dynamic) fitting to catch and effort data used only catch by weight (Cw), and relied on CwPUE as a measure of relative fishable biomass. The qR model adds catches by numbers to the fitted data set. Because catch-by-weight divided by catch-by-number gives the mean weight of an average lobster, the addition of the catch-by-number time series gives information about yearly mean size in the legal catch, otherwise available only from length-frequency samples. Because catches by weight and number constitute a 100% sample of the catch, the quantity of information obtained about changes in *mean* size from catch-log data is far greater than that obtained from length frequency pot samples, which typically constitute about a 0.1% to 1% sample fraction. Thus the qR model uses CwPUE as a measure of change in abundance and mean weight as a measure of change in size structure. However, the qR model does not use catch length-frequency samples and thus does not have information about higher moments than the mean of the size-frequency distribution.

The qR model is run yearly for each zone separately. Growth and estimated catchability differ in the two zones. Yearly catches by weight and number and effort (as total pot lifts set each year) were extracted from the lobster catch-log database back to 1970. These qR model runs yielded a time series for recruitment and egg production back to 1970 in each zone.

Performance assessments of the qR model, in studies using simulated data for a range of possible recruitment time series patterns, indicated that the model gave accurate estimates of yearly recruitment as absolute numbers (Figure 3, McGarvey and Matthews 2001).

The model is age-based. This permits the estimation of yearly egg production, again as total absolute number of eggs hatched yearly. Only legal-size lobsters are estimated in the qR-model population.

For this reason previous versions of the qR model omitted eggs produced by undersize (also known as 'sublegal') lobsters. In the Northern Zone, because most lobsters mature above legal size, this omission would not leave out many eggs. However, to improve the quality of yearly egg production estimates in the Southern Zone, where some females spawn prior to reaching legal size, the qR estimates of yearly egg production were modified to include one additional age class of undersize lobsters. This also provides a sensitivity test to the effect on stock-recruitment correlation outcomes of neglecting undersize lobsters' contribution to yearly egg production. This was done by (1) using the same ogives (i.e. function curves) versus age for fecundity and maturity used in prior egg production time series estimates, (2) taking the estimated number of recruits in each yearly cohort from the standard qR fit, and (3) assuming the same constant natural mortality, M, over that year. The numbers of pre-recruits of age one year younger $N_{SubLeg}(y-1)$ than those recruited $N_R(y)$ in each yearly cohort, was calculated as $N_{SubLeg}(y-1) = N_R(y) \cdot \exp[M]$. For the last year of this time series, namely the most recent fishing season gone by, where undersize numbers $N_{SubLeg}(y_{last})$ would need to be inferred from the recruits

$N_R(y_{last}+1)$ to the future year still to come, sublegal numbers were set equal to those from the year prior $N_{SubLeg}(y_{last}) = N_{SubLeg}(y_{last}-1)$.

The model requires a growth vector of mean weights at age (McGarvey et al. 1999) to which (like all size-based models) it is sensitive. However, the principal effect of error in growth will be to change both recruits and all adult numbers, up or down by a (roughly constant) factor, thus not substantially altering any calculated stock-recruitment correlation.

The stock-recruitment relationship was derived assuming a single unit stock. In other words, because eggs hatched can move large distances over the 18-24 months of free-floating pelagic phase, the best supposition is that there is mixing of eggs in the open ocean and that eggs from each zone can settle back into the either zone with roughly equal or not greatly differing probability. Thus, for population reproduction purposes, we assume the two zones form a single unit stock. Time series of South Australian recruitment and egg production were therefore formed as the sums from the two zones.

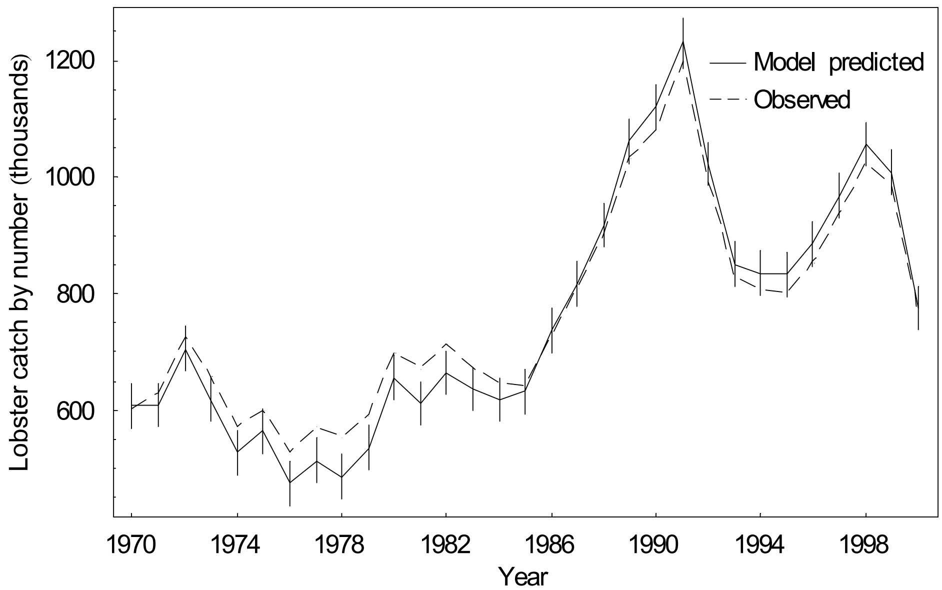
Results

Validation of qR Model Performance

Fits to catches by number and weight of the qR model for the Northern (Figure 3.1) and Southern (Figure 3.2) Zones are satisfactory. For the Southern Zone, a separate catchability coefficient was estimated for the years since 1994/95 when a quota system was established. The estimated catchability was about 25% higher for those last 8 fishing seasons under quota.

The fit of CwPUE versus qR-model biomass for the Northern Zone (Figure 3.3) shows a modest trend of deviation. This reflects deviations in reality from the single constant catchability that is implicitly assumed. This might result, for example, if an expanding range of fishing has continuously allowed larger lobsters to be discovered and included in the numbers captured.

In the qR model fit to the SZ, a separate catchability parameter is estimated for the two time periods of the fishery, namely prior to and under quota. The noticeable switch of CwPUE being below to being above the model biomass in the Southern Zone (Figure 3.4) expresses the output expected when model q does rise through time. In the SZ fit, the 25% higher q for 1993 onward explains this difference.



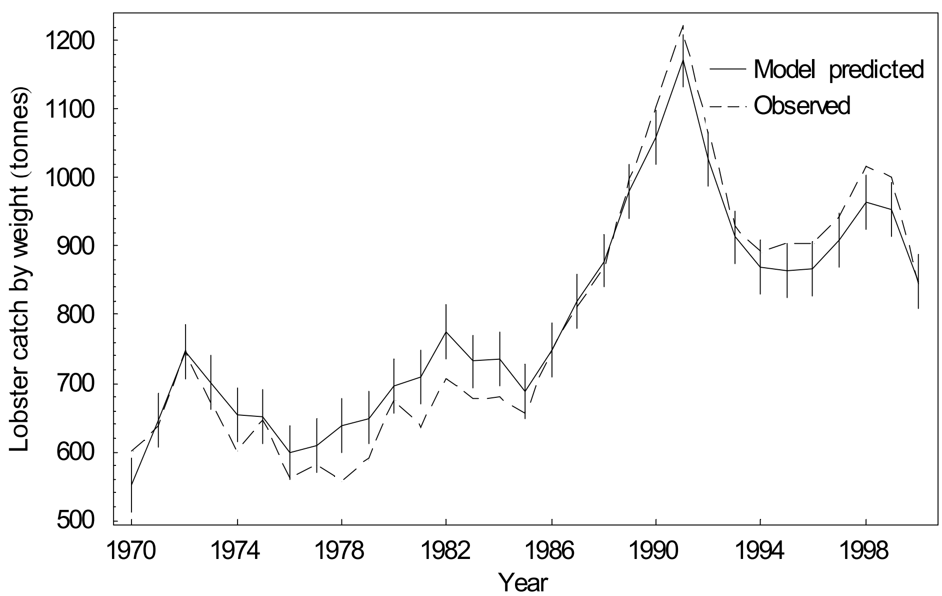


Figure 3.1. Northern Zone qR model fits (dashed lines) to yearly catches by numbers and by weight (solid lines), 1970/1971 to 2000/2001 rock lobster fishing seasons. Error bars indicate one standard deviation of the fitted normal likelihood, i.e. of the residuals.

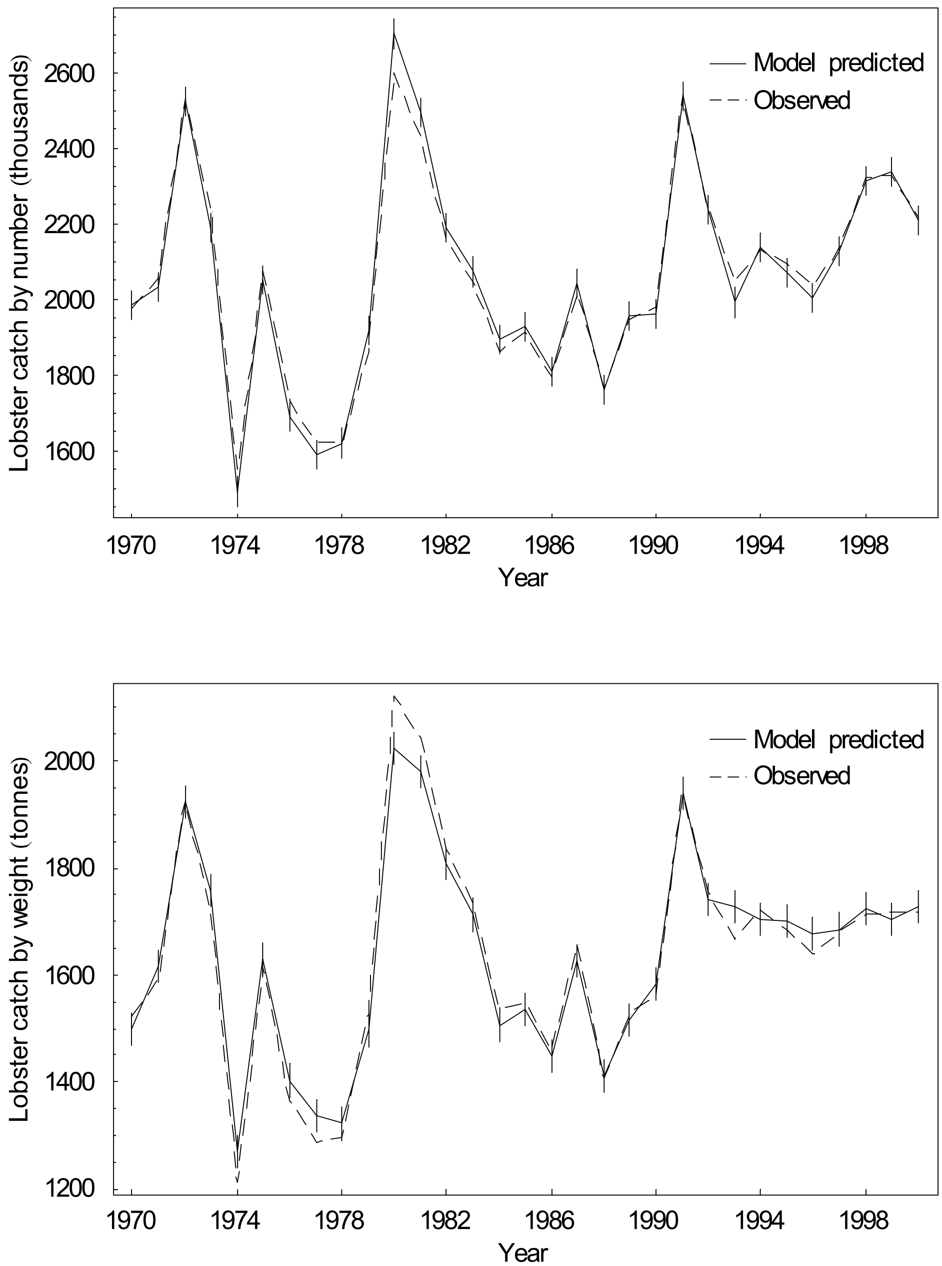


Figure 3.2. Southern Zone qR model fits (dashed lines) to yearly catches by numbers and by weight (solid lines), 1970/1971 to 2000/2001 rock lobster fishing seasons.

