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Evaluating empirical decision rules for southern rock lobster fisheries: A South Australian example

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ABSTRACT

The fishery for rock lobsters in South Australia's southern zone has been in decline for several years. Previous harvest strategies included limit reference points, but did not specify explicit total allowable commercial catches (TACCs) when these reference points were breached. Two alternative catch-rate-based decision rules for setting TACCs for this fishery were proposed by stakeholder groups, including government scientists and the fishing industry. The two decision rules ("discrete" and "linear") set TACCs based on changes in catch-rates, with the general aim of achieving a constant exploitation rate. The two rules differed in terms of how TACCs are changed given changes in catch-rate. Management strategy evaluation is used to evaluate these decision rules. The "discrete" rule leads to greater variation in catches, but to somewhat lower risks. However, unlike the linear rule, the discrete rule cannot reduce [or increase] catches markedly. Based on the trade-offs between risk and catch, as well as the need for buy-in of impacted stakeholders, the discrete rule was selected as the basis for setting TACCs for the southern rock lobster fishery for the next 3–5 years.

1. Introduction

Crustaceans constitute some of the world's most valuable fisheries. Southern rock lobster (*Jasus edwardsii*) is South Australia's most valuable fishery resource, worth in excess of AU$100 million annually (Knight and Tsolos, 2009). The fishery is divided into two zones for management purposes: a southern zone (SZ) that extends from the Victorian border to the mouth of the Murray River and a northern zone (NZ) from the mouth of the Murray River to the Western Australian border (Fig. 1). Approximately 80% of the annual catch of rock lobsters off South Australia is taken in the SZ (Linnane and Crosthwaite, 2009), which comprises over 22,000 km^2 of relatively narrow (<30 km) continental shelf. Fishing methods have generally remained unchanged over time consisting of steel framed baited pots that are set individually overnight and hauled at first light.

The SZ has a long history of management that includes both input and output controls (Sloan and Crosthwaite, 2007). It has been a limited entry fishery since 1967, currently with a total of 181 licenses. The season extends from 1 October to 31 May of the following year. There is a minimum legal size (MLS) of 98.5 mm carapace length, CL, prohibition on the taking of berried females, and several sanctuaries within which lobster fishing is prohibited. The dimensions of lobster pots, including mesh and escape gap size, are also regulated. Fishers have to use between 40 and 100 of the total number of pots endorsed on their license at any one time to take lobster. In 1993, output controls in the form of total allowable commercial catches (TACCs) and individual transferable quotas (ITQs) were also implemented.

Despite these explicit regulations, the status of the SZ fishery has declined considerably in recent seasons (Linnane et al., 2010). Catch per unit effort (CPUE) has decreased from an historical high of 2.1 kg/potlift in 2002/2003 to just 0.6 kg/potlift in 2009/2010 (Fig. 2), the lowest on record. This decrease reflects declines in estimated legal size biomass from ~4800 tonnes to ~1800 tonnes and a doubling of exploitation rates from ~0.35 to ~0.7 over the same period (Linnane et al., 2011), and has resulted in substantial reductions to the TACC from 1900 tonnes in 2002/2003 to 1250 tonnes for the start of the 2010/2011 season. Importantly however,

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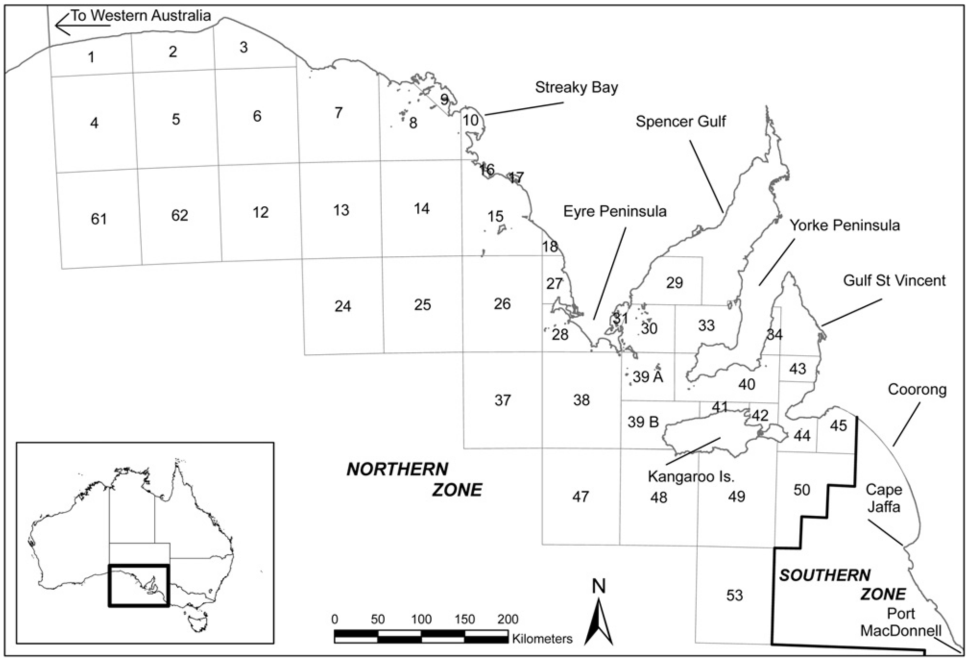

Fig. 1. Northern and southern zone rock lobster fisheries of South Australia. Numbers show the locations of the marine fishing areas which are used for statistical purposes.

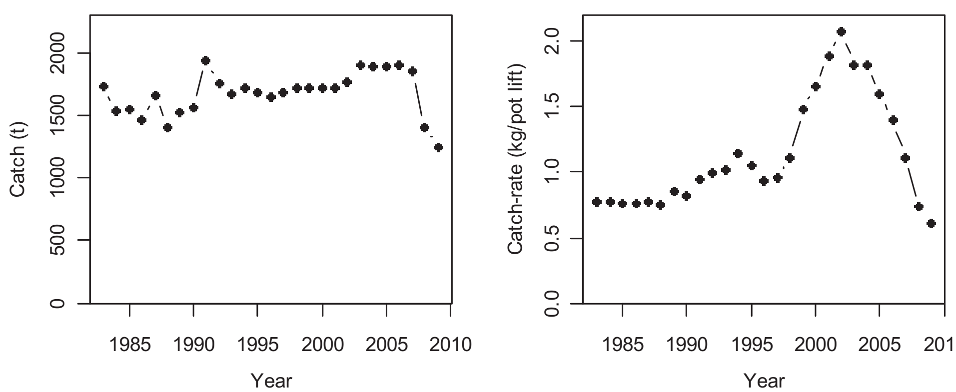

Fig. 2. Trends in commercial catches and catch-rates of SZ rock lobster.

reductions during this period were largely made in the absence of formal decision rules that advised on TACC levels.

The harvest strategy for the South Australian SZ rock lobster fishery was reviewed at the end of the 2009/2010 fishing season. At this time, there was clear agreement between industry sectors, resource managers and stock assessment scientists on the need for a rule-based system that provided explicit advice on appropriate TACC levels based on current fishery performance. With this common objective, two decision rules[1] (DRs) were proposed for evaluation, one by government scientists and the other by industry. Both of the DRs were based on the notion of maintaining a constant exploitation rate without explicitly attempting to estimate exploitation rate annually. Both DRs modified TACCs based on changes in catch-rates from one year to the next. However, it was unclear when they were proposed how well these DRs would achieve the conflicting goals of low probabilities of the resource dropping to undesirably small population sizes and high catches and catch-rates.

