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Management implications of including a climate-induced recruitment shift in the stock assessment for jackass morwong (*Nemadactylus macropterus*) in south-eastern Australia

Sally E. Wayte*

Wealth from Oceans Flagship, CSIRO Marine and Atmospheric Research, GPO Box 1538, Hobart, Tasmania 7001, Australia

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ABSTRACT

Fishery responses to climate change are occurring on time-scales relevant to the provision of short-term management advice. This is especially the case in climate change 'hotspots' such as south-eastern Australia, where the rate of ocean-warming is 3–4 times the global average. The application of harvest strategies utilizing biological reference points that do not take into account the effect of the changing environment on fish productivity may lead to unsustainable catch recommendations. Jackass morwong (*Nemadactylus macropterus*) is a moderately long-lived demersal species inhabiting continental shelf waters of the southern hemisphere. The most recent Stock Synthesis assessment for the species suggests that this stock has recently declined in abundance off south-eastern Australia. The stock assessment attributes the decline to mostly below average recruitment since 1985, but the recommended catch levels are based on an assumption of average recruitment from a stationary stock–recruitment relationship. The ability of Stock Synthesis to include an environmental variable to adjust the stock–recruitment relationship is used to model a regime shift on the average level of recruitment. Management strategy evaluation (MSE) is then used to examine the consequences of using the wrong recruitment assumption in the assessment used in the harvest strategy for setting the catches. The MSE shows that the consequences of mis-specifying the assessment model are greater if the assessment continues to assume that no shift in recruitment has occurred. Thus the more precautionary approach for management wishing to meet all the aims of the Australian government Harvest Strategy Policy is to assume that a shift in recruitment has occurred. A possible mechanism for how observed oceanic changes could be impacting jackass morwong recruitment is presented.

1. Introduction

Recruitment of marine fishes is a naturally highly variable, complex process, which can be influenced by both environmental variation and human intervention. If the effect of environmental variability on recruitment is taken into account in stock assessments it is likely that scientific advice provided to management agencies will be improved. In particular, estimation of biomass reference points used in the implementation of harvest control rules typically assumes a stationary stock–recruitment relationship. If, however, average productivity over time has been influenced by changing environmental conditions, then catch targets may not be sustainable if they are based on average future recruitment under conditions that no longer exist (Haltuch et al., 2009).

Two alternative approaches for accounting for the influence of environmental variability on recruitment are commonly used in stock assessments: development of a short-term predictive model of year-to-year variability in recruitment using a known environmental factor; or the incorporation of the effect of longer-term climate variability on recruitment via a 'regime shift' approach, where a multi-year shift in climate/ocean conditions is linked to a shift in the productivity of fish stocks (Beamish et al., 1999). Recent examples of these two approaches are demonstrated by Schirripa et al. (2009), who evaluated different methods of including the influence of sea surface height data on recruitment of US west coast sablefish (*Anoplopoma fimbria*) directly into stock assessment models, and A'mar et al. (2009), who examined the impact of regime shifts in the North Pacific Ocean on the performance of management strategies for walleye pollock (*Theragra chalcogramma*). Most evidence for the impact of climate variability on ecosystems is from the northern hemisphere (e.g., Hollowed et al., 2001; Mantua and Hare, 2002; Mueter et al., 2007), and conclusions from these studies are not readily applicable to Australia (Poloczanska et al., 2007).

* Tel.: +61 3 6232 5464; fax: +61 3 6232 5000.
E-mail address: sally.wayte@csiro.au

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However, recent studies have begun to examine climate impacts on Australian marine species (Caputi et al., 2010; Booth et al., 2011; Johnson et al., 2011; Last et al., 2011).