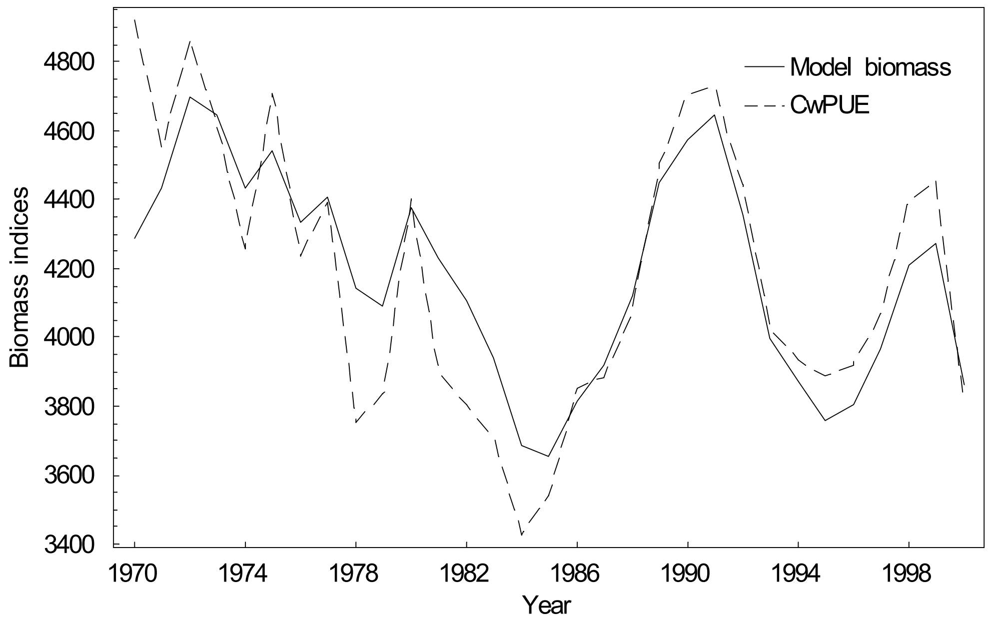


Figure 3.3. Northern Zone qR model-estimated fishable biomass and reported yearly catch-by-weight per pot lift.

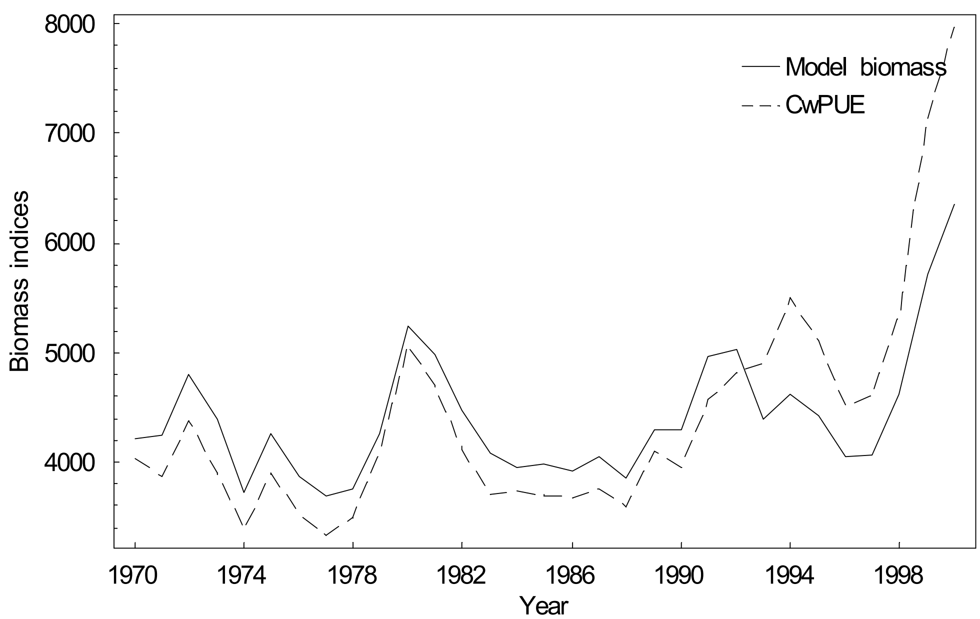


Figure 3.4. Southern Zone qR model-estimated fishable biomass and reported yearly catch-by-weight per pot lift.

The best validation measure of qR model performance comes from an independent time series of yearly recruitment. Fishers report numbers of undersize (lobsters captured in a pot but whose carapace length is below the legal minimum length) and female egg-bearing lobsters that they throw back each day. Undersize provide a direct measure of yearly recruitment which is independent of qR-inferred recruitment, the latter derived from legal-size catch totals and effort. The 'pre-recruit index' (PRI) used only undersize numbers for the 5 overlapping months of November to March, since catch variation due to weather and other extraneous factors is higher in the early and later months of the rock lobster fishing season. To remove changes in undersize numbers due to yearly variations in effort, the PRI is formed as a per-unit-effort quantity (numbers of undersize Nov-Mar) / (pot lifts Nov-Mar) of each year. For both the Northern (Figure 3.5) and Southern (Figure 3.6) Zones, the agreement in temporal trends between the two measures of yearly recruitment are relatively close.

Thus overall, the temporal trends in qR-model estimates of recruitment and biomass agree with PRI and CwPUE respectively. Fits to catches by weight and number are consistent. Thus, qR model outputs appear to provide a reasonable or good picture of temporal trends in recruitment and egg production.

Figure 3.5. Northern Zone yearly recruitment indices. Estimated qR-model recruitment numbers (dashed line) and pre-recruit index (solid), the latter calculated as numbers of undersize lobsters per pot lift during the five months from November to March.

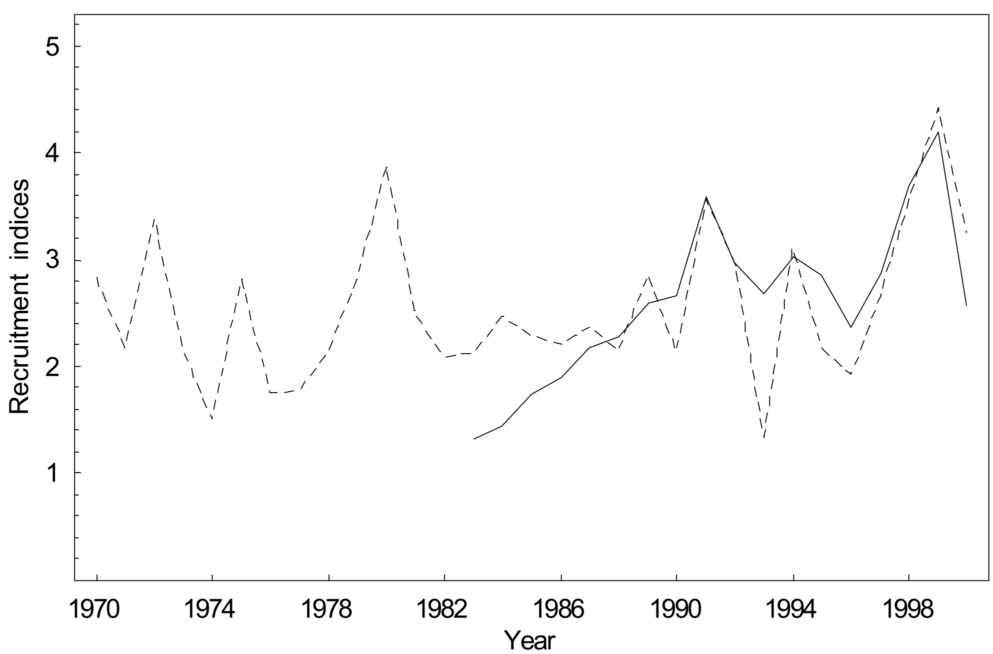


Figure 3.6. Southern Zone yearly recruitment indices. Estimated qR-model recruitment numbers (dashed line) and pre-recruit index (solid), the latter calculated as numbers of undersize lobsters per pot lift during the five months from November to March.

Stock-Recruitment Correlation

The two resulting time series of yearly recruitment to the legal stock and egg production are shown as a scatterplot in Figure 3.7. In order to assess the correlation of recruit numbers with egg production in each year those recruits were spawned, the 6-year time lag between spawning and subsequent recruitment was made explicit. The resulting regression of recruit numbers on egg production for the South Australian rock lobster population taken as a whole finds no evidence of correlation. The outcome is a negative slope approximately equal to 0. Moreover, within each zone individually, the result was the same; both stock-recruitment regressions were flat. Thus, there is no evidence of higher recruitment in years of higher egg production.

Sensitivity to including undersize females' yearly egg production, done for the SZ only, showed a very slight effect. The change in slope for SA overall was from -4×10^{-7} to -3×10^{-7}.