Management strategy evaluation (MSE; Smith et al., 1999; Butterworth, 2007; Rademeyer et al., 2007) has in the past been used to evaluate approaches for setting TACCs for rock lobster resources (e.g. Johnston and Butterworth, 2005; Punt and Hobday, 2009; Starr et al., 1997) and TACCs are set for New Zealand and South African rock lobster resources using approaches similar to the two decision rules proposed for use in the SZ rock lobster fishery. MSE provides a means to identify the trade-offs among alternative TACC-setting approaches given uncertainty regarding the true state of the system and future data prior to their use in practice, giving decision makers the opportunity to objectively select among the alternative candidate DRs and to have some reassurance of the likely impact of applying any selected DR. This paper therefore uses MSE to compare the two DRs proposed for the SZ rock lobster resource. Although it is common to consider a range of values for the parameters of DRs when applying MSE (e.g. De Oliveira and Butterworth, 2004; Plagányi et al., 2007), such results are not

[1] We use the term 'decision rule' here rather than the more conventional term 'harvest control rule' because harvest control rules usually only indicate how the results of assessments should be used to determine management actions and not how the assessment is to be conducted. The DRs of this paper in contrast are fully specified because they specify which data are to be used to apply them. As such the DRs are more similar to 'Operational Management procedures' (Johnston and Butterworth, 2005).

shown here because the evaluated DRs are those specifically proposed by the stakeholders concerned for implementation in the SZ rock lobster fishery.

2. Materials and methods

2.1. Overview and operating model

Fig. 3 outlines the basic simulation framework used to evaluate the DRs. The population model used for stock assessment of SZ rock lobster and here used for forecasting the consequences of the two DRs (i.e. the operating model) is size- and sex-structured. This model is fitted to data on catches by fishing fleet (commercial and recreational) and time-step (monthly time-steps during the fishing season from October to May and one time-step from June to September spanning the winter closure), catch-rates for the commercial fleet by time-step, total catch-in-numbers taken by the commercial fleet by time-step, and length–composition information by sex and time-step from on-board pot sampling. The last year for which data were available was 2009/2010. Variants of this model and its associated estimation scheme have formed the basis for assessments of southern rock lobster off Tasmania, Victoria and South Australia for many years (Punt and Kennedy, 1997; Hobday and Punt, 2001; McGarvey et al., 2010).

There are three ‘fleets’ in the operating model: (a) the commercial fleet, (b) the recreational fleet, and (c) a survey fleet. The survey fleet is included in the operating model so that the data from an on-board pot sampling program can be used for parameter estimation. However, the catch by the survey fleet is assumed to be negligible. The selectivity patterns for the commercial and recreational fleets are set equal to the selectivity pattern for the survey fleet, except that allowance is made for the minimum legal size, MLS, for the commercial and recreational fleets of 98.5 mm CL. Growth is modeled in the operating model as the probability of growing from one size-class to another, with the size-transition matrix based on the method of McGarvey and Feenstra (2001). Growth is assumed to occur at the end of December and at the end of May.

Each projected season (see Fig. 3) involves first applying the DR to determine the TACC (based on the previous fishing season’s catch-rate), calculating the recreational catch for the season, updating the size of the population based on the resulting commercial and recreational catches, generating future recruitment, and generating the catch-rate for the most recently completed season. The projections are based on 30 future seasons (long enough that the consequences of the DRs are evident) and 500 projections were conducted for each combination of scenario (see below) and DR. There are a number of other specifications related to projecting the population forwards and applying the DRs:

1. The MLS remains at 98.5 mm.
2. The recreational catch is calculated as the total exploitable biomass (the biomass above the MLS which is selected by the gear) at the start of the year multiplied by the ratio of the sum of the recreational catches over 2007/2008, 2008/2009, and 2009/2010 to the sum of exploitable biomasses at the start of these three years, i.e. the recreational exploitation rate is assumed to remain at its current level. Future recreational catches are broken down by monthly time-step within each year based on the average monthly break-down for 2007/2008–2009/2010.
3. Similarly, the commercial catch by monthly time-step is based on the average split to time-step for 2007/2008–2009/2010.
4. The catch-rate used to apply the DR is the total yearly catch divided by the total yearly effort (i.e. unstandardized catch-rate is used; Fig. 2).

Table 1
Fixed control parameters needed to apply the two DRs. The TACC (tonnes) for the next season is based on the current season catch-rate for both DRs.

Discrete DR		Linear DR	
Current season CPUE	Next season TACC	Parameter	Value
<0.8	960	a_B	408.06
>0.8 and <1.0	1280	b_B	2340.6
≥1.0 and <1.2	1400	H^T	0.4
$X \geq 1.2$	1600	H^L	0.3
		H^U	0.5
		$\text{CPUE}^L_{2011/2012}$	0.605 kg/potlift
		$\text{CPUE}^U_{2011/2012}$	1.125 kg/potlift

5. The DRs are first applied in 2011/2012. However, the terminal point of the current assessment is the start of the 2010/2011 season. The population is therefore projected forward to the start of the 2011/2012 season under catches that equal the actual TACC for 2010/2011 (1250 tonnes).
6. ‘Implementation error’ is assumed to be negligible, i.e. the catch removed from the simulated population is assumed to be the TACC unless this is not possible given the size of the population.

2.2. The decision rules

Both DRs use the catch-rate for the most recent completed fishing season as the only input (or performance indicator).

The first DR (the ‘discrete’ DR) sets the TACC for the next fishing season based on the commercial catch-rate for the current fishing season (see Table 1). The discrete DR maps catch-rates within four discrete catch-rate sub-intervals (the middle two sub-intervals being 0.2 kg/potlift in width) on to single fixed values of TACC, one TACC value for each catch-rate sub-interval. Thus, given the current (most recent season’s) catch rate, the discrete rule will prescribe one of the four possible discrete values of TACC for the following season. The levels of TACC assigned to the discrete subintervals of catch-rate in the discrete rule (Table 1) were obtained, by industry peak body members, based on chosen target levels of yearly effort.

The second ‘linear’ DR is based on an assumed linear relationship of lobster biomass to catch-rate. The stated objective of the linear rule is to restore the TACC to a level that returns the fishery to a specified harvest rate. Catch-rate is used as a yearly index of harvestable biomass (Fig. 4c). Under the linear DR, the TACC for next season ($y+1$) is increased or decreased only when the catch-rate for the previous season (y) breaches upper or lower trigger levels, which are determined based on selected upper and lower harvest rates. Following fishing seasons when the catch-rate (i.e. $CPUE_y$) exceeds the current upper trigger level (CPUE^U_y) or falls below the current lower trigger level (CPUE^L_y) (see also Fig. 4c):

a. the TACC for the next season is reset based on the target harvest rate, $H^T = 0.4$, i.e. $\text{TACC}_{y+1} = H^T \cdot B_y = H^T \cdot (a_B + b_B \cdot \text{CPUE}_y)$;
b. the upper trigger level is adjusted to $\text{CPUE}^U_{y+1} = (\text{TACC}_{y+1}/H^L - a_B)/b_B$; and
c. the lower trigger level is adjusted to $\text{CPUE}^L_{y+1} = (\text{TACC}_{y+1}/H^U - a_B)/b_B$.