Jackass morwong (*Nemadactylus macropterus*) is a moderately long-lived (up to 30 years) demersal fish species that occurs in the coastal and continental shelf waters of southern Australia, New Zealand, South America and South Africa, in depths of down to 450 m (Smith, 1994). The species has been landed in south-eastern Australia since the inception of the steam trawl fishery off New South Wales in the early twentieth century (Klaer, 2001). Jackass morwong standardized catch rates in south-eastern Australia have declined recently, despite lower catches than in the past (Fig. 1). This decline is attributed by the most recent stock assessment to mostly below average recruitment since 1985, and detailed examination of the data inputs and assessment has confirmed that this pattern does not appear to be an artifact of the fit to the data (Wayte, 2012). The stock assessment model estimates recruitment deviations up to four years prior to the last year of fishery data, as the recruitment signal from young fish is not present in the data until they appear in the catch in sufficient numbers. Thus, projections of the recruitment from this time onwards are based on the predicted value from the stock recruitment relationship. Use of the current model may lead to an over-optimistic assessment of current stock status, given that recruitment for the most recent 20 years appears to have been below average. This is a concern for the management of the stock, as the determination of the following year's Total Allowable Catch (TAC) depends on an estimate of current stock status, as well as estimation of appropriate biomass reference points.

Attempts to improve the estimates of current stock status and the management reference points for jackass morwong began by the development of a short-term predictive model for recruitment based on the strength of the westerly wind, but this relationship has broken down in recent years. It is postulated that the breakdown of this relationship is due to changes in large-scale oceanographic conditions off south-eastern Australia that have resulted in other environmental drivers becoming more important in determining recruitment levels, and have led to a shift in the jackass morwong population to lower average recruitment levels. A stock assessment implemented in Stock Synthesis (Methot and Wetzel, 2013), incorporating a shift to lower recruitment, is contrasted with the original assessment based on pre-fishery recruitment levels. Management strategy evaluation (MSE) is used to explore the implications of making management decisions under the wrong recruitment assumption, and shows that the most precautionary approach to management of the stock is to assume that a recruitment shift has occurred.

2. Background

Jackass morwong is one of 34 quota species or stocks in Australia's Southern and Eastern Scalefish and Shark Fishery (SESSF; Smith et al., 2008). The species is managed using a harvest strategy which comprises a data collection strategy, a fully integrated quantitative stock assessment, and a harvest control rule (Fig. 2). The aims of the harvest strategy as specified in the Australian government Commonwealth Harvest Strategy Policy introduced in 2007 are to: maintain fish stocks, on average, at a target biomass point equal to the spawning biomass (SB) required to produce maximum economic yield (B_{MEY}); ensure fish stocks remain above a limit biomass where the risk to the stock is regarded as too high; and, ensure that the stock stays above the limit biomass level at least 90% of the time (DAFF, 2007). The limit biomass level is set as half of the SB required to produce maximum sustainable yield (B_{MSY}). The use of proxies of B_{40} (40% of unfished equilibrium SB)

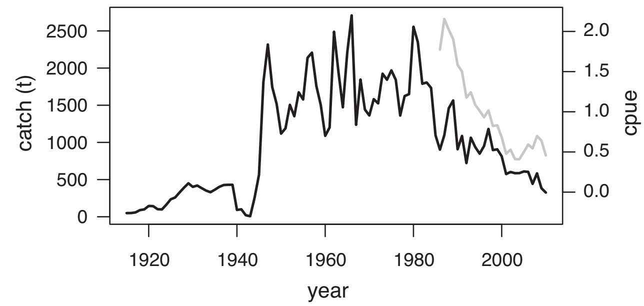

Fig. 1. Catch history of jackass morwong 1915–2010 (black), and standardized cpue index for the main fleet 1986–2010 (gray).

for B_{MSY}, and $1.2B_{MSY}$ for B_{MEY} result in a limit SB reference point of B_{20}, and a target SB reference point of B_{48}. Stock status in any particular year y is defined as the ratio of that year's SB (B_y) compared to the unfished equilibrium SB (B_0). The harvest control rule calculates the exploitation rate as a function of the current stock status, and a Recommended Biological Catch (RBC) is calculated by applying this exploitation rate to the estimate of exploitable biomass at the start of the quota year for which the RBC is required.