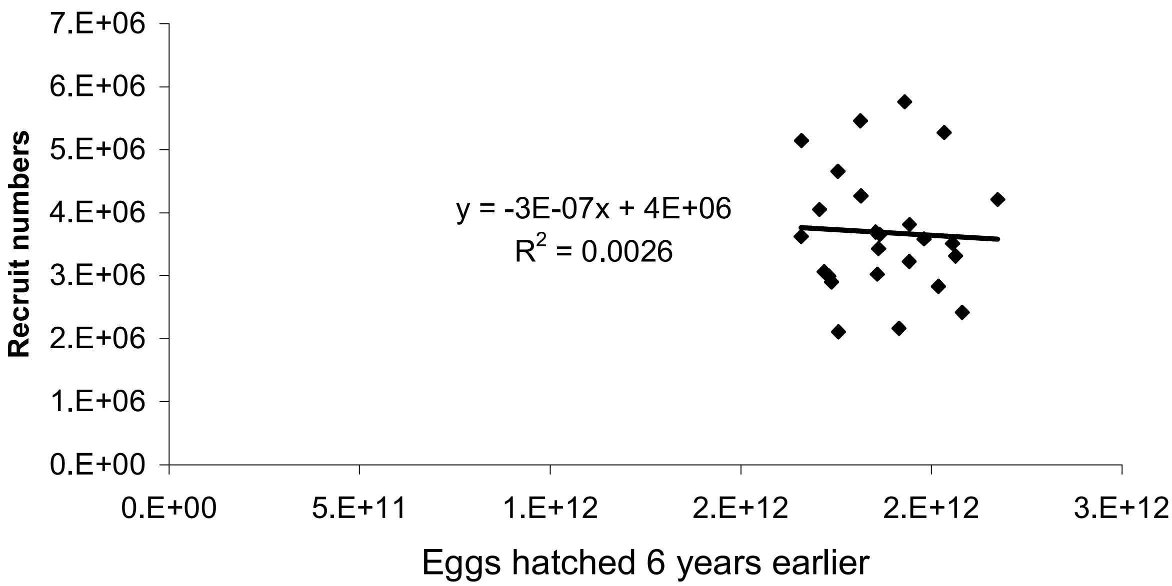


Figure 3.7. Linear regression of egg production versus recruitment, both zones combined. Egg production is lagged back 6 years assuming a 6-year time of development from egg hatching to reaching fishable size.

Discussion

Inability to Estimate Increases in Catch due to Higher Egg Production from MPAs

The lack of any identifiable stock-recruitment relationship means that further analysis of the impact of higher egg production from MPAs would not be quantifiable. This does not mean that more eggs do not, even in any particular year, give rise to more recruits. To the extent that the factors obscuring a stock-recruitment relationship are environmentally driven and are thus density independent, recruitment would rise in direct proportion to increases in egg production in any given year. However, it is also fairly certain that relatively strong density-dependent processes do also affect recruitment, notably since otherwise (1) some overall increasing trend in the stock-recruitment relationship should be evident, (2) the population size would rise or fall exponentially. Density-dependent limitation of recruitment probably acts most strongly to reduce survival and increase emigration from densely settled rocky reef at the juvenile to adult transition phase.

The problem for the current analysis is that we cannot rigorously estimate something for which no data is available to draw the required inferences. That is clearly the case with identifying a relationship between South Australian lobster egg production and subsequent increased recruitment.

This is common to essentially all lobster fisheries. In the extreme example of the New England American lobster population, where despite average lifetime egg production per female dropping (due to very high rates of exploitation and very low minimum size) to about 1-3% of its unexploited level, catches have undergone a dramatic increase by approximately 200-300% over the last two decades (Ennis and Fogarty 1997; Steneck and Wilson 2001). (In 2003 however, declines in this stock have become evident in its southern range.) Estimated egg per female recruit is an order of magnitude lower than in South Australia (where percent virgin egg-per-recruit estimates are about 18% in the Southern Zone (Ward et al. 2002a) and 21% in the Northern (Ward et al. 2002b)). If 1-3% of virgin egg production is sufficient to engender the huge increases in catch that occurred there, it is at least plausible that the 20% level current in South Australia is more than is needed, and that increases in recruitment with higher egg production would be small.

Lobster populations worldwide have long exhibited strong stability in catches in the face of relatively high levels of exploitation. This stability implies that density dependence more strongly regulate population size of lobster than for most exploited species.

In addition to density dependence, egg may drift elsewhere. The highly local nature of egg production in no-take areas, and the vagaries of currents which carry these eggs/larvae to their place of settlement, means we do not know where those spawn will ultimately settle after 18-24 months of pelagic/surface drift in the Southern Ocean. Some preliminary modelling studies in South Australia have suggested that some or many may be transported south to Victoria and Tasmania.

Thus we must conclude that, given the data available, it is not possible to generate reliable predictions of change in South Australian lobster catches due to recruitment of eggs hatched in any given sub-block or marine reserve. If pots are bought out sufficient to leave levels of exploitation approximately unaffected in the remaining fished areas, egg production for the population overall (because of increases in density and mean size of lobsters inside the reserve) would almost surely rise. But we do not know, and probably will never know, by how much recruitment will subsequently increase. Based on the general population trends of lobster populations worldwide, the increase may be small.

Rationale for Omitting No-take Area Egg Production from Pot Buy-Out Estimates

In this section, I will present the reasons why, in Chapter 4, I will omit egg production increases in the calculation of net catch loss.

The main reason is pragmatic. In this chapter we have seen (1) that it is not possible to predict how much catches may be expected to rise from higher egg production in declared South Australian no-take areas. (2) Particularly for lobster populations, this increase may be small, due to likely strong density dependent processes in recruitment. (3) If those eggs are transported to other states, buying pots back in South Australia is not justified. So, for the objective of this project, estimating net give-back of catch from higher egg production within no-take areas is not feasible.

In Appendix 4, the results of diver field survey to get a more direct estimate of egg production inside two existing reserves is presented. Specifically, research diver visual counts of lobsters over 60 m^2 transects on reef habitat inside and outside of the two principal lobster sanctuaries in South Australia were undertaken. These yielded estimates of density inside and outside of both sanctuaries. The result was that densities inside were a bit higher but this difference was not significant. Thus based on density of females inside these two no-take areas, increases in egg production may be small. However, though size of lobsters could not practically be measured in these diver surveys, it is likely or possible that females would, on average, be larger inside the reserve. In this case, some increase of egg production would be anticipated, but it remains unquantified to date.

From a more broad perspective, enhancing sustainability of exploited populations is often cited by proponents of no-take reserves as justification for their establishment. Fishery scientists and managers have generally found this argument unconvincing. Managing a fish stock involves managing the whole fish stock, and spatial closures, particularly small ones proposed for no-take areas under the current NRSMPAs are thought to be of minor value by comparison to the fishery management measures currently in place for controlling levels of exploitation on the population overall.

It is worth noting that the marine habitat in which most marine fisheries operate is, in fact, a natural ecosystem (apart from specific zones under heavy anthropogenic impacts like aquaculture or in harbours and dredging operations). Fishing in the sea is analogous to hunting in a natural forest on land, rather than being akin to agriculture wherein the natural ecosystem is effectively replaced. Thus, for species in the natural marine ecosystem which are commercially exploited, it is the overall fishery management system that will determine sustainability for both that fishery and for that species as an element of the whole ecosystem. I would argue that small (and probably also large) no-take areas are unlikely to figure large in that conservation goal because they address only a subset of the whole population. Only effective fishery management can achieve successful sustainability of exploited marine species in the entire natural marine ecosystem on which those species and the associated fisheries rely.

But if planners of no-take areas nevertheless do seek to achieve some contribution to the sustainability of natural fish stocks as an objective, this can be achieved by removing egg production increases from the calculations for pot buy-back. For lobster, as for many species, we cannot calculate the catch benefit of eggs produced. But it cannot be negative. Some of those additional eggs produced by larger (and sometimes more numerous) females inside the no-take area will make it through as recruits to the fishery.

Thus, leaving out an estimation of egg production from within no-take reserves achieves two objectives. (1) The calculation of net catch loss is made tractable. (2) The no-take area can claim some (unquantified) benefit to higher sustainability (and increased fishery production). If it were possible and egg production were rigorously accounted for, the effect of no-take areas on sustainability of these natural populations would be neutral by definition. The pots removed would just compensate for lost catches and resulting exploitation rates would remain constant in the remaining fished areas. If egg production is excluded from the calculation as I am advocating here and as I have done in this report, then it would leave effectively no doubt that the effect on exploited natural populations overall will be a positive one, and some increase in overall yearly egg production, and thus in fishery catches, would result. Thus the fishing industry, recreational fishers, and seafood consumers would indeed, with near certainty, be beneficiaries. Though again, we do not know by how much.

For purposes of this report, I have excluded the net effect of higher egg production from within reserves on pragmatic grounds. It cannot be even approximately estimated with the data available. With that in mind, how to proceed remains a question for negotiation among policy makers, state managers, fishing industry and conservation NGOs.

References

Ayling, A.M. 1978. Cape Rodney to Okakari Point Marine Reserve Survey. Leigh Marine Laboratory. Bulletin 1, Leigh Marine Laboratory, Aukland.

Babcock, R.C., Kelly, S., Shears, N.T., Walker, J.W., Willis, T.J. 1999. Changes in community structure in temperate marine reserves. Marine Ecology Progress Series 189: 125-134.

Cole, R.G., Ayling, T.M., and Creese, R.G. 1990. Effects of marine reserve protection at Goat Island, northern New Zealand. New Zealand Journal of Marine and Freshwater Research 24: 197-210.

Edgar, G.J., and Barrett, N.S. 1997. Short term monitoring of biotic change in Tasmanian marine reserves. Journal of Experimental Marine Biology and Ecology 213: 261-279.

Ennis, G.P., and Fogarty, M.J. 1997. Recruitment overfishing reference point for the American lobster, *Homarus americanus*. Marine and Freshwater Research 48: 1029-1034.

Gardner, C, Frusher, S., and Ibbot, S. 2000. Preliminary modelling of the effect of marine reserves on the catch, egg production, and biomass of rock lobsters in Tasmania. Technical Report Series Number 12. Tasmanian Aquaculture & Fisheries Institute, University of Tasmania. 38 pp.

MacDiarmid, A.B., and Breen, P.A. 1993. Spiny lobster population change in a marine reserve. In: C.N. Battershill, D.R. Schiel, G.P. Jones, R.G, Creese, and A.B. MacDiarmid [eds.], Proceedings of the 2nd International Temperate Reef Symposium. NIWA Marine, Wellington.

McGarvey, R. 1996. Is long-term persistence of harvested populations evidence of density dependence? pp. 65-77, In: R.B. Floyd, A.W. Sheppard, and P.J. De Barro [eds.], Frontiers of Population Biology. CSIRO Publishing, Melbourne.

McGarvey, R., Matthews, J.M., and Prescott, J.H. 1997. Estimating lobster recruitment and exploitation rate from landings by weight and numbers, and age-specific weights. Marine and Freshwater Research 48: 1001-1008.

McGarvey, R., Ferguson, G.J., and J.H. Prescott. 1999. Spatial variation in mean growth rates at size of southern rock lobster, *Jasus edwardsii*, in South Australian waters. Marine and Freshwater Research 50: 333-342.

McGarvey, R., and J.M. Matthews. 2001. Incorporating numbers harvested in dynamic estimation of yearly recruitment. ICES Journal of Marine Science 58: 1092-1099.

McGarvey, R. 2002. Draft Report to Southern Zone Rock Lobster Fishery Management Committee Assessing Implications of a proposed 50-Tonne Increase in Total Allowable Catch. SARDI Aquatic Sciences. 10 pp.

Prescott, J., McGarvey, R., Ferguson, G., and Lorkin, M. 1997. Population dynamics of southern rock lobster in South Australian waters. Final Report for Australian Fisheries Research and Development Corporation Project 93/086.

Steneck, R.S., and Wilson, C.J. 2001. Large-scale and long-term, spatial and temporal patterns in demography and landings of the American lobster, *Homarus americanus*, in Maine. Marine and Freshwater Research 52: 1303-1319.