The TACC remains unchanged in years when the upper and lower trigger catch-rates are not breached. Table 1 lists the values for the parameters of the linear DR, including the initial values for the trigger levels (see Appendix 1 for details). The values for the control parameters of the linear DR (Table 1) were derived based on a linear regression of estimated year-average biomass from the ‘qR’ model of McGarvey and Matthews (2001) on observed yearly catch-rate from 1993 to 2009 ($R^2 = 0.994$; Fig. 4b). This rule was, in part, adapted from the TACC-setting rule for southern rock lobster

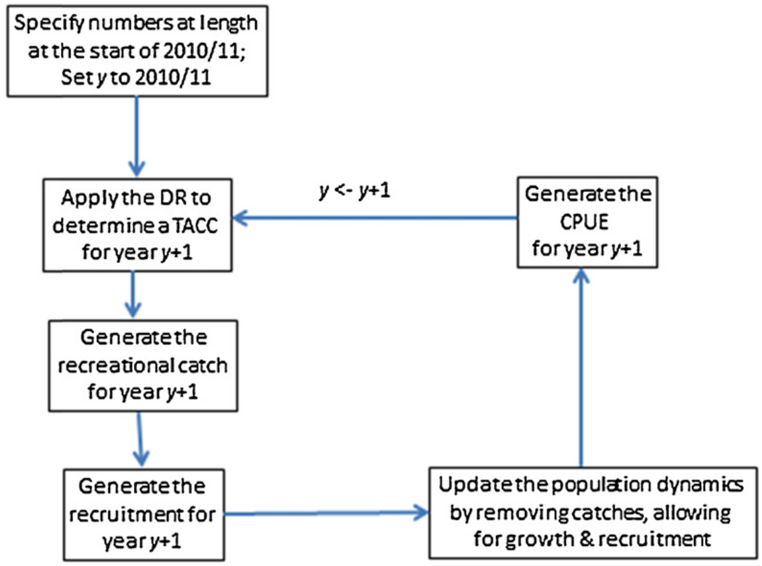

Fig. 3. Overview of the process used to evaluate decision rules.

off New Zealand, fishery regions CRA 7 and 8 (New Zealand Rock Lobster Industry Council, 2008; Breen et al., 2009).

2.3. Scenarios

It is not possible to consider all possible variables which might influence the relative performance of the two DRs. Rather, the scenarios considered reflect our experience with the factors that are most likely to impact the performance of DRs for rock lobster populations:

1. *Recruitment*. The baseline scenario assumes that recruitment is selected at random from the recruitments from 2003 to 2007. These years were selected because the associated year-classes are recent and well-determined by existing data. Sensitivity to the baseline scenario assumption regarding recruitment is explored by selecting recruitment (a) at random from a longer-period (1998–2007); (b) as for the baseline scenario, but reducing recruitment to 50% of the generated value; and (c) as for the baseline scenario, but with recruitment raised to 150% of the generated value. The latter two scenarios test for sensitivity to future levels of productivity of the stock. The analyses are not based on simulating future recruitment from a stock–recruitment relationship *inter alia* because it is unlikely given the long larval duration for rock lobsters that recruitment to the SZ is produced mainly by spawning in the SZ (Bruce et al., 2007).
2. *Variability in catch-rates*. The baseline scenario involves generating the future catch-rates for each time-step during the year with the level of variation estimated by fitting the operating model to the actual data, as is common when applying MSE. Sensitivity is explored to: (a) setting the extent of variation to zero; and (b) increasing the standard errors for catchability by 50%. The data are generated under the assumption that the deviations in catch-rate from expected catch-rate are independent among time-steps. This assumption is unlikely to be fully valid, and scenario (b) implicitly examines the implications of allowing for correlation in catchability among time-steps.
3. *Current stock status*. The baseline scenario involves setting the estimates of numbers-at-length at the start of the most recent year using the output of the stock assessment. Sensitivity is explored to (a) halving the numbers-at-length for this year; and (b) increasing the numbers-at-length for this year by 50%. Recruitment for these scenarios is generated in the same manner as for the baseline scenario and catchability is twice the baseline values for (a) and half the baseline values for (b) so that future catch-rates remain consistent with biomass levels. These sensitivity tests allow testing of the robustness of the DRs to uncertainty about the current status of the stocks.
4. *Trends in catchability*. The baseline scenario assumes that there are no trends in catchability into the future, i.e. no future changes in efficiency. One scenario explores the implications of a 1% annual rate of increase in catchability.
5. *Variation in natural mortality*. The baseline scenario only allows for process variation in recruitment. One scenario explores the case in which natural mortality varies inter-annually with a CV of 20%.

2.4. Performance metrics

The performance metrics used to summarize performance are: (a) the median and 90% quantiles [over simulations] of the average annual catch over the simulation interval [the range between the upper and lower 5% quantiles therefore indicates uncertainty about the mean catch and not that of the annual catch], (b) the probability that the egg production drops below the egg production in 2009/2010 (abbreviation *P*(mat)), (c) the probability that the exploitable biomass in the middle of November drops below the corresponding exploitable biomass in 2009/2010 (abbreviation *P*(expl)), and (d) the mean over simulations of the average annual variation in catch (AAV)[2]:

$$\mathrm{AAV} = \frac{\sum |\mathrm{TACC}_{y+1} - \mathrm{TACC}_y|}{\sum \mathrm{TACC}_y} \qquad (1)$$

Values for these performance metrics are shown for the first five years of the projection (2011/2012–2015/2016) as well as for the

[2] The mean is used instead of the median because the AAV is zero (TACCs are constant) for many of the simulations, making the median a poor summary statistic.

Table 2
Summary statistics for the 5- and 30-year stochastic projections for the southern zone.

Case	DR	Average catch			P(expl)	P(mat)	AAV
		Lower 5%	Median	Upper 5%			
(a) 5-Year projections							
Baseline	Discrete	960	1200	1352	2.5	6.1	13.7
Recruitment from 1998 to 2007	Discrete	1088	1328	1472	0.3	0.8	14.0
Recruitment = 50% baseline	Discrete	765	941	960	75.6	90.8	9.9
Recruitment = 150% baseline	Discrete	1240	1408	1496	0	0	12.9
No catchability variability	Discrete	960	1216	1368	2.3	6.1	12.7
Catchability variation = 150% baseline	Discrete	960	1176	1328	2.4	5.9	14.7
Current abundance is half baseline	Discrete	721	929	1088	97.9	94.7	14.7
Current abundance is double baseline	Discrete	1176	1352	1472	0	0	11.3
Q increases by 1% per annum	Discrete	960	1200	1368	2.9	6.5	14.0
M has a CV of 20%[a]	Discrete	960	1200	1368	2.3	5.2	13.8
Baseline	Linear	870	1250	1257	10.6	13.8	6.1
Recruitment from 1998 to 2007	Linear	997	1250	1436	2.4	2.8	4.3
Recruitment = 50% baseline	Linear	655	755	833	77.1	91.1	15.8
Recruitment = 150% baseline	Linear	1250	1370	1607	0.1	0.1	6.5
No catchability variability	Linear	891	1250	1265	12.6	15.3	4.8
Catchability variation = 150% baseline	Linear	852	1138	1257	6.4	9.4	10.1
Current abundance is half baseline	Linear	638	897	1118	64.4	64.3	40.6
Current abundance is double baseline	Linear	1237	1251	1341	0	0	0.9
Q increases by 1% per annum	Linear	880	1250	1270	10.9	14.2	6.1
M has a CV of 20%[a]	Linear	880	1250	1267	9.4	11.8	6.4
(b) 30-Year projections							
Baseline	Discrete	1117	1261	1401	4.9	8.9	9.0
Recruitment from 1998 to 2007	Discrete	1397	1527	1576	0.1	0.4	3.7
Recruitment = 50% baseline	Discrete	531	593	652	95.9	98.5	12.5
Recruitment = 150% baseline	Discrete	1519	1568	1583	0	0	2.0
No catchability variability	Discrete	1111	1259	1393	5.7	10.2	7.5
Catchability variation = 150% baseline	Discrete	1121	1263	1405	3.5	7.2	10.5
Current abundance is half baseline	Discrete	937	1086	1222	90.9	78.6	11.7
Current abundance is double baseline	Discrete	1228	1371	1511	0	0	6.8
Q increases by 1% per annum	Discrete	1113	1263	1403	13.6	17.3	9.4
M has a CV of 20%[a]	Discrete	1129	260	1380	4.2	8.3	9.0
Baseline	Linear	1123	1259	1402	2.7	4.9	6.1
Recruitment from 1998 to 2007	Linear	1396	1570	1749	0.5	0.6	6.3
Recruitment = 50% baseline	Linear	589	657	734	73.4	98.1	7.9
Recruitment = 150% baseline	Linear	1666	1873	2077	0	0	6.0
No catchability variability	Linear	1119	1259	1402	3.6	6	5.0
Catchability variation = 150% baseline	Linear	1115	1265	1402	1.5	3.1	7.9
Current abundance is half baseline	Linear	989	1124	1248	57.1	51.1	17.0
Current abundance is double baseline	Linear	1200	1352	1487	0	0.1	3.2
Q increases by 1% per annum	Linear	1130	1269	1410	4.9	8.3	6.8
M has a CV of 20%[a]	Linear	1138	1261	1373	2.6	4.5	6.1