Prior to considering environmental drivers for the recruitment decline, the possibility that jackass morwong recruitment has declined as a result of the decline in stock abundance was examined. This would suggest either that depensation is occurring or that the steepness of the stock–recruitment relationship is lower than that used in the assessment. Depensation is considered to be unlikely, as the stock is not at critically low levels from a reproductive point of view. A value for steepness of 0.7 is used in the assessment, based on a simulation study by Francis (1993) which suggested that a reasonable default value for steepness should be between 0.5 and 0.95; and a meta-analysis of 700 spawner-recruitment series in which the mean value for steepness for members of the order Perciformes (perch-like fishes), to which jackass morwong belong, is 0.73 with a 95% confidence interval of 0.11 (Myers et al., 1999). A likelihood profile analysis on steepness performed for a previous jackass morwong assessment showed that a steepness of 0.33 produced the best overall fit of the model to the data (Wayte, 2010). As this was considered unrealistically low for a broadcast spawning species such as morwong, the assessment was run using an alternative steepness value of 0.5, but this assessment continued to estimate recent recruitments consistently below

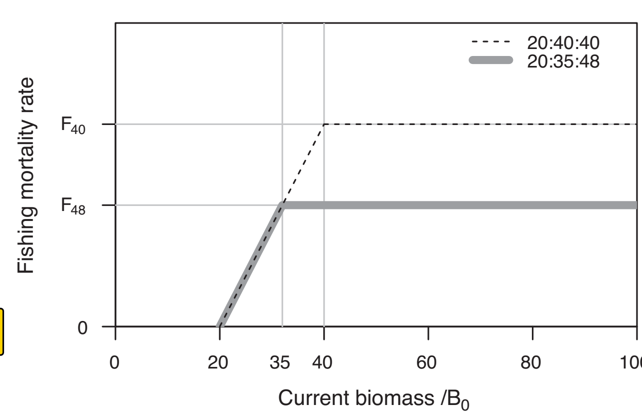

Fig. 2. The harvest control rule. F_X is the fishing mortality that on average leads to the spawning stock equilibrating at B_X (X% of equilibrium SB). The current form of the rule applied in the SESSF is the 20:35:48 (limit:breakpoint:target) rule as shown by the dark line, which follows the trajectory of the 20:40:40 rule until fishing mortality reaches F_{48} (calculated as B_{35} for most SESSF stocks), whereupon fishing mortality is set to F_{48}.

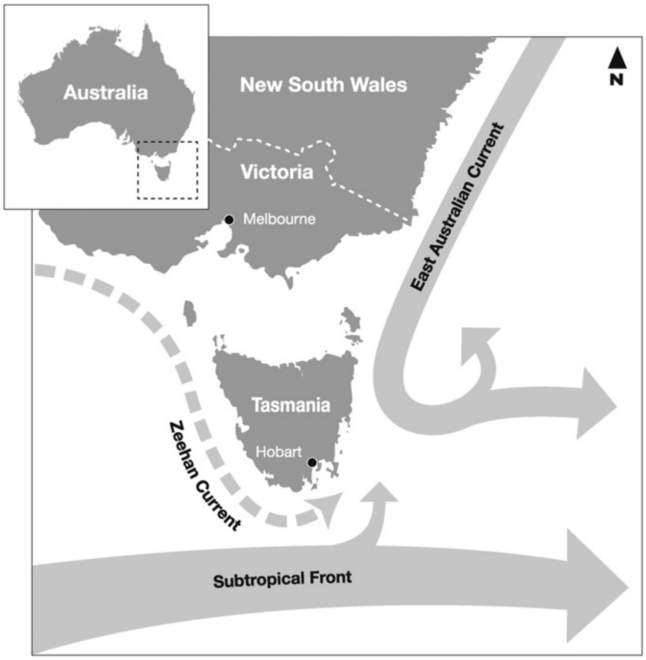

Fig. 3. Schematic representation of major surface current systems off south-eastern Australia. The location of these water masses is seasonally and interannually variable. Bruce et al. (2001) suggest that morwong larvae originating from NSW and Victoria are advected southwards by the EAC, and morwong larvae from Tasmania are advected northwards by subantarctic waters extending up the east coast of Tasmania.

average, so it was concluded that lower steepness could not account for the recruitment decline (Wayte, 2010).