Tuck, G.N., and H.P. Possingham. 2000. Marine protected areas for spatially structured exploited stocks. Marine Ecology Progress Series 192: 89-101.

Ward, T.M., R. McGarvey, Y. Xiao, and D.J. Brock. 2002a. Southern Zone Rock Lobster (*Jasus edwardsii*) Fishery. South Australian Fisheries Assessment Series 2002/04a. SARDI Aquatic Sciences, Adelaide. 70 pp.

Ward, T.M., R. McGarvey, Y. Xiao, and D.J. Brock. 2002b. Northern Zone Rock Lobster (*Jasus edwardsii*) Fishery. South Australian Fisheries Assessment Series 2002/04b. SARDI Aquatic Sciences, Adelaide. 109 pp.

CHAPTER 4. Estimates of net catch loss and pot numbers for buy-back

Introduction

In this chapter, the three stages of results presented in Chapters 1-3 are combined to yield the principal outputs of this project, namely estimated overall net catch loss per km^2 per year from each of the 30 state-waters sub-blocks. From the estimate of annual net catch loss, the corresponding number of pots (per unit area of no-take area in each sub-block) needed to harvest that amount of catch is calculated in the two South Australian rock lobster fishery zones. This gives the estimated number of licensed pots needing removal from each zone to (1) compensate for long-term lost catch, and (2) yield a neutral effect on exploitation levels, i.e. to displace no pot lift effort from no-take zones into the remaining open lobster fishery areas.

Methods

The estimation of catch lost from each 'MFA sub-block' begins with the historical catches ($\hat{\bar{C}}_{<3}(b)$, Table 1.4). The fishing industry has from the outset acknowledged that compensation should be for the *net* catch loss. That is, the long-term average reduction in yearly catch due to each MPA established. The net loss would include only that portion of the lobsters recruiting to each no-take reserve that do not subsequently move out into the fishable zone. The emigration rate (62%) estimated from Gleesons Landing (Chapter 2), is applied equally to all MFA sub-blocks, because as noted in Chapter 2, no other estimates of reserve emigration rate have been generated for *Jasus edwardsii* in SA or elsewhere.

The potential increase in catches due to increased egg production from within protected areas (stock-recruitment) cannot be quantified and therefore was not incorporated into the calculation of net catch loss as concluded in Chapter 3.

Pots are licensed by management zone, that is, Northern and Southern Zones. Thus, pots are to be bought out in proportion to the net catch loss from each zone's catch overall. On a sub-block by sub-block basis, the calculation of pot numbers needing removal to compensate net catch loss from an MPA no-take area that covered all of sub-block *b*, is done under the natural assumption that the proportion of pots to remove as a fraction of the total pot numbers in each zone equals the proportion of net catch lost from that zone.

Denote $C_T(Z(b))$ = total average yearly catch over past 11 years in fishery zone Z (either Northern or Southern Zone) which includes block b inside that zone (Table 4.1), $P_T(Z(b))$ = the total number of licensed pots held in that zone (Table 4.1), and $P_N(Z(b))$ = the number of pots to remove from zone Z corresponding to that portion of net catch lost (where the 'N' subscript denotes 'no-take').

Table 4.1. By-zone totals: the yearly catches of southern rock lobster in each South Australian fishery zone, averaged over the last 11 fishing seasons, and the current pot holdings.

	Yearly catch average (kg)	Pot holdings
Northern Zone	983997	3950
Southern Zone	1708740	11923

The assumption of equality in proportion of pots needing removal over total pots licensed and net yearly catch lost over total yearly catch is then written:

$$P_N(Z(b)) = P_T(Z(b)) \cdot \frac{\hat{\hat{C}}_{<3}(b)}{C_T(Z(b))}. \qquad (4.1)$$

Eq. 4.1 gives the formula for $P_N(Z(b))$, the number of pots needing removal to achieve proportional compensation for net catch lost if the entire area of sub-block b were set aside as no-take.

To obtain the net catch losses and number of pots needing removal per unit area, the areas of each sub-block were divided through to give the pots needing removal per average 1 km^2 of no-take area ($P_N(Z(b))/A_{<3}(b)$) in each state waters sub-block b.

To quantify uncertainty in the estimates of $P_N(Z(b))$, two methods, profile likelihood and Bayesian markov chain monte carlo (MCMC, using the Metropolis-Hastings algorithm), were employed. Both used routines included in the AD Model Builder model estimation software used throughout this project. All components of the estimation (notably from Chapters 1 and 2) were integrated into the negative log likelihood. Therefore all likelihood-modelled data uncertainty, and all interactions among these various sources of uncertainty, are reflected in the estimates of the calculated standard deviation in the estimate of $P_N(Z(b))$.

Results

The principal outputs from this project are presented in Tables 4.2 and 4.3. Both give the estimates of net catch loss, and the corresponding number of pots needing removal for catch lost, in each MFA-state sub-block. Table 4.2 gives the estimates under a scenario where entire sub-blocks are set aside for protection. Table 4.3 gives the estimates per average km^2 of lobster no-take area in each sub-block.

Table 4.2. Sub-block totals: Estimates of net catch loss and corresponding licensed pots needing removal alleviate effort displacement for each entire MFA-state sub-block (the intersection of each MFA block with state waters). Standard errors on the pots needing removal were obtained by MCMC.

MFA state-waters sub-block	Historical mean yearly catch (kg)	Estimated net catch loss (kg)	Number of pots to remove	Standard error of pots to remove
55	22861.9	8659.5	60.4	10.6
56	140568.0	53243.6	371.5	64.4
39	155479.0	58891.6	236.4	40.9
58	141267.0	53508.5	373.4	64.7
51	15838.6	5999.3	41.9	7.3
28	127247.0	48198.0	193.5	33.5
49	11272.7	4269.8	17.1	3.0
40	76948.3	29146.1	117.0	20.2
48	47094.4	17838.2	71.6	12.4
15	56664.0	21462.9	86.2	15.0
26	476.3	180.4	0.7	0.2
27	27865.0	10554.6	42.4	7.4
3	15406.7	5835.7	23.4	4.1
7	16487.1	6244.9	25.1	4.4
8	24857.0	9415.2	37.8	6.6
38	9218.8	3491.8	14.0	2.5
30	5853.5	2217.2	8.9	1.5
44	4998.2	1893.2	7.6	1.3
18	10841.8	4106.6	16.5	2.8
33	5151.1	1951.1	7.8	1.4
10	9956.7	3771.4	15.1	2.6
41	4661.1	1765.5	7.1	1.2
46	999.4	378.6	1.5	0.3
9	1154.2	437.2	1.8	0.3
45	266.2	100.8	0.4	0.1
31	85.4	32.3	0.1	0.0
17	1.0	0.4	0.0	0.0
16	469.8	178.0	0.7	0.1
2	57.3	21.7	0.1	0.0
42	1539.7	583.2	2.3	0.4

Table 4.3. Per unit area: Estimates of net catch loss and pots to remove per average km^2 of no-take area declared in each MFA-state sub-block (inside state waters). The quantities below were obtained by dividing the sub-block totals of Table 4.2 by the areas (km^2) of each sub-block.

MFA-state sub-block	Historical mean yearly catch (kg km^{-2})	Estimated net catch loss (kg km^{-2})	Estimated number of pots to remove (pots km^{-2})	Standard error of pots to remove (pots km^{-2})
55	47.921	18.151	0.12665	0.02221
56	294.455	111.532	0.77823	0.13497
39	28.181	10.674	0.04285	0.00741
58	502.381	190.290	1.32777	0.23022
51	15.439	5.848	0.04081	0.00715
28	103.524	39.212	0.15741	0.02726
49	15.044	5.698	0.02287	0.00401
40	14.811	5.610	0.02252	0.00389
48	165.581	62.718	0.25177	0.04359
15	29.650	11.231	0.04508	0.00784
26	18.676	7.074	0.02840	0.00628
27	29.402	11.137	0.04471	0.00778
3	24.767	9.381	0.03766	0.00651
7	12.330	4.670	0.01875	0.00326
8	6.970	2.640	0.01060	0.00184
38	10.321	3.910	0.01569	0.00276
30	1.429	0.541	0.00217	0.00038
44	2.591	0.981	0.00394	0.00068
18	38.153	14.452	0.05801	0.01003
33	1.766	0.669	0.00269	0.00046
10	9.381	3.553	0.01426	0.00246
41	6.778	2.567	0.01031	0.00178
46	3.199	1.212	0.00486	0.00084
9	1.201	0.455	0.00183	0.00032
45	0.581	0.220	0.00088	0.00015
31	0.191	0.072	0.00029	0.00005
17	0.013	0.005	0.00002	0.00000
16	10.456	3.960	0.01590	0.00275
2	0.107	0.040	0.00016	0.00003
42	1.580	0.599	0.00240	0.00042

To visually assess the mutual reliability of the two uncertainty estimation procedures, confidence intervals were calculated two ways for one block (56). The close agreement between the profile likelihood and MCMC outcomes (Figure 4.1) of the sample distribution of the estimate of number of pots needing removal from 56 if the entire sub-block were set aside as no-take indicates that both methods give satisfactory accuracy for estimate uncertainty. The estimate of pots needing removal about which these sample distributions vary is given as 371.5 pots in Table 4.2.

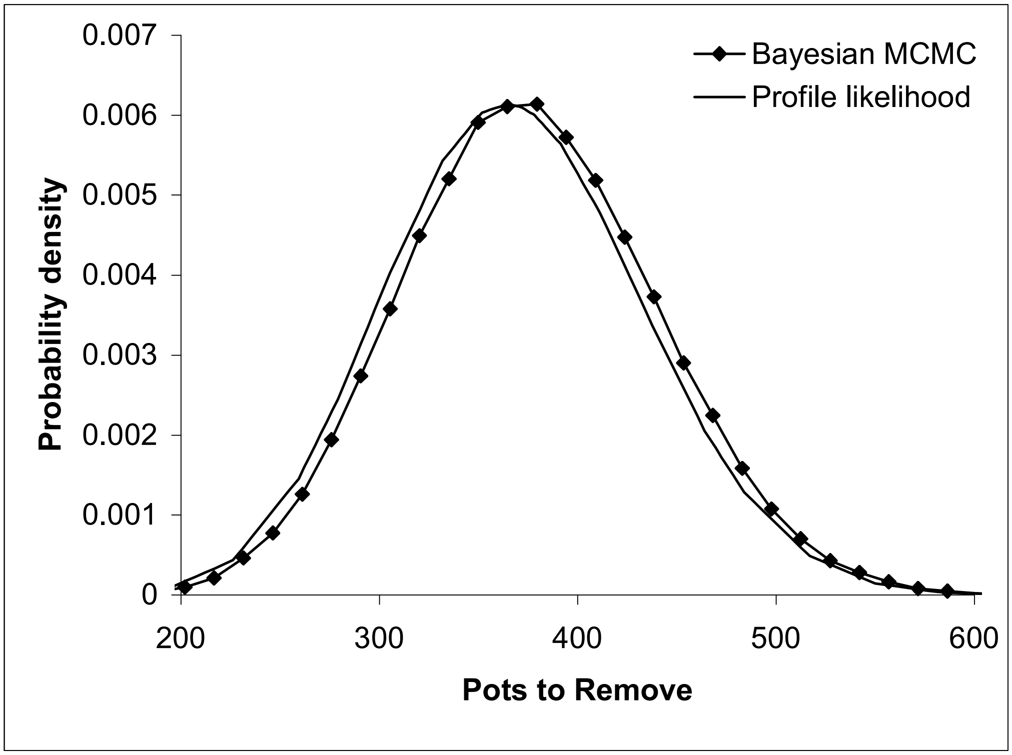


Figure 4.1. Estimation uncertainty in the number of pots needing removal to compensate for net catch lost in MFA-state sub-block 56. The two curves represent the estimated range of probable estimates using two independent methods: profile likelihood, and Bayesian MCMC, both obtained using the AD Model Builder software.