[a] Additional sensitivity run is response to a reviewer comment; not available when a HCR was selected for the southern zone rock lobster stock.

entire 30-year projection period (2011/2012–2040/2041) to allow the short- and medium-term performances of the DRs to be considered. Best performance occurs for higher average catches, lower variation in catch, and lower probabilities of declines in egg production and exploitable biomass (although care needs to be taken when interpreting these probabilities for the cases in which the initial state of the stock is changed).

In addition to summary statistics, the results are also summarized by time-trajectories of exploitable biomass and catch. Note that even though the tables and figures report results in absolute numbers (e.g. TACCs in various future years), the focus of the analysis is on characterizing the relative performance of the DRs.

3. Results

3.1. Baseline results

Fig. 5 shows example time-trajectories for the annual catch (TACC after 2010/2011), catch-rate, exploitable biomass and egg production (relative to that in 2009/2010) for the two DRs. For ease of understanding, the results in Fig. 5 ignore future variation in recruitment (future recruitment is constant and equal to the average over 2003–2007) and future variation in catchability. This simplifies interpretation of the impacts of the DRs. The trajectories under both rules are relatively variable. In particular, the discrete DR tends to increase (or decrease) the TACC abruptly and seemingly when there is little change in catch-rate, while the linear DR reduces the TACC for the SZ substantially in 2032/2033 when catch-rate drops slightly below the lower trigger level (Fig. 5a and b). The discrete DR is more conservative than the linear DR until 2032/2033 (Fig. 5c and d), when the linear DR reduces the TACC markedly and there is a large increase in biomass and egg production. Under the assumed constant recruitment, a DR would ideally approach this state of higher biomass, egg production and catch rate more smoothly.

Table 2 (row "baseline") and Figs. 6 and 7 summarize the results of the baseline scenario when recruitment is stochastic and catchability varies among years. As expected, there is now uncertainty regarding annual TACC levels as well future levels of catch-rate and biomass, with the extent of uncertainty increasing into the future before stabilizing. The TACCs under the discrete DRs demonstrate their discrete nature, with the TACC constrained within minimum and maximum values, but varying fairly considerably

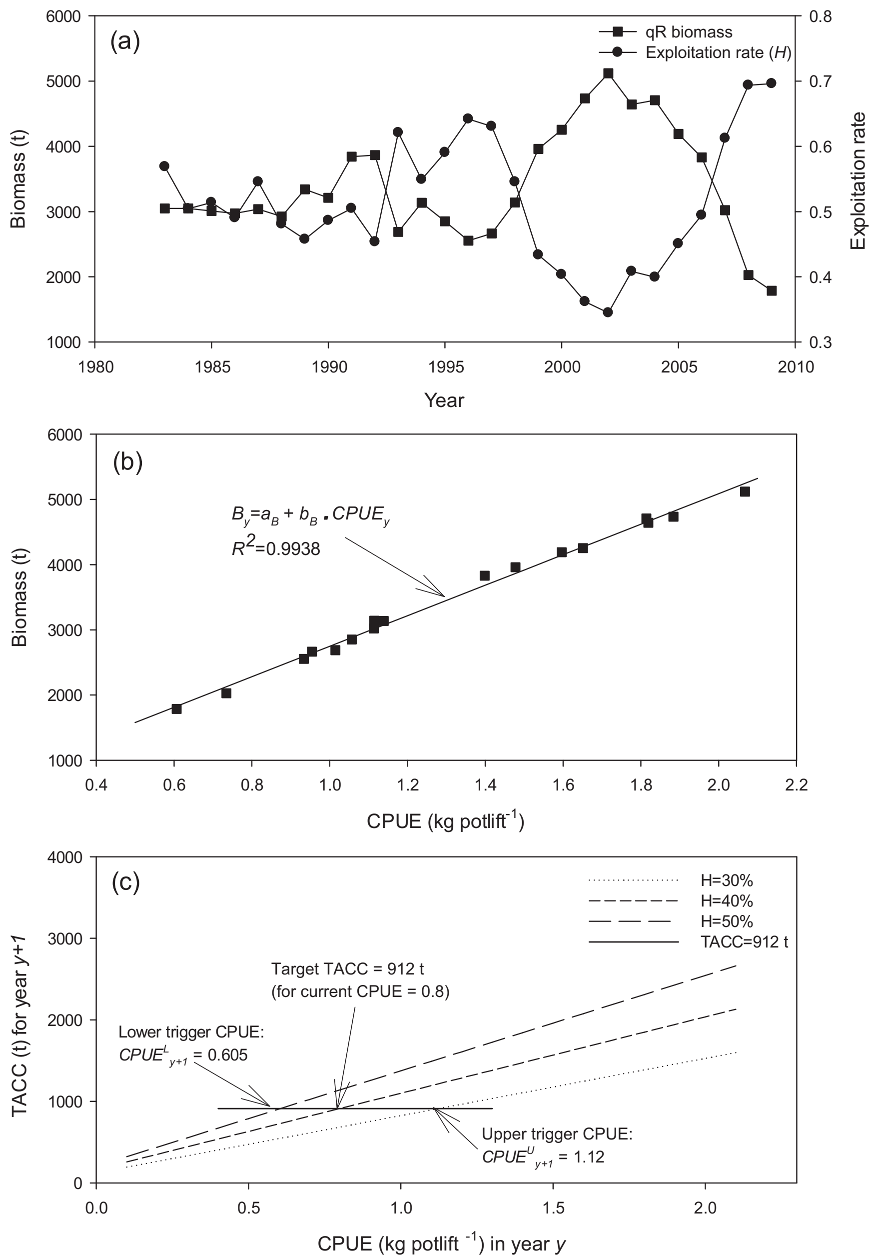

Fig. 4. Illustration of the linear DR. (a) Yearly time series of biomass and harvest rate from the qR model were used in the (b) linear regression of biomass versus yearly CPUE. Given a specified target level of harvest rate (*H*) that the linear DR seeks to maintain, the resulting parameter estimates for biomass versus CPUE are in turn used to (c) relate CPUE in the previous fishing season to predicted catch given harvest rate *H*, and thus the TACC for the next season. See Appendix 1 for further details.

within these ranges (Fig. 6). The linear DR leads to slightly higher average catches than the discrete DR over the first five years of the projection period, but the two DRs lead to essentially the same average catches over the entire 30-year projection period. The linear DR leads to less inter-annual variation in catch, particularly over the first five years of the projection period. This is due to this DR setting the TACC to a fixed value for several years and only changing it (substantially) on occasion (Figs. 5 and 8). The discrete DR leads to values for AAV of 15%, 11%, 11%, 11%, and 11% for the five simulations in Fig. 8 while the linear DR leads to values for AAV of 16%, 0%, 0.1%, 0% and 0% for these simulations. A key reason for the high AAV for the discrete DR is that it increases the TACC in the first year by a larger extent than the linear DR. The variability of the discrete DR would have been much lower had the AAV statistic ignored the change in TACC from 2010/2011 to 2011/2012.