The unusual early life-history of jackass morwong makes it likely that recruitment is environmentally driven. Jordan (2001) suggests that variations in year-class strength for jackass morwong are primarily driven by post-larval supply. The species is atypical among temperate finfish species in that they have an extended offshore pelagic post-larval stage, spending 9–12 months in the offshore surface waters of south-eastern Australia (Vooren, 1972; Bruce et al., 2001), before settling into deeper sub-tidal habitats at a size of 70–90 mm (Jordan, 2001). Thus it is likely that environmental factors to which morwong are exposed during this extended offshore pelagic phase have a substantial influence on post-larval survival. The strength of the westerly wind was considered as a possible predictor of recruitment, as previous authors have suggested a link between wind strength and recruitment of other species in south-eastern Australia (Harris et al., 1988; Thresher, 1994; Jenkins, 2005). A westerly wind index was found to be highly correlated ($r = 0.84$) with model-estimated morwong recruitment deviations over a 22-year period from 1968 to 1989, but in recent years this relationship has deteriorated ($r = 0.03$ for 1990–2006; Fig. 4b; Wayte, 2012). It is postulated that the breakdown of this relationship is due to observed changes in large-scale oceanographic conditions off south-eastern Australia.

In the oceans off south-eastern Australia inhabited by the jackass morwong post-larvae the dominant oceanographic features are the southward-flowing East Australian Current (EAC), and the eastward-flowing Subtropical Front – the frontal zone between subtropical and subantarctic water masses (Ridgway, 2007a; Fig. 3). The rate of ocean-warming in this area is 3–4 times the global average, making this area a global climate change 'hotspot'. The warming is a result of a poleward shift of the southern hemisphere subtropical ocean circulation and a southward extension of the EAC over the past 60 years, due to a southward shift of the circumpolar westerly winds (Ridgway, 2007b). Climate model simulations show consensus that the EAC will continue this increased southward flow over the next 100 years (Hobday and Lough, 2011). The observed southward shift of the ocean current system off south-eastern Australia may have reduced the suitability of the offshore environment to jackass morwong post-larval survival. If this is the case, then the prospect of continued and further southerly extension of the EAC system may mean that the lower recruitment regime will continue.

3. Materials and methods

3.1. Stock assessment

A stock assessment for jackass morwong was conducted in 2011 using a statistical age- and length-structured model implemented in the software package Stock Synthesis (version 3.21d; Methot, 2011), and data up to the end of 2010 (Wayte, 2012). The population dynamics model and the statistical approach used in the fitting of the model to the various types of data are specified in Methot and Wetzel (2013).

The assessment model assumes an unexploited biomass and equilibrium age structure at the start of 1915 when the fishery commenced. It models the impact on the jackass morwong population of six fishing fleets: three early fleets using different fishing methods, and three recent (from 1986) fleets corresponding to different areas or fishing methods. Standardized catch rates are available for four of these fleets, and also for a period that overlaps two of the early fleets. Separate logistic functions are used for the length selectivity ogives for each fleet. The two parameters of the selectivity function for each fleet are estimated within the assessment. Retention is modeled as a logistic function of length, and estimated for the recent fleets where discard information is available. The rate of natural mortality, M, is set to $0.15\,\mathrm{yr}^{-1}$ and is assumed to be age- and time-invariant. The parameters of the Von Bertalanffy growth function are estimated within the model-fitting procedure from age-at-length data, with an assumption of no differences in growth by gender. A plus-group is modeled at age 25, and maturity is modeled as a logistic function with 50% maturity at 24.5 cm. The estimated parameters of the model are: average recruitment at unfished equilibrium SB (calculated at the start of the fishery in 1915, and, for the recruitment shift assessment, also at the start of the lower recruitment regime in 1988), recruitment deviations from 1945 to 2006, growth curve parameters, and selectivity and retention parameters.

The data used in the assessment comprise: landed catches from 1915 to 2010, standardized catch per unit effort (cpue), retained and discarded length-composition, discard rates, age-at-length data and an aging error matrix. Each data source (except for catch) is available for only some fleets and years.

3.1.1. Recruitment estimation

Annual recruitment (age 0 in the model) is assumed to follow a Beverton–Holt type stock–recruitment relationship, parameterized by the average recruitment at unfished equilibrium SB, R_0 (a measure of the carrying capacity of the population); and the steepness parameter, h:

$$\hat{R}_y = \frac{4hR_0B_y}{B_0(1-h)+B_y(5h-1)}e^{\varepsilon_y-0.5\sigma_R^2} \tag{1}$$

where B_y is the SB at the start of year y, B_0 is the unfished equilibrium SB corresponding to R_0, ε_y is the recruitment deviation in year y, and σ_R^2 is the variance of the recruitment in log-space. σ_R is set to 0.6, based on the model-estimated recruitment variability. Steepness is set to 0.7.