Discussion

The estimated numbers of lobster pots needing removal per km^2 of no-take zone varied by a factor of about 1000 among the 30 sub-blocks covering the South Australian coastal zone (Table 4.3). In the highest production areas of the Southeast, for example sub-blocks 56 and 58, approximately 1 pot per km^2 would need to be removed to compensate for lost catch and thereby prevent effort displacement. In Venus Bay (sub-block 17), comprised of sand and seagrass, no lobster catch was reported. Low catch sub-blocks have values of 1% of a pot or less per km^2 of no-take. Thus, high variation in the amount of catch per unit area across state coastal waters means equally high variation in the levels of compensation needed to remove displaced effort, for every km^2 of no-take area established.

Because it is difficult to intuit the size of a 1 km^2 area by comparison to the entire South Australian coastal zone, the estimates for the entire area of each sub-block were provided (Table 4.2). This allows for a simple visual inspection from the maps in this report (Figures 1.1, 1.3 and 2.1) of how many pots would need removal for no-take areas of sub-block size (which is generally thought to be bigger than the core no-take zones currently under consideration).

A marine protected area is currently being considered for the area between eastern Kangaroo Island and the lower Fleurieu Peninsula, including parts of Backstairs Passage. As an example, if the no-take zone covered all of MFA-state sub-blocks 42 and 44 (Figure 1.2), the estimated number of pots needing removal is 10.6, or rounding to the nearest whole number, 11 pots.

Costs of pot buy-out would be calculated by multiplying the number of pots needing removal by the purchase price. For example, if Northern Zone lobster pot license endorsement purchase values were $35,000 per pot, the buy-out cost to government of protecting all of sub-blocks 42 and 44 would be $385,000.

The South Australian state government MPA policy documents released to the public have indicated that the percentage to be declared core high protection zones (i.e. no-take) will in most cases be substantially less than 100% of the total MPA area to be managed. Thus, the cost calculated above is a maximum, and the buy-out cost would be less, assuming the actual area set aside as no-take is some portion of sub-blocks 42 and 44.

Benefits

The estimates of numbers of pots licensed to commercial lobster fishers that will need to be removed to prevent effort displacement should benefit all stakeholders in the MPA program. It will make the implementation of an effort buy-back possible by providing an essential quantitative input to negotiations, the estimated cost of pot buy-back. Removing effort displaced from MPA no-take areas has a beneficial impact in four ways: (1) It prevents an MPA-induced increase of harvesting pressure on populations in the remaining still fished but natural habitats. (2) It mollifies political opposition to MPAs from both the fishing industry and coastal rural communities which block MPAs from becoming established. (3) It guarantees that the effect of MPAs will be positive on the natural marine ecosystem, thus protecting marine biodiversity while enhancing or not reducing sustainability of exploited populations. (4) It provides reasonable and now state-government declared one-off compensation to fishers for long-term reductions in sustainable catches due to MPAs created.

Further Development

One process not sufficiently well understood is the effect as higher recruitment from higher (within-reserve) egg production. Further scientific effort in this domain is unlikely to yield clear evidence of a stock-recruitment relationship because the processes of compensatory density dependence in recruitment are very difficult to quantify.

Nevertheless, to obtain better estimates of the levels of percentage increase in egg production inside no-take areas, field studies inside the two existing South Australian lobster no-take areas were undertaken. This work is described in Appendix 4. The objective was to estimate the relative levels of egg production per area of reef in these protected habitats by comparison to similar reef lying outside in fished areas. The final draft of this report was not able to provide any such estimate. Moreover, the basic conclusion of Chapter 3 still applies, that estimating increases in catch for any given increase in egg production is not possible because strong density-dependent limits on recruitment seem to be acting in South Australia (and worldwide in most lobster populations), we can by this means set an upper bound on how much catch could rise (assuming a complete absence of compensatory density dependence) from the estimated percentage increase in egg production.

Bayesian methods could potentially be applied to address this uncertainty. Specifically a Bayesian panel of experts including all stakeholders could meet to agree on a reasonable level of assumed percentage recruitment increase per unit percentage increase in egg production. This agreed level (and its associated uncertainty, also to be decided by the Bayesian panel) would be incorporated as a prior into the estimates of net long-term catch loss. Because the estimator is currently formulated as an integrated numerical likelihood with which Bayesian (markov chain monte carlo) integration was employed to estimate confidence bounds, this approach is mathematically and computationally feasible. The Bayesian formulation could thereby serve as a compromise mediation tool among stakeholders in displaced effort buy-out negotiations.

Planned Outcomes

There were four principal project outputs: (1) the GIS tool (Objective 1) used to process point spatial information on lobster catches for estimating historical mean yearly catches in each MFA-state sub-block; (2) the estimation procedure for emigration rate from no-take zones using tag-recovery data; (3) the stock-recruitment analysis; (4) the overall maximum likelihood estimation algorithm which combines all these elements to generate the principal project outcomes, namely estimates of the numbers of pots needing to be bought-out to prevent effort displacement. All of these except (3) were essential inputs to this project outcome.

Conclusions

Objective 1. To provide a GIS tool that will show specific areas of rock lobster harvest, and allow computation of historical mean total catches from each MPA area proposed in SA.

This objective was met as described in Non-Technical Summary, Benefits and Planned Outcomes. The ArcView GIS tool containing an electronic spatial map of lobster fishery catches remains available for subsequent use.

Objective 2: To develop a model for estimating mean net losses of production of rock lobster as an impact of six proposed MPAs in SA.

The project was originally intended to calculate net catch loss for six specific MPA no-take zones, where the proposed boundaries were thought to have been formally declared. But to date, no specific reserve boundaries have been announced and a new method was sought to fulfil Objective 2. The GIS was also used to partition state territorial waters into 30 sub-blocks. The GIS tool (Objective 1) was then used to estimate the net catch loss of lobster per unit area annually in each sub-block. To protect the confidentiality of catch rate information, industry elected not to produce a (krig) contour map showing areas of higher and lower than average catch per km^2 across the coastal zone. The project counter-proposal to calculate overall mean catch losses per unit area of no-take zone inside each of the MFA blocks (1) permitted the completion of the project, notably of Objective 2, in the absence of any declared no-take zones, (2) provided a method which covered the entire state-waters coastal zone where parks are currently being planned, and (3) protected the confidentiality of individual pot lifts. Thus, 30 average net catch loss estimates were produced, rather than the six specified in Objective 2.

Appendix 1: Intellectual property

The FRDC's share of intellectual property, based on inputs, is 27.18%.

Appendix 2: Project Staff

SARDI Aquatic Sciences:	Rick McGarvey
	Mike Connell (database queries)
	Tim Ward (Internal Reviewer)
	Steve Mayfield (Internal Reviewer)
	Alan Jones (Appendix 4 dive survey)
University of Washington and CSIRO	André Punt (External Reviewer)
University of Queensland	Hugh Possingham (External Reviewer)

Appendix 3: External Reviews

Dr. Punt reviewed only the first two chapters; the latter two chapters were still in progress at that time. His review covers the two likelihood estimators, the binomial estimation of proportion of catch coming from inside state waters for each sub-block, and the movement estimation from Gleesons Landing.

Prof. Possingham reviewed all four chapters of the report and assessed its overall usefulness for the main project objective of estimating the numbers of lobster pots needing removal to redress displaced effort.

Note: Responses by the Principal Investigator are shown in italics.

Appendix 3.1. Review of an earlier draft of Chapters 1 and 2 by Dr. André Punt

From: Andre Punt [punt@marine.csiro.au]
Sent: Saturday, 17 August 2002 1:13 PM
To: McGarvey, Richard (PIRSA - SARDI)
Subject: Your project
Hi Rick,

I looked at your report. I don't really have too much to say about it. A few comments / thoughts:

1. You don't (in this report) evaluate the net benefits. You estimate a movement rate but not the biomass to which that movement rate applies (i.e. 60% of what biomass move out of the reserve).
These net benefits for lobster catch of proposed no-take reserves are specifically addressed (and were, in fact the principal objective of this project overall) in Chapter 4, which Dr. Punt did not see. The question of biomass versus numbers is also addressed in Chapter 4. There the observation was made that the lobster size of recruitment to the fishery (around 100 mm CL) is about the same as the minimum size where most movement occurs (around 100-150 mm CL for males and around 100-140 mm CL for females), both being linked to age of maturity. Thus, the assumption was made that lobsters emigrating from the sanctuary into the fished zone can be treated as another source of recruits to the fishery, but where the mean size of recruitment lies somewhere above 100 mm. Thus, the net increases in harvested biomass can be approximately calculated by the increased yield-per-recruit of each such emigrating recruit. For the unexploited population, growth and natural mortality estimates imply a small yield-per-recruit benefit for recruitment at those larger sizes above 100 mm, though only for males. If lobsters from the sanctuary experience slower growth or slightly higher natural mortality than those in the fished zone due to density dependence, some or all of this yield-per-recruit benefit would be lost and therefore recruits from the sanctuary can be taken as having a roughly equal effect on the harvestable biomass, and subsequent catch as regular recruits from within the fished zone. In that case, the lobsters emigrating out can be treated as normal recruits. The question of whether or how much growth might slow or average mortality might rise inside reserves is difficult to address in practice.

2. The approach used to calculate the proportions gives weight proportional to sample size. Is this really a good idea? Do the annual proportions differ from the mean in a notable way (for blocks like 55-49 for which sample size is large).

Dr. Punt refers to the fact that a binomial estimator for the proportion of catch from each MFA block falling inside state waters (like all multinomial likelihood estimators) naturally gives higher weighting to larger samples in direct proportion to sample size. However, in this case the estimates for each of the 21 sub-blocks are, in fact, independent. They share no data or parameters, and the correlation matrix from the estimated proportions taken inside state waters are all zero except along the diagonal, confirming this assertion of independence. For this reason, the relative sample sizes from different blocks do not, in the end, have any effect on the estimation outcome. The absolute sample size for each MFA block will, however, be taken as an important input in the calculation of confidence interval for each estimate.