The discrete DR leads to a lower probability of dropping the stock below the levels of exploitable biomass and egg production in 2009/2010 over the first five projection years, but to slightly higher probabilities over the 30-year period for the baseline simulations (Table 2).

3.2. Sensitivity tests

In general, the DRs behave as expected for the sensitivity tests; catches are higher and risks lower when recruitment is higher than the baseline scenario [“recruitment from 1998 to 2007” and “recruitment = 150% baseline” in Table 2] while the opposite effect is evident when recruitment is lower than for the baseline scenario [“recruitment = 50% baseline” in Table 2]. Figs. 9 and 10 show the time-trajectories of model outputs for the case in which recruitment is selected at random from 1998 to 2007, a period

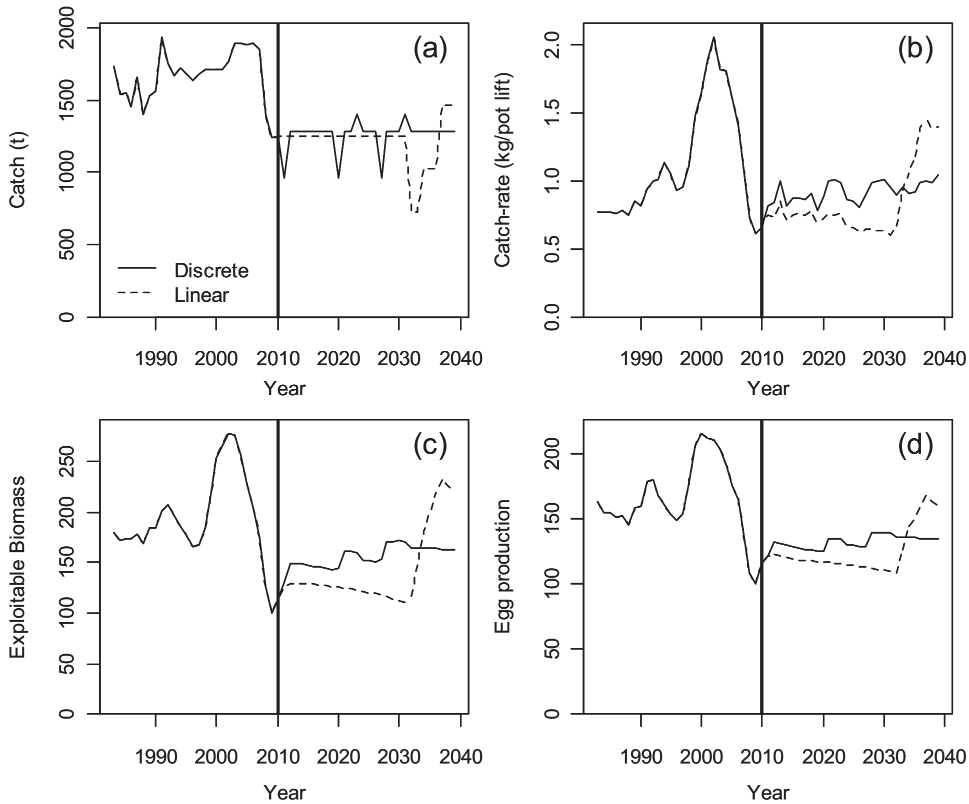

Fig. 5. Example time-trajectories of catch (TACC after 2010/2011), annual catch-rate, exploitable biomass (relative to that in 2009/2010), and egg production (relative to that in 2009/2010) for the southern zone rock lobster fishery under two DRs for the baseline operating model and in the absence of observation and process error, including no yearly variation in recruitment.

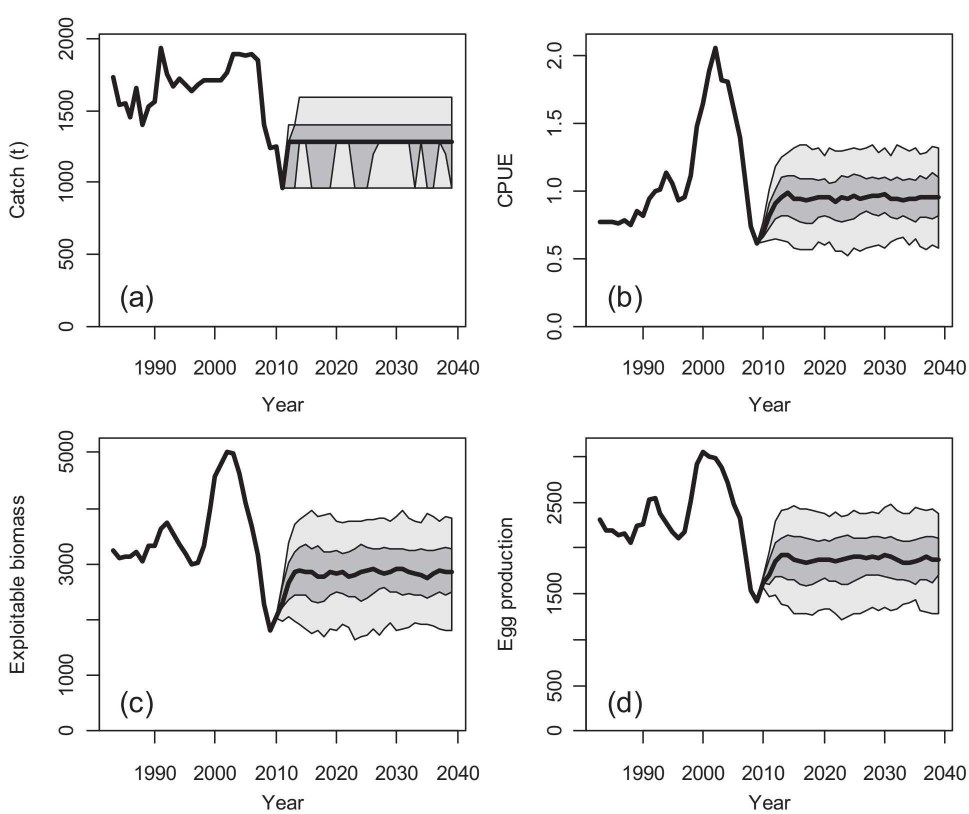

Fig. 6. Distributions (solid line: median, 50% intervals: dark shaded area, 90% intervals: light shaded area) of TACC, catch-rate, exploitable biomass and egg production. The TACCs are set using the discrete DR.