Recruitment deviations are estimated for 1945–2006. Recruitment deviations are not estimated prior to 1945 as there are insufficient length and age-composition data prior to this date to inform them, or after 2006 as fish spawned after this time are not represented in the data. The annual recruitment deviations are modified by the lognormal bias correction factor, $-0.5\sigma_R^2$, to ensure that the time series of estimated recruitments is mean unbiased, rather than median unbiased (Maunder and Deriso, 2003). The degree of bias adjustment depends on the degree of recruitment signal that can be estimated (Methot and Taylor, 2011). The Stock Synthesis software allows the user to control the rate at which the bias adjustment is ramped in during data-poor years, and then ramped back to zero for the forecast years. In this case the recruitment bias adjustment is phased in from 1945, with full bias adjustment not being applied until 1990, two years before the first age sample is available, and bias adjustment is ramped back to zero from 2005 to 2007.

3.1.2. Modeling the recruitment shift in the stock assessment

The period of reduced recruitment is determined by a method based on a sequential *t*-test analysis for detection of regime shift (Rodionov and Overland, 2005). This method is applied to the time series of estimated log recruitment deviations from the original assessment, and detects a recruitment shift in 1988.

Stock Synthesis allows the parameters of the stock assessment model to become time-varying by making them a function of an environmental data series. For jackass morwong the environmental changes are considered to have affected the average recruitment at unfished equilibrium SB, R_0. The recruitment shift is modeled in the stock assessment by estimating two R_0 values: one at the start of the fishery in 1915 (${R_0}^{1915}$), and the other at the start of the lower recruitment regime in 1988 (${R_0}^{1988}$). Thus in this case the environmental variable is simply a series of zeroes and ones corresponding to the two regime periods. The stock assessment is run with and without the recruitment shift (henceforth referred to as the 'recruitment shift' and 'no shift' assessments, respectively).

For the 'no shift' assessment, stock status is calculated by comparing estimated SB for each year to estimated unfished equilibrium SB in 1915 (${B_0}^{1915}$), whereas for the 'recruitment shift' assessment, SB after 1988 is compared with unfished equilibrium SB for the regime starting in 1988 (${B_0}^{1988}$; i.e. the hypothetical unfished equilibrium SB based on the estimated 1988 stock–recruitment relationship using ${R_0}^{1988}$).

3.1.3. Stock assessment outcomes

The assessment results are summarized by the following quantities:

1. 2012 stock status: the 2012 SB expressed as a percentage of the unfished equilibrium SB corresponding to the appropriate recruitment regime (i.e. $B_{2012}/{B_0}^{1915}$ or $B_{2012}/{B_0}^{1988}$);
2. 2012 RBC: the Recommended Biological Catch for 2012 calculated by the harvest control rule;
3. long-term RBC: the constant catch that can be taken when the stock has stabilized at the target SB reference point (B_{48});
4. $-\ln L$: the negative of the logarithm of the likelihood function;
5. the contribution to the negative-log-likelihood from each source of data fitted in the assessment; and
6. AIC: the Akaike Information Criterion, which is a goodness-of-fit statistic that takes into account the number of parameters in the model.

3.2. Management strategy evaluation

Management strategy evaluation (MSE) is used to examine the effects of model mis-specification in the stock assessment on the stock status and recommended catches of jackass morwong. MSE is a technique that uses Monte Carlo simulation methods to evaluate the entire management system of a fishery (e.g. Smith et al., 1999; Punt et al., 2001; Wayte and Klaer, 2010).

Table 1
Description of the scenarios in the MSE. For the operating model 'no shift' means annual recruitments for all years are calculated using Eq. (1) with ${R_0}^{1915}$, and 'recruitment shift' means recruitments after 1988 are calculated from Eq. (1) with ${R_0}^{1988}$. The R_0 values are taken from the 2009 morwong stock assessment, with and without the recruitment shift. For the assessment model, 'no shift' means that the SS assessment run within the MSE estimates ${R_0}^{1915}$ only, and 'recruitment shift' means it estimates ${R_0}^{1915}$ and ${R_0}^{1988}$.