I have averaged across years because we require an estimate that applies for long times (namely all time subsequent to the establishment of a no-take area). The variation from year to year is part of this, and is almost surely predominantly due to which fishers returned pot sample data in any given year, and where they happened to fish on those days, rather than any identifiable yearly trend. As Dr. Punt implies, identifying a yearly pattern requires far more data than the steady state analysis of proportion taken inside state waters undertaken above. If any such time trend were identified, I suspect it would be unreliable to assume it will be sustained over long times into the future. This is not a problem since a single estimate of average proportion from within each sub-block is what is required in this application.

3. Your binomial variances are pretty low because you assume each sample (pot lift) is independent. Is this a valid? It might have been better to weigh trips rather than pots.
This is a statistically insightful observation. It is probably true that the effective sample size is lower than implicitly assumed by this likelihood estimator, due to within-trip correlation. However, for many trips, pots would have been set both inside and outside the 3-mile state waters boundary line. Moreover, on many of these trips only 2 or 3 pots were sampled (of the 40-80 pots actually set and fished) and so, when these were interspersed randomly or systematically among the fishers' 40-80 pots (as pot-sample fishers were requested and generally did do), the individual pot locations are more independent than they otherwise would have been. Thus, weighting by either the sample size or the total pots set from each sample trip raises other complications in this variance that are difficult to quantify. Certainly, most likelihood estimates do underestimate variance, either due to simply not making explicit some sources of variation or by ignoring the (often slight) finite sample correction of (n/(n-1)).

4. The CVs for areas 33 and 10 in table 1.3 should be zero - the numbers you report are ADMB rounding errors.
Good point. Those numbers of around 10^{-5} *should, in fact, have been zeros. Now corrected.*

5. It might have been interesting to plot the area-ratio-based estimates and model-based proportions to see how good the area-based ratios are likely to be.
For time constraint reasons, this was not undertaken.

6. para 3, Appendix 1.1. "402!" will not be correctly interpreted by 99% of readers - best explain what "!" is here.
Agreed. The factorial symbol (!) is now defined

7. You refer to a full Bayesian analysis but that isn't here...
That's right. It is described in Chapter 4, which Dr. Punt did not see.

8. Your estimator makes sense - one would like to evaluate its robustness by simulation but you don't have the time for that!
True. This project was run on a very tight budget.

9. You refer to result that 60% moved as surprising but I would argue that the movement rates for animals in the fished area drive this and they moved a lot too! Perhaps you tagged animals as they moved out of the reserve.

After this comment was written, and in part because of it, I have now undertaken more extensive graphical analysis of the tag data set. As elucidated in much greater detail in the current draft of Chapter 2 compared with the version which Dr. Punt read, both the distances moved (Figure 2.4) and the rate moved (≥ 3 km) per year (62% in sanctuary, 24% in the fished zone) are substantially higher for lobsters from the sanctuary. There are also qualitative differences, namely in the distance distribution, which is very nearly exponential for lobsters from the fished zone at essentially all spatial scales examined (interpreted to imply a homing tendency overall) while the sanctuary lobsters showed no such tendency in the distance histograms. Thus movement behaviour is different for sanctuary lobsters in other ways besides the higher (62%) rate of emigration.

10. The estimator is very simple, you could plot its behaviour (e.g. movement rate for the reserve versus movement rate outside the reserve and recapture probability).
The simplicity of the estimation formula is its advantage. The full likelihood estimator is less simple but provides rigorous confidence bounds. We have not produced this plot due to time and space constraints, but may do so in future.

11. Did you think of movement as a Poisson process? I think if you do, you could interpret your movement probability as rate (and convert it to an annual rate). It would be interesting to see the recaptures plotted against time at liberty (for the fished and non-fished recaptures).
With this suggestion, a scatterplot of distance moved versus time-at-large (Figure 2.3) was undertaken. This is indeed an interesting graph as Dr. Punt intuited. In particular, it illustrates an unexpectedly clear independence of distance moved versus time at large, especially for lobsters from the sanctuary. As now noted in the text, this suggests that movement for most lobsters is a one-off event. If movement were more frequent, one would expect an increasing mean distance with time in the water. In other words, we would expect a gradual diffusion away from the home reef that increased with time, specifically (and here, literally) a random walk.

12. Why do variances for the movement rate - surely the likelihood estimator gave you some variance estimates?
Yes. My apologies for this omission. The estimation variance (of about ±21% of the mean rate) on the estimate is now presented in the Results.

Hope the above helps

Andre

P.S. I destroyed my copy of the document given it is confidential.

Appendix 3.2. Review of most recent draft of all Chapters by Prof. Hugh Possingham

Notes on McGarvey, R.: "Assessing the impact of proposed marine protected areas on South Australian Rick Lobster Catches

I have read this report and found that it is sound. The author has extracted a considerable amount of information and insight from the existing data and presented useful information on the likely impact of no-take marine reserves on rock lobster catches.

As the author states this assessment should be taken with caution since much of the data was not collected for the purpose for which it has been used. As I have argued on several occasions a full assessment of the impact of no-take marine reserves on rock lobster catches will require an experimental approach to the design of the reserve system. This is likely to be costly and time consuming (many years and millions of dollars) and hence McGarvey's assessment is extremely useful and timely. Notably he has presented his results cautiously and extracted a considerable amount of information from the data he has access to using relatively advanced and clever modelling methods.

I have no substantive criticisms and what follows is a small number of points. To do a full assessment of the technical details of the report would take about a week so I have not done such a detailed assessment. However since the results are sensible and the techniques used sound I have no reason to believe there are any substantial technical flaws in the report. In general this is an excellent report.

Specific comments
Page 2: para 3 – the statement about "absence of a stock recruitment signal" reads a bit like the author is accepting a null hypothesis
It might well be read that way and I would not wish to give that impression. Rather, it should be understood that absence of evidence is not evidence of absence, and we simply do not, with current data and levels of environmental noise in the stock and recruitment time series, have any evidence that there is higher recruitment in years of higher egg production. Hopefully this important distinction is clarified in the now more detailed text of Chapter 3, notably in the first paragraph of the Discussion.

Page 3: in the background section the author implies that DEH/EPA is taking a systematic approach to marine reserve system design in SA. As far as I know this is not so as they generally ignored our advice on the use of optimisation methods to design a marine reserve system. In 1998 I outlined a methodology for government and industry to achieve conservation goals that minimise the economic loss to all industries. This approach is not being taken. If such an approach were taken then McGarvey's report would provide essential information that would enhance the efficiency of any reserve system design. The statements about "optimal" could be tempered in this section.
The word "optimally ' has now been removed.

Page 4: a citation/source for the statement in para 2 "The fishing industry has long accepted that the amount of catch lost …" would be good.
I must confess that this position of the South Australian lobster fishing industry was gathered in my experience simply from the request about how the calculations for this FRDC project should be undertaken. They requested the net *catch loss. I have enquired of the industry executive officer (Roger Edwards) and there is apparently no written reference to cite, however, he confirmed this industry position by email.*

Page 12: para 3 refers to qR stock assessment model. This is an example of where jargon or symbols might best be replaced by plain English (with the jargon or symbols in parentheses). This would help overall readability and just involve some minor editing.
True. The 'qR' model would be known to those familiar with SA rock lobster stock assessment, but few others. However, descriptions of this approach are included in both the

*paper cited (McGarvey and Matthews 2001), and in less technical form in SA rock lobster stock assessment reports, notably in the most recent one (Ward, T.M., R. McGarvey, Y. Xiao, and D.J. Brock. 2002b. Northern Zone Rock Lobster (*Jasus edwardsii*) Fishery. South Australian Fisheries Assessment Series 2002/04b. SARDI Aquatic Sciences, Adelaide. 109 pp.). Rather than repeat this prose, we refer the readers to those other references.*

Page 12: end of page – it is about here I would like to see some equations that define the models mathematically.
The equations underlying the qR model are those given in McGarvey and Matthews (2001). The model has not changed since that paper (after considerable improvement previously).

Page 24: in the intro I would overview the progress of the chapter a bit more before launching in to details of Gleesons landing eg. I use two sets of data – 1 … 2 and combine these by …. To ultimately …

Page 25 – although not that important here important to remember that the distances of the recaptures don't actually represent where the animals moved – they could go further and come back – there is often a natural truncation of far moving animals – they disappear to un-sampled waters.
This is certainly true. The truncation effect is probably fairly small for this study because lobster fishers harvest over essentially the full range of occurrence of southern rock lobster, essentially the entire coastal shelf, and thus few lobsters would find refuge by travelling farther away, but some probably reach areas of relatively lower exploitation. The (1) small size of the reserve (1 km wide), notably compared with the mean distances travelled (37.4 km, from sanctuary), together with (2) earlier observations of Prescott et al. (1997) that nearly all lobster movements greater than about a kilometre are directed away from coast and out toward the shelf edge, probably mean that very few leave the reserve and return.

Pages 29-45 – the modelling here is clear and clever. While many rough assumptions are made to get the answers, these assumptions are all detailed. In some senses the work uses the logic of a basic Lincoln's index. McGarvey should publish this bit and look up relevant background refs from wildlife and fisheries.

Chapter 3 is a careful discussion of why no-take area egg production should not be taken in to account in pot buy-out estimates. I have read the analysis and discussion and think that it is sensible given the information available. Given this may be contentious it might be interesting if industry/FRDC found someone (maybe such a person does not exist, and maybe such a case cannot be argued) that could put an alternative view and back it with data and theory.
I would be happy to hold that discussion as requested. In the Further Development section above, I suggested that the uncertainty in this relationship, of how many more recruits would accrue from a given increase in egg production due to no-take reserves, could be addressed by a Bayesian approach. The various stakeholders in this decision, of what value to provide for this recruit-per-additional-egg input parameter, could form a Bayesian panel of experts. They would be asked to agree on a prior distribution for this parameter. In this application of Bayesian statistics, namely compromise mediation, the experts are simply all the parties to the negotiation. The alternative that I advocate in Chapter 3, certainly the more efficient approach, and the one that can claim a likely or certain benefit to the fishery, would be to simply leave off calculation of egg production entirely, and to set that parameter equal to 0. I believe any realistic Bayesian prior for that parameter should include 0 as a finite probability, because as demonstrated in Chapter 3, there is no (stock-recruitment) evidence for a value higher than 0. The Bayesian approach would be to make the best agreed-on guess

as to what the realistic range of values might be. In that way the calculation would take on board the input and implicit consensus of all stakeholders with representatives on this panel.

Chapter 4 is a sensible integration of previous chapters to estimate actual buy-out costs. This seems a fair base from which to estimate such costs. Within region heterogeneity will be an important issue for government and fishers to reach a consensus with respect to buy-outs given fact this analysis is at a necessarily coarse scale.

Appendix 4: Visual-Count Diver Surveys Inside and Outside Two Lobster Sanctuaries

R. McGarvey, S. Mayfield, A. Jones

Introduction

The results of diver transect surveys are presented in this appendix. These were undertaken to measure the density of lobsters inside and outside two currently existing South Australian lobster sanctuaries. Density estimates were obtained for two size categories, legals and undersize.