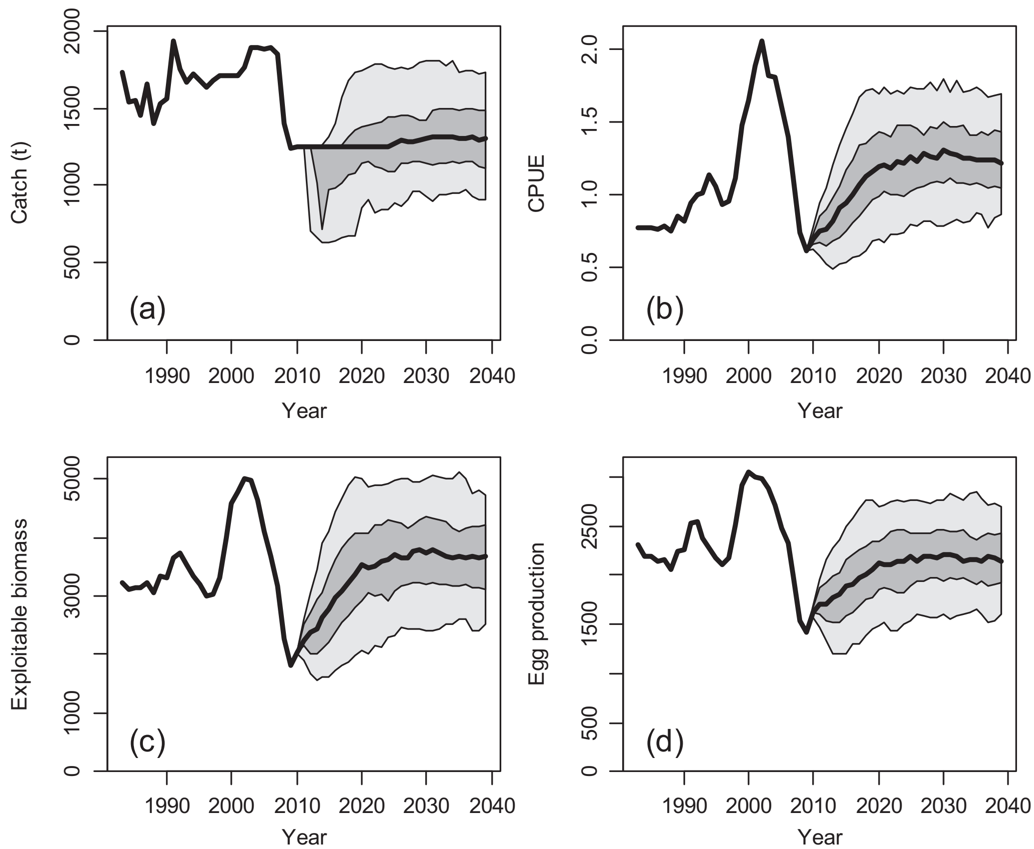

Fig. 7. Distributions (solid line: median, 50% intervals: dark shaded area, 90% intervals: light shaded area) of TACC, catch-rate, exploitable biomass and egg production. The TACCs are set using the linear DR.

during which recruitment was closer to the long-term average than 2003–2007.

The linear DR does not impose maximum and minimum TACCs, which means that it can utilize the higher productivity for the "recruitment = 150% baseline" scenario. However, even though it did not impose a minimum TACC, the linear DR still dropped the stock below the levels in 2009/2010 when average recruitment was lower than for the baseline scenario. The level of catchability variation only noticeably impacted the inter-annual variation in TACCs [quantified by AAV in Table 2], although the effect was larger for the discrete than for the linear DR, while allowing natural mortality to vary inter-annual had limited impact on the results.

Starting the projections at a different level ["current abundance is half baseline" and "current abundance is double baseline" in Table 2] had relatively little impact on average catches or AAV over the longer-term, but (as expected) short-term catches were higher for the "current abundance is double baseline" scenario and *vice versa* for the "current abundance is half baseline" scenario. The lower 5% quantile of the average catch distribution is lower than the minimum level for the scenario in which current abundance is half of the baseline for the discrete DR. This indicates that the discrete DR sets a TACC higher than the current exploitable biomass [the stock does not "collapse" even in this case because recruitment is independent of egg production]. Although less evident, the linear DR also sets a TACC higher than the current exploitable biomass for this scenario. This occurs in the first few years of the projection period before data are accumulated which suggest that abundance is less than indicated by the baseline assessment.

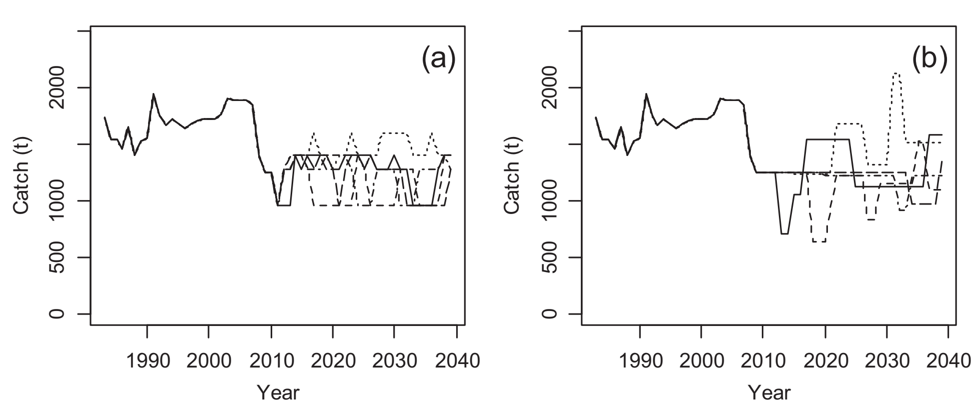

Fig. 8. Time-trajectories of catch (TACC) for five simulations. The results for the discrete DR are shown in (a) and those for the linear DR in (b).

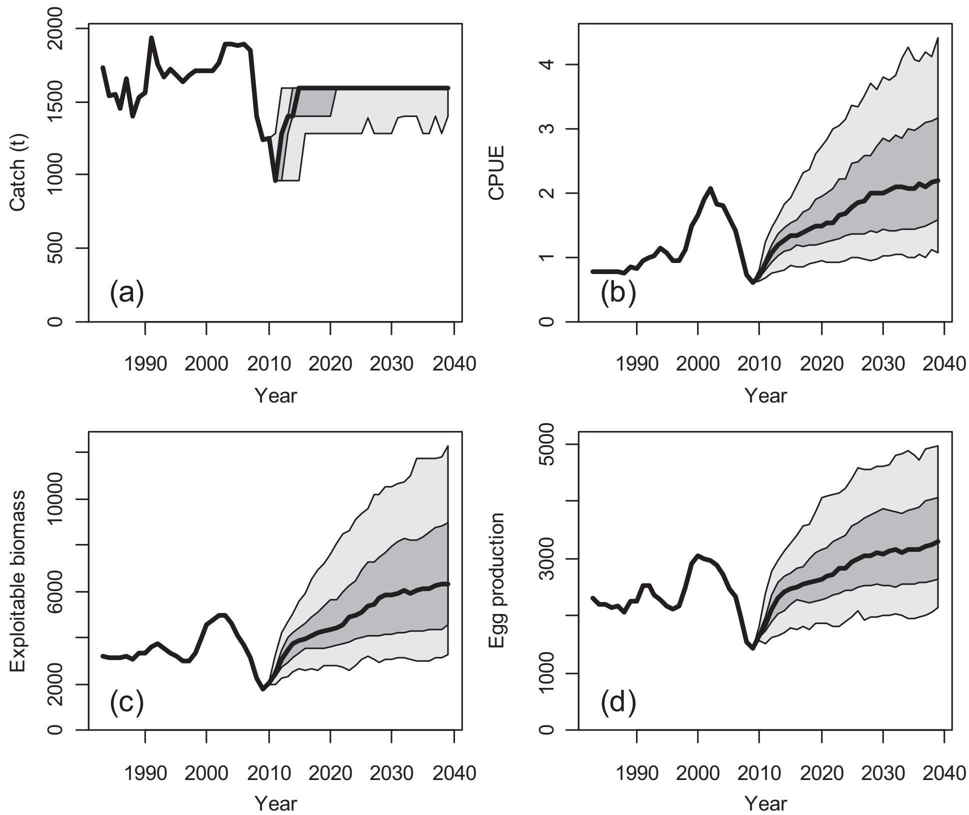

Fig. 9. Distributions (solid line: median, 50% intervals: dark shaded area, 90% intervals: light shaded area) of TACC, catch-rate, exploitable biomass and egg production. The TACCs are set using the discrete DR and recruitment is drawn from 1998 to 2007.