Scenario	Operating model	Assessment model
a	No shift	No shift
b	No shift	Recruitment shift
c	Recruitment shift	Recruitment shift
d	Recruitment shift	No shift

The MSE comprises a formally coded mathematical model of the population dynamics of the fishery (the 'operating model'), a data generation module, and an assessment component that implements the harvest strategy. The operating model representing the 'true' fish stock is an age-structured multi-fleet population dynamics model, described in detail in Fay et al. (2011). The specifications for the current stock status and population dynamics used to parameterize the operating model are based on the 2009 quantitative stock assessment of jackass morwong (Wayte, 2010), with and without the recruitment shift. Thus the operating models are consistent with the available historical and biological information for this stock. The fishery population model is projected into the future, and simulated cpue, length- and age-composition data are generated from the known 'true' population each year (both historical and future) to represent what would be collected from the fishery. The generated sample sizes were 1000 for retained length-composition data, and 500 for discarded length-composition and age-composition data. These 'data' are then used in a Stock Synthesis assessment which calculates stock status as estimated current SB relative to estimated unfished equilibrium SB. The unfished equilibrium SB used is either in 1915 if the assessment assumes the recruitment shift has not occurred, or in 1988 if the assessment assumes the recruitment shift has occurred. Estimated current stock status is used in the harvest control rule (Fig. 2) to calculate the next year's Recommended Biological Catch (RBC). The Total Allowable Catch (TAC) is calculated from the RBC by taking into account discards, and applying management constraints whereby the TAC cannot change by more than 50% from year-to-year, and the TAC remains the same if the change from one year to the next is less than 10%. The resulting TAC is then applied to the 'true' population structure within the operating model.

The MSE is run for four scenarios – all four combinations of the 'true' model and the assessment model – in order to examine the implications of assessing the stock under the wrong recruitment assumption (Table 1). For each simulation the fishery population model is projected 30 years into the future, and 100 simulations are run for each scenario. The differences between the simulations are observation error in the generated data and process error in the operating model population dynamics (future recruitment deviations).

4. Results

4.1. Stock assessment with and without the recruitment shift

The 'recruitment shift' assessment gives a more optimistic estimate of current stock status than the 'no shift' assessment, as current biomass is compared to a lower unfished equilibrium biomass; thus the 2012 RBC is higher for the 'recruitment shift'