In addition to the Gleesons Landing sanctuary from where lobster tag-recoveries were analysed for movement rate and behaviour in Chapter 2, there is one other important lobster sanctuary, Margaret Brock, lying adjacent to Cape Jaffa in the Southern Zone, 20 km southwest of Kingston. These lobster no-take areas were established in South Australia cooperatively by the rock lobster industry and state government in previous decades of fishery management decision making. One of the reasons the Gleesons location was chosen for a reserve was that larger than average levels of smaller lobsters were being taken, interpreted to imply greater rates of puerulus settlement in this area.

The diver transects were completed during April 2003. Thus, the analysis of these surveys presented below was completed subsequent to approval and review of this Final Report. However these survey measures of lobster density inside and out provide information directly relevant to this FRDC project and will be included.

The diver estimates of density had two primary objectives: (1) The first was to estimate the increase in eggs produced inside the two reserves, due to presumed higher densities and larger-size females. At the time of writing Chapter 3, no data were available to assess the likely increase in eggs released inside a protected habitat. Moreover, no evidence was found for a stock-recruitment relationship, and thus for higher recruitment and thereby higher catches, if total population egg production were raised. (2) The second objective of this field work was to gather direct evidence to support or refute the density dependent movement hypothesis presented in Chapter 2.

Below we shall (1) predict how much higher densities are expected to be inside the reserve based on prior estimates of natural and fishing mortality rates; (2) determine the statistical probability that the densities are different inside versus outside; (3) estimate the observed survey lobster densities inside and outside the two sanctuaries; (4) assess the evidence for or against density dependence (of which movement is a likely mediating process) in the regulation of lobster population density inside the reserves.

Methods

The method was for SARDI research divers to visually count lobsters while searching the bottom over temperate reef inside and outside the two sanctuaries. All transects were 30 m long by 2 m wide, thus 60 m^2 of area searched.

There were five sites surveyed, including two separate reef locations outside the Gleesons sanctuary. Inside Gleesons, inside Margaret Brock, and outside Margaret Brock, transects were all swum at a single reef habitat site. The number of transects at each site varied from 5 to 11 (Table 1).

The transect locations inside Margaret Brock reserve were chosen where areas of reef habitat were identified from the boat where 30m transects could be swum without extending onto sand, if possible. The areas outside the reserve were chosen by a fisher to lie in areas of known exploitable lobster habitat. Similarly, transect locations at Gleesons Landing were chosen by an ex-commercial lobster fisher as areas of known lobster habitat.

Survey density from each transect and the estimated mean density at each site were obtained by dividing the number counted by the area covered. Variances (and from these, estimates of standard error and thus confidence interval for the mean) were obtained by considering each transect count as an identical independent measure.

Pairwise t-tests assuming unequal variances were run for two kinds of mean density comparison: (1) inside and outside each lobster sanctuary; and (2) between the two sanctuaries. We did not compare density inside Margaret Brock with that outside Gleesons or vice versa.

Predicted Differences in Density Inside Sanctuaries versus Outside Based on Prior Estimated Fishing Mortalities

The underlying null hypothesis we seek to test is that there is no density dependent effect, i.e. that densities are not significantly higher inside the reserve where removals of lobsters by fishing are presumed to be nil (or much lower than in fished areas).

The question becomes, How much higher should we expect densities inside the reserve to be, in the absence of movement or other density-dependent compensating factors? This question can be addressed by a range of approaches, of varying complexity. Here we shall adopt a model based on the dynamic model currently used for lobster stock assessment in South Australia, called the qR model, to estimate how much higher lobster density is expected to be in the two sanctuaries.

The method is to derive predicted numbers with age for the population lying inside and outside the two reserves. Inside we assume only natural mortality is acting. Outside, numbers with age decline more rapidly due to the addition of fishing mortality. This permits a derivation of the numbers of lobsters surviving to all legal ages, given an assumed level of recruitment. The recruitment levels we employ will simply be the approximate observed survey densities of undersize.

The following assumptions were made: (1) No movement in or out. (2) The same rate of natural mortality, $M = 0.1$, used for all southern rock lobster stock assessments (in South Australia, and elsewhere), applies equally to lobsters inside and out. (3) Fishing mortality was taken to be $F = 0$ inside the reserve, and was assigned the yearly values estimated by the qR model for all years back to 1983, averaging around $F_{NZ} = 0.27$ for the Northern Zone (Ward et al. 2002b) and $F_{SZ} = 0.55$ declining last year to 0.3 for the Southern Zone (Ward et al. 2002a). (4) Recruitment density was taken to be equal inside the sanctuary and out and fixed at the approximate observed value for undersize of 0.01 m^{-2} (Table 2). The recruitment density is, in fact, arbitrary. Because we seek only the relative numbers of legal lobsters inside and out, given a fixed level of recruitment, any choice of recruit density would yield the same outcome.

These assumptions permitted a time-dependent prediction of relative numbers at age, and thus the relative legal population densities, inside and outside each reserve, up to the most recent (2001/2002) fishing season for which stock assessment was undertaken.

The other parameters and model time and age structure from the qR models used for stock assessment in the two zones (Ward et al. 2002a; Ward et al. 2002b; McGarvey and Matthews 2001) were adopted. This model uses standard Baranov cohort depletion equations, namely

$$N_{a,t} = N_{a-1,\, t-1} \cdot \exp\left[-\left(F_t + M\right)\right] \qquad \text{for } a = 2, \ldots, 20;\ t = 1984, \ldots, 2001.$$

The initial population age vector, namely numbers-at-age for the start of the first rock lobster season ($N_{a,1983}$, $a = 2, \ldots, 20$), is estimated as part of the standard qR model fit.

While the qR model does yield estimates of yearly recruitment, the values for recruitment we adopt to compare the predicted levels of legal lobsters inside and outside are fixed at a constant yearly level,

$$N_{1,t} = R_{density} = 0.01 \text{ m}^2 \qquad \text{for } t = 1983, \ldots, 2001.$$

The fully dynamic variation in yearly recruit numbers could be employed, but it would be unlikely to have much affect on the outcome since these yearly variations would presumably be applied in the model equally to the two spatial areas of interest, namely inside and outside the reserves. More relevant to the question of how densities are predicted to vary inside versus outside would be any observed differences in numbers of juveniles, i.e. in any spatial rather than temporal differences in recruitment rate.

Results

Predicted Differences in Density Inside Sanctuaries versus Outside Based on Prior Estimated Fishing Mortalities

Gleesons Sanctuary versus the Northern Zone: Using yearly fishing mortality rate estimates for all past years in the Northern Zone, the age-based depletion model predicted that legal-size densities inside the reserve should be 3.2 times higher than outside the reserve. This assumes that no density dependence is acting, and in particular, that there is no movement out of the Gleesons Sanctuary.

Because higher levels of undersize density were observed inside Gleesons Sanctuary (Table 2a), this model was run second time. Though this diver-observed higher recruitment was not statistically significant (Table 3), the reserve was established in this location because undersize lobsters were historically captured there in larger-than-average numbers. Assuming this survey-observed but not statistically confirmed effect of higher recruitment density inside Gleesons is real, the analysis was redone by setting the yearly recruitment densities inside and out equal to the observed survey densities for undersize. Setting recruitment density inside the reserve to 0.012 m^{-2}, and for that outside to 0.008 m^{-2}, the legal size lobster densities are predicted to be 4.75 times higher inside.

Margaret Brock Sanctuary versus the Southern Zone: Again using the yearly fishing mortality rates for all past years in the Southern Zone, the age-based depletion algorithm predicted that legal-size density should be 4.2 times higher inside the reserve.

Observed Lobster Density Inside versus Outside the Sanctuaries

The raw data as diver counts of lobsters in two size categories, legals and undersize are given in Table 1.

The survey-estimated densities inside and outside Gleesons (Table 2a) and inside and outside Margaret Brock (Table 2b) showed generally small differences.

At Margaret Brock (Table 2b), the observed mean legal densities of 0.032 m^2 inside and 0.029 m^2 outside, differ by 10%. Two pieces of this outcome provide evidence of strong density dependence (with movement as the most likely mediating process): (1) The qR model-adapted algorithm predicts that densities inside should be 4.2 times higher than in the fished areas of the Southern Zone, i.e. 420%, compared with the 10% observed. (2) This 10% higher density inside is observed for undersize also, which rules out the alternative hypothesis that the nearly equal densities observed inside and outside the Margaret Brock reserve are due to much lower recruitment inside. Confidence intervals were 84% and 70% of the mean density inside and outside respectively. The observed 10% difference is thus much lower than the precision (~80%) and or very much lower than the predicted difference (~ 400%). Thus, at Margaret Brock the diver-observed densities were only slightly higher inside the sanctuary and this difference was not statistically significant.

At Gleesons, two outside sites were examined. The observed legal density inside Gleesons Sanctuary was 0.018 m^2, compared with the same value at the South outside site and 0.010 m^2 at the North outside reef location. The undersize densities at the North reef were also lower than inside Gleesons by the same percentage. Therefore, lower recruitment at the North site would fully explain the lower density observed there. Thus, the result at Gleesons was, again, equal densities inside and outside for the South outside site, and a lower density at the North outside site, though this was explainable by the lower undersize densities observed there. The model-predicted values were 3.2 or 4.75. In either case, the observed differences in density at Gleesons were far less than the predicted differences of 320% or 475% higher inside the sanctuary.

Confidence intervals on all survey mean density estimates are quite wide, ranging from 64% to 278% of the mean (Table 2). Further field work (i.e. more transects) would be needed to improve the precision of these density estimates. But there is no reason to suspect they are biased, i.e. they are presumed accurate, but are imprecise due to high spatial variation in diver lobster counts.

Statistical tests (Table 3) confirm that the measured densities are not significantly different inside versus outside. One could argue that higher power field study would show a difference. But it is unlikely to show a difference approaching the predicted densities of 300-500% higher inside the sanctuary.

Table 1. Lobsters counts over 2 m x 30 m transects by research diver visual survey. Legal lobsters are those greater than legal minimum carapace length, 105 mm CL at Gleesons Landing Lobster Sanctuary and 98.5 mm CL at Margaret Brock Lobster Sanctuary. 'Undersize' lobsters are those counted below this size limit.

	Inside Gleesons		Outside Gleesons South Site		Outside Gleesons North Site		Inside Margaret Brock		Outside Margaret Brock	
	Legals	Undersize	Legals	Undersize	Legals	Undersize	Legals	Undersize	Legals	Undersize
Transect 1	0	0	4	1	0	0	0	0	6	0
Transect 2	2	1	0	0	0	1	2	2	1	0
Transect 3	2	0	0	1	0	0	0	0	2	2
Transect 4	2	0	2	0	3	1	7	2	4	0
Transect 5	3	1	1	1	0	0	0	0	0	0
Transect 6	0	0	0	0			2	0	0	1
Transect 7	1	1	1	0			4	2	2	0
Transect 8	1	0	0	0			2	0	1	0
Transect 9	1	3	1	1			0	0	1	0
Transect 10	0	2	2	1			2	0	1	0
Transect 11	0	0							1	3
Count total	12	8	11	5	3	2	19	6	19	6
Density (m^{-2})	0.018	0.012	0.018	0.008	0.010	0.007	0.032	0.010	0.029	0.009

Table 2a. Summary statistics for mean density of legal and undersize lobsters inside and outside of Gleesons Landing Lobster Sanctuary.