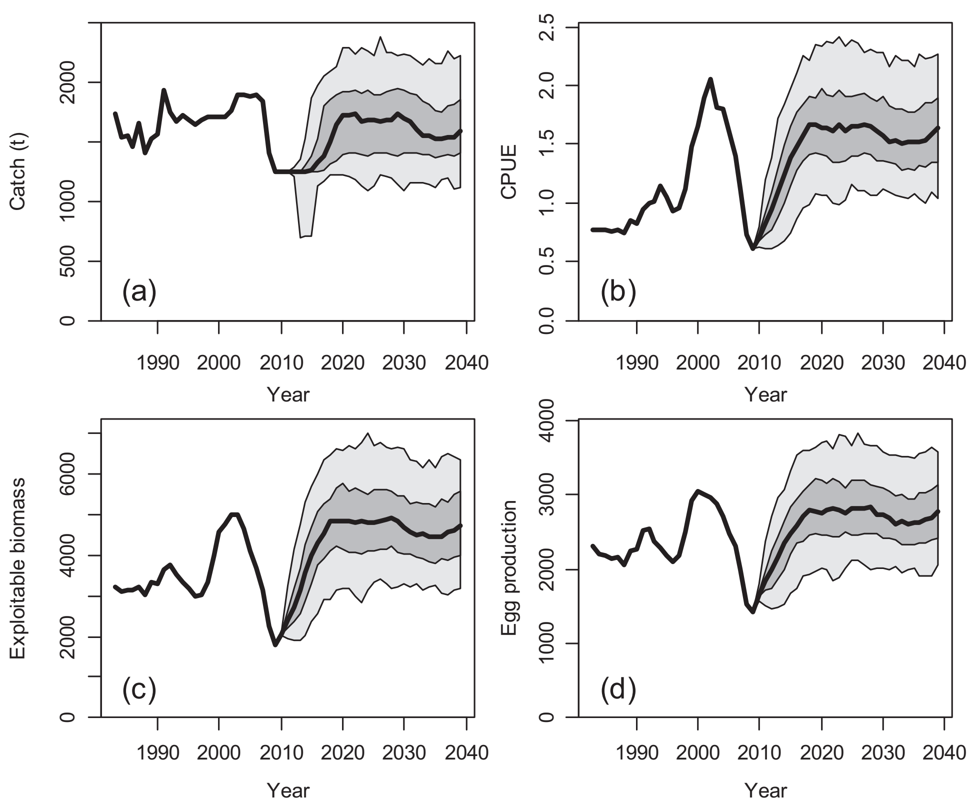

Fig. 10. Distributions (solid line: median, 50% intervals: dark shaded area, 90% intervals: light shaded area) of TACC, catch-rate, exploitable biomass and egg production. The TACCs are set using the linear DR and recruitment is drawn from 1998 to 2007.

Population size is smaller (and TACCs higher) if catchability was increasing at 1% annually. This effect is most noticeable for the long-term projections because the impact of a 1% annual increase in catchability over five years is negligible.

4. Discussion

4.1. Implications for South Australian rock lobster

The results of the simulations allow some general conclusions to be drawn regarding the overall performance of the two DRs (and potentially regarding the classes of DRs of which they are members). Specifically, both DRs lead to considerable variation in TACCs because of variation in recruitment and catchability. However, the discrete DR leads to greater inter-annual variation in catches [except if future recruitment is 150% of the baseline recruitment]. This appears to be due to this DR "tracking noise" rather than signal in the catch-rate data. In contrast, the linear DR has some built-in resilience to inter-annual fluctuations in catch-rates although even this DR can lead to occasional large changes in TACC (Fig. 5). In principle, the amount of inter-annual variation in catch could be reduced by imposing limits on the amount by which the TACC can change among years, as is common for many DRs (e.g. Johnston and Butterworth, 2005; De Oliveira and Butterworth, 2004; Smith et al., 2008).

There is clearly a trade-off between how often changes are made to the TACC and how large a change in needed when the decision rule requires a return to the target exploitation rate (i.e. few large TACC changes versus more regular, but smaller, changes to the TACC). Both decision rules tested here require fairly substantial changes in catch-rate before changes are made to the TACC. It is possible that DRs which change the TACC every year would achieve more stability (less change in an average year, i.e. a lower AAV). The TACC is adjusted each year in response to yearly changes in catch-rate in some New Zealand lobster fisheries (New Zealand Rock Lobster Industry Council, 2008).

The discrete DR is generally more conservative than the linear DR (lower probabilities of dropping below 2009/2010 levels), but performs poorer than the linear DR for the case where current abundance is half of the best estimate. A more conservative outcome for the discrete rule at higher levels of abundance reflects the inclusion of an upper cap on TACC of 1600 tonnes. The linear DR does not impose upper or lower limits on the TACC. This allows it to make better use of periods of good recruitment. However, it should have also allowed this DR to reduce catches substantially if recruitment was poorer on average into the future, but this was not evident from the performance of the linear DR, presumably because the changes in catch-rate were not sufficient to detect the changes in recruitment quickly.

Although the number of scenarios considered was not sufficient to conclude that all possible factors were considered, and the various scenarios were not weighted by the prior probabilities, the results of the analyses presented above assisted the selection of a DR for SZ rock lobster. The selected DR was the discrete rule. This selection was based on a number of factors, some based on results of the MSE and some based on other considerations. Specifically, the performances of the two DRs were fairly similar with neither "dominating" the other. However, the discrete DR was seen to be more balanced (equally likely to increase as decrease the TACC) whereas it is more difficult to increase the TACC in the linear DR. Also, the discrete DR was proposed by the fishing industry and its acceptance increased stakeholder buy-in, a factor which cannot be over-emphasized during times when catch-rate trends are similar to those for recent years in Fig. 2. Although not outlined in detail in this paper, a similar, but not identical, process of specification of candidate DRs, followed by simulation evaluation and selection was followed for the NZ rock lobster fishery.

The two DRs were designed to retain the fishery within a selected range of exploitation rates. A target level of exploitation rate was explicit (linear rule) or implicit (discrete rule). The linear rule targeted an annual overall harvest rate level of 40%, with upper and lower bounds of 30% and 50%. Examination of historical time series for the SZ lobster fishery showed stable and (compared to recent) higher levels of catch at exploitation rates around or below 50% (Fig. 4a). Recent declines, however, challenge the assumption that 50% remains a sustainable level of exploitation. The discrete rule would be expected to yield harvest rates in the high 40%.

4.2. Future work

The DRs evaluated and finally selected are 'empirical' (rather than 'model-based'), in common with the approaches for setting TACCs selected for rock lobster off South Africa and New Zealand. While model-based decision rules might have outperformed these empirical rules, particularly in terms of reducing inter-annual variation in TACCs (Butterworth and Punt, 1999) (although this was not tested for the SZ rock lobster fishery), the transparency associated with simple DRs increased stakeholder buy-in. A second 'advantage' of testing empirical DRs was that the entire process of evaluation could be conducted much more quickly (a few weeks) than would have been the case had model-based DRs been evaluated (months to years) because only minor changes had to be made to the existing stock assessment to allow projections to be made in which future catches are determined using the DRs.

The DRs examined in this paper base decisions regarding future TACCs on the catch-rate for the most recent year. The DRs consequently react quickly to changes in catch-rates. However, the DRs consequently run the risk of following noise rather than signal which could lead to unnecessary high levels of inter-annual variation in TACCs. DRs for other rock lobster fisheries (e.g. Johnston and Butterworth, 2005) are based on average catch-rates over recent years. Future work could consider the trade-off between DRs that use a single catch-rate datum and those which use average catch-rates for recent years.

The performance measures used to identify trade-offs are essentially 'biological' (population size and catches). Data on costs and prices are being collected which would allow future evaluations of candidate DRs for southern rock lobster to summarize performance in terms which relate to profits from fishing rather than simply the mass of product landed.

The scenarios ignore implementation error. Some implementation error undoubtedly occurs in this fishery. For example, dead lobsters are discarded and some high-grading occurred when catch-rates were high between 2003 and 2007. Two preliminary analyses were conducted to explore the general effects of implementation error. Assuming that the actual catch is log-normally distributed about the TACC from the DRs rather than equal to this TACC led to little impact on the performance measures except that inter-annual variation in catches increased. Assuming that the actual catch is 10% larger than the TACC leads, as expected, to higher risks for both DRs. These analyses are, however, preliminary. To effectively explore the impact of implementation error, data on high-grading and discarding need to be collated and included in the stock assessment on which the projections are based, a model developed for the probability of violating the regulations as a function of, for example, catch-rates and TACCs, and this model used in the projections.

There are several ways in which the DRs could have been improved (and the DRs will be reviewed in a few years). In particular, improved performance may have been possible had the DRs been based on average catch-rate over several years rather than that for a single year to avoid the TACC following noise in the data. This is particularly the case for the discrete DR which relies very heavily on the current catch-rate. An "exceptional circumstances" provision (De Oliveira and Butterworth, 2004) which would substantially reduce the TACC in the case of a major reduction in catch-rate could be considered, including a lower level of CPUE below which fishing would cease. Such a provision has been agreed to and incorporated in the management plan subsequent to the DR testing considered here and so this aspect of the decision rule remains untested (although the projections would seldom have resulted in the stock approaching the lower limit catch-rate).

Imposing a maximum TACC for the linear DR might lead to improved performance. Consideration could also be given to imposing a constraint on the extent to which a TACC may be permitted to change from one year to the next as noted above. The DRs have no explicit notion of a "target" catch-rate. In contrast, the DRs developed by Starr et al. (1997; see also Bentley et al., 2005; Breen et al. 2009) for rock lobsters off New Zealand and by Little et al. (2011) for species in Australia's south east and scalefish and shark fishery have a "target" catch-rate which the DR aims to move the stock to. A target catch rate had been used in the decision rules applied for the previous 5-year plan for the SZ fishery, but these proved to be sub-optimal because recruitment and thus stock production declined substantially and unexpectedly during these years, and so the target catch-rate was not reached; rather catch-rates continued to decline. One important advantage of decision rules based on a target exploitation rate is that they can apply, and sensibly determine TACCs, under a wider range of possible future recruitment levels than DRs with target catch-rates. Finally, the DRs tested here use only catch-rate as input for setting the TACC; other data are available which could be used in future DRs. Specifically, the monitoring data provide information on pre-recruits. Use of these data might lead to better performance because DRs that use pre-recruit data could take likely trends in recruitment, as well as the size of incoming cohorts, into account unlike catch-rate-only-based DRs. However, pre-recruit data can be very variable and it is not clear how much better DRs which use these data would be.

Testing of DRs by means of simulation, while still subject to concerns and issues related to implementation (e.g. Rochet and Rice, 2009; Butterworth et al., 2010) remains state-of-the-art, and the availability of the results of the analyses of this paper was an important component of how a DR was selected for the SZ rock lobster fishery. In particular, managers agreed that either DR could be implemented given the similarities in performance, which directly led to agreement on a DR.

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Appendix 1.

A method is presented for deriving the parameters used in the linear DR (Table 1). The TACC is set to a level that will restore the fishery to the target level of harvest rate. The basic assumption of this method is that there is a linear relationship between catch-rate and stock biomass. Also needed is a rule specifying when to change the TACC, that is, how far the yearly harvest rate can stray from the target level before a TACC change is mandated. The historical time series for harvest rate and biomass show the rapid rise in harvest rate from the low of $H = 0.35$ in 2002 to 0.7 in 2009 (Fig. 4a). On this basis, a target of $H = 0.4$ was sought.

The first step was to regress yearly model-estimated biomass, B_y, from the qR model (McGarvey and Matthews, 2001) on yearly reported catch-rate, CPUE_y,

$$B_y = a_B + b_B \cdot \text{CPUE}_y, \qquad \text{(A.1)}$$

using ordinary least squares. The resulting estimates for slope, b_B, and intercept, a_B, are given in Table 1. The close regression fit ($R^2 = 0.994$; Fig. 4b) was expected insofar as biomass varies in proportion to catch-rate.

From Eq. (A.1), the linear rule specifying TACC_{y+1} given CPUE_y and a target harvest rate H^T follows directly from the definition of harvest rate, namely $H = C/B$. Setting TACC_{y+1} as the catch (C) which restores the target harvest rate, using CPUE_y as the index of current biomass, yields the equation specifying the linear DR given in Section 2.2:

$$\text{TACC}_{y+1} = C_{y+1} = H^T \cdot B_y = H^T \cdot (a_B + b_B \cdot \text{CPUE}_y). \qquad \text{(A.2)}$$

This target TACC line is shown in Fig. 4c for a target harvest rate of $H = 40\%$.

Once the TACC is reset, it remains at that new level until harvest rate, determined from yearly catch-rate, deviates sufficiently far away from the target level of harvest rate. The upper and lower levels of catch-rate (CPUE^U_{y+1} and CPUE^L_{y+1}) which, if breached, trigger a TACC reset are specified by lower and upper bound levels of harvest rate, H^L and H^U. For a given TACC, as catch-rate rises, H declines, so an upper limit on harvest rate (H^U) is associated with a lower limit on catch-rate (CPUE^L_{y+1}) and *vice versa*. Solving Eq. (A.2) for the upper trigger level of catch-rate associated with a chosen lower bound for harvest rate yields $\text{CPUE}^U_{y+1} = (\text{TACC}_{y+1}/H^L - a_B)/b_B$ and similarly for CPUE^L_{y+1} as specified in Section 2.2. The upper and lower bound lines for catch-rate, given the most recent (2009) SZ fishery $\text{CPUE}_y = 0.8$ kg/potlift, are illustrated in Fig. 4c. This catch-rate would imply a TACC of 912 tonnes for 2010 under the linear DR, assuming $H^T = 0.4$. A TACC reset would occur in any future year if catch-rate rose above $\text{CPUE}^U_{y+1} = 1.12$ kg/potlift (that is, if H fell below $H^L = 0.3$) or if catch-rate fell below $\text{CPUE}^L_{y+1} = 0.605$ kg/potlift (if H exceeded $H^U = 0.5$).

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