	Inside Gleesons		Outside Gleesons South Site		Outside Gleesons North Site	
	Legals	Undersize	Legals	Undersize	Legals	Undersize
Number of transects	11	11	10	10	5	5
Mean density (m^{-2})	0.018	0.012	0.018	0.008	0.010	0.007
SE (mean)	0.005	0.005	0.007	0.003	0.010	0.004
Confidence interval (for mean)	±0.012	±0.011	±0.015	±0.006	±0.028	±0.011
CI (as % of mean)	±64%	±93%	±84%	±75%	±278%	±170%

Table 2b. Summary statistics for mean density of legal and undersize lobsters inside and outside of Margaret Brock Lobster Sanctuary.

	Inside Margaret Brock		Outside Margaret Brock	
	Legals	Undersize	Legals	Undersize
Number of transects	10	10	11	11
Mean density (m^{-2})	0.032	0.010	0.029	0.009
SE (mean)	0.012	0.005	0.009	0.005
Confidence interval (for mean)	±0.027	±0.012	±0.020	±0.012
CI (as % of mean)	±84%	±115%	±70%	±128%

Table 3a. Pairwise t-test comparisons of mean density inside and outside of the two reserves, for legal lobsters. P-values of 0.05 or less would indicate a significant difference in mean density at the 95% confidence level.

Pair of survey mean densities compared	P-value
Gleesons: Inside versus Outside South Site	0.52
Gleesons: Inside versus Outside North Site	0.42
Gleesons: Outside South Site versus Outside North Site	0.74
Margaret Brock: Inside versus Outside	0.90
Two sanctuaries: Outside Gleesons versus Outside Margaret Brock.	0.82
Two sanctuaries: Inside Gleesons versus Inside Margaret Brock.	0.77

Table 3b. Pairwise t-test comparisons of mean density inside and outside of the two reserves, for undersize lobsters.

Pair of survey mean densities compared	P-value
Gleesons: Inside versus Outside South Site	0.99
Gleesons: Inside versus Outside North Site	0.50
Gleesons: Outside South Site versus Outside North Site	0.51
Margaret Brock: Inside versus Outside	0.85
Two sanctuaries: Outside Gleesons versus Outside Margaret Brock.	0.23
Two sanctuaries: Inside Gleesons versus Inside Margaret Brock.	0.32

Table 4a. Summary statistics for numbers counted in 60 m^2 transects of legal and undersize lobsters inside and outside of Gleesons Landing Lobster Sanctuary.

	Inside Gleesons		Outside Gleesons South Site		Outside Gleesons North Site	
	Legals	Undersize	Legals	Undersize	Legals	Undersize
Mean	1.09	0.73	1.10	0.50	0.60	0.40
Variance	1.09	1.02	1.66	0.28	1.80	0.30
Skewness	0.43	1.37	1.34	0.00	2.24	0.61
Kurtosis	-0.93	1.32	1.86	-2.57	5.00	-3.33

Table 4b. Summary statistics for numbers counted in 60 m^2 transects of legal and undersize lobsters inside and outside of Margaret Brock Lobster Sanctuary.

	Inside Margaret Brock		Outside Margaret Brock	
	Legals	Undersize	Legals	Undersize
Mean	1.90	0.60	1.73	0.55
Variance	4.99	0.93	3.22	1.07
Skewness	1.43	1.04	1.64	1.83
Kurtosis	2.22	-1.22	2.55	2.45

Egg production Inside versus Outside the Sanctuaries

The result above of insignificant difference in lobster densities inside and out implies that higher egg production from establishment on an MPA in South Australian rock lobster would come principally from the presence of larger females on average inside reserves. We suspect that lobsters inside are larger, because of the size dependence of movement, most migrating female lobsters being in the 100-140 mm CL size range (Prescott et al. 1997). Thus larger females presumably remain in the reserve.

However, egg production increases inside versus outside were not quantified because length frequencies were not obtained from the diver surveys. (Divers could not feasibly approach and thereby measure carapaces of lobsters counted.)

Potting cannot provide unbiased length-frequency samples because southern rock lobsters show large temporal trends in sizes of lobsters trapped. Larger lobsters are known (from wide ranging and highly consistent explanation from fishers) to enter the pots when they are first set on relatively unexploited reef. Smaller lobsters are captured in subsequent days of potting after the larger ones are removed. This effect is bound to be much stronger inside a reserve. Other size/capture probability interactions may be occurring, which could further bias pot length-frequency samples of sanctuary versus fished areas.

As noted in Chapter 3, the NRSMPA no-take reserves proposed will lie in the closest three miles to shore. Large distance female movements are almost uniformly directed from inshore to offshore (Prescott et al. 1997). Moreover immature females exhibit the highest rates of large-scale movement. One evolutionary hypothesis for the selection of this behaviour is that females move toward the shelf edge because eggs released there have a higher rate of survival.

Thus, the increase in egg production inside the two reserves cannot be quantified in the absence of length samples. Lobster densities are not substantially higher inside reserves. And because these no-take areas lie close inshore, increases in numbers of eggs released by larger females may be offset by lower survival of these eggs released from inshore reserves. Thus, increases in egg production per km^2 of protected habitat may be relatively small.

Recall also, that this analysis assumes displaced effort is removed. In other words, we have taken no account of reductions in egg production outside the reserve if effort is shifted there from no-take areas established.

Discussion

More rigorous statistical tests would be attained by using a negative binomial rather than using the normal assumed by the standard two-tailed t-tests employed here. The skewness and kurtosis moments observed (Table 4) differ substantially from the values that normally distributed variates would assume, namely 0 and 3 respectively. Moreover, as count data, many of the variances were considerably larger than the means (Table 4), thus these survey counts have a spread greater than assumed by a Poisson distribution (where the variance equals the mean). A higher-than-Poisson variance indicates the need for a negative binomial likelihood. In future, this analysis should be redone using negative binomials. The t-tests could be replaced using a bootstrap or a likelihood-ratio test. However, the t-tests reported above showing no significant differences in observed densities inside versus outside were not close calls, notably, none of the P-values in Table 3 come close to the significance boundary line of 0.05, and thus the outcome is unlikely to be altered.

The broad conclusion on this evidence is that diver-observed lobster densities are not as much higher inside the two sanctuaries as would be predicted given known differences in mortality rate. Thus, the observed densities are not consistent with the null hypothesis of no density dependence. Therefore in both sanctuaries, some (by definition density-dependent) process appears to be acting to equilibrate lobster densities on reefs within a general area. Based on known qualitative differences in movement of lobsters within compared to outside the Gleesons sanctuary (Chapter 2), it is probable that movement is an important, if not the primary, process of spatial density regulation.

These results differ from measures of *Jasus edwardsii* density inside versus outside marine reserves elsewhere. Studies in Leigh Reserve in New Zealand (see the review in this report in Section 'Evidence for Higher Lobster Densities and Larger Size in Marine Protected Areas' of Chapter 3) and at Maria Island Reserve in Tasmania (Frusher et al. 2003) showed substantially higher densities inside. The density increases reported inside Leigh reserve subsequent to establishment are similar to those predicted in this Appendix, that is factors of increase of about 4-5.

One factor that may explain this is the relative rates of settlement inside Leigh Reserve where much larger densities of undersize lobsters were also found inside the reserve (MacDiarmid and Breen 1993, Fig. 7). Thus recruitment to the Leigh reserve appears to be substantially higher than at neighbouring sites. Another nearby reserve, at Poor Knights Island had, after four years of protection, only a sparse population of mainly adult *J. edwardsii*; lower densities were found here than in nearby fished areas (MacDiarmid and Breen 1993). Five marine reserves in South Africa were surveyed for a closely related species (*Jasus lalandii*) only one yielding evidence of higher densities (Mayfield et al., submitted).

A second observation to explain the higher densities at Leigh reserve is that while densities rose in the first five years subsequent to establishing the reserve, densities began to gradually decline, as mean size of the lobsters inside continued to rise (MacDiarmid and Breen 1993). The South Australian sanctuaries have been established long enough that these transitory density effects are likely to have succeeded to a state more closely resembling a density equilibrium.

The third factor explaining these differing outcomes is the known differences in lobster behaviour, notably movement. Large-scale migrations have been documented in the South Island of New Zealand (Annala and Bycroft 1993; McKoy 1983). Similarly, at Leigh reserve, protection had no obvious effect on densities of another *Jasus* lobster species, *J. verreauxi* (MacDiarmid and Breen 1993), explained by high rates of northward migration. Thus, in some areas, lobsters have a greater tendency to move under density gradients than at other areas. Reasons for this spatial difference in movement behaviour are not known.

Thus spatial variations in density response to protection and in movement behaviour are widely observed in *Jasus* spp.

The results employed in this report are those obtained by direct analysis of data for the South Australian *J. edwardsii* population. The evidence in South Australia from both diver surveys of density inside and outside two reserves and tag-recovery movement analysis is self-consistent. Strong density dependence is implied. Assuming that the estimates of net catch loss must be based on rigorous statistical analysis of data from South Australia, the results of the diver survey support the estimates of net catch loss given above.

References

Annala, J.H., and Bycroft, B.L. 1993. Movements of rock lobsters (*Jasus edwardsii*) tagged in Fiordland, New Zealand. New Zealand Journal of Marine and Freshwater Research 27: 183-190.

Frusher, S., Gardner, C., Mackinnon, C., and Haddon, M. 2003. Tasmanian rock lobster fishery 2001/2002. Fishery Assessment Report, Tasmanian Aquaculture & Fisheries Institute.

MacDiarmid, A.B., and Breen, P.A. 1993. Spiny lobster population change in a marine reserve. In: C.N. Battershill, D.R. Schiel, G.P. Jones, R.G, Creese, and A.B. MacDiarmid [eds.], Proceedings of the 2nd International Temperate Reef Symposium. NIWA Marine, Wellington.

McGarvey, R., and J.M. Matthews. 2001. Incorporating numbers harvested in dynamic estimation of yearly recruitment. ICES Journal of Marine Science 58: 1092-1099.

McKoy, J.L. 1983. Movements of rock lobsters *Jasus edwardsii* (Decapoda: Palinuridae) tagged near Stewart Island, New Zealand. New Zealand Journal of Marine and Freshwater Research 17: 357-366.

Prescott, J., McGarvey, R., Ferguson, G., and Lorkin, M. 1997. Population dynamics of southern rock lobster in South Australian waters. Final Report for Australian Fisheries Research and Development Corporation Project 93/086.

Ward, T.M., R. McGarvey, Y. Xiao, and D.J. Brock. 2002a. Southern Zone Rock Lobster (*Jasus edwardsii*) Fishery. South Australian Fisheries Assessment Series 2002/04a. SARDI Aquatic Sciences, Adelaide. 70 pp.

Ward, T.M., R. McGarvey, Y. Xiao, and D.J. Brock. 2002b. Northern Zone Rock Lobster (*Jasus edwardsii*) Fishery. South Australian Fisheries Assessment Series 2002/04b. SARDI Aquatic Sciences, Adelaide. 109 pp.