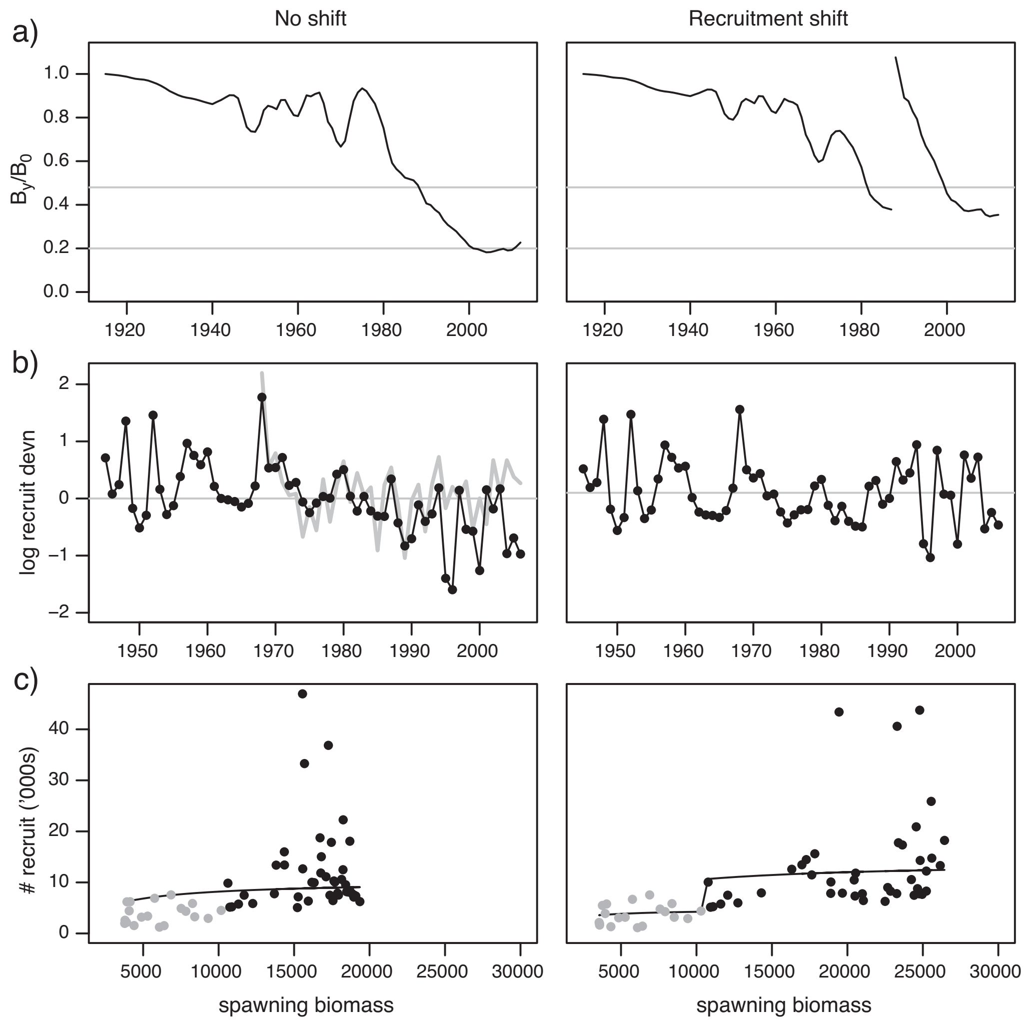

Fig. 4. Results of the stock assessments using the 'no shift' and 'recruitment shift' assumptions. (a) Stock status (B_y/B_0) over time. The gray lines show the target and limit stock status levels. (b) The time trajectory of estimated log recruitment deviations. The thick gray line in the left-hand plot is the standardized westerly wind index. (c) The stock–recruitment relationship (black line) and estimated recruitments (points). The gray points are estimated recruitments from 1988 to 2006.

assessment, but the estimated long-term catch is greatly reduced (Fig. 4a, Table 2).

The recruitment deviations under the 'recruitment shift' assessment no longer show serial correlation in recent years (Fig. 4b). The average recruitment deviation after the recruitment shift year is −0.55 for the 'no shift' assessment, and −0.03 for the 'recruitment shift' assessment. The 'recruitment shift' assessment provides a much better fit of recruitment to the stock–recruitment curve, as the model now has two stock–recruitment relationships (Fig. 4c). In terms of the AIC and negative-log-likelihood the 'recruitment shift' assessment is a better fit to the data (Table 2), with most of the improvement in fit coming from the recruitment component. The relative fit to the length frequency data declines slightly, but the fits to the age data and the cpue improve slightly, although these changes are barely discernible by eye.

4.2. *Management strategy evaluation*

The MSE results are summarized by operating model ('true') stock status and TAC for all four scenarios (Fig. 5). To calculate stock status in the operating model recruitment shift scenarios, 'true' SB in each year is compared to 'true' hypothetical unfished equilibrium SB based on the 1988 stock–recruitment relationship assumptions ('true' $B_0{}^{1988}$) rather than the 'true' unfished equilibrium SB in 1915 ('true' $B_0{}^{1915}$). The results are displayed for each version of the operating model ('reality') in order of whether the assessment model is mis-specified or not, so as to make clear the trade-offs and risks associated with the decision of which recruitment assumption to use in the assessment.

If a recruitment shift has not occurred in 'reality' (Fig. 5, left-hand plots), and the assessment is consistent with this (scenario a), then the initial estimated stock status is low, so the TAC drops

Table 2
Results of the stock assessments for both recruitment assumptions. Lower values of AIC and $-\ln L$ mean a better fit.

Assessment	2012 stock status (%)	2012 RBC (t)	Long-term RBC (t)	AIC	Total $-\ln L$	Negative log-likelihood components			
						cpue	Lengths	Ages	Recruitment
No shift	23	92	1053	8947	4388.5	−100	1459.6	2676.3	12.41
Recruitment shift	35	358	488	8913	4370.7	−105	1463.5	2672.6	1.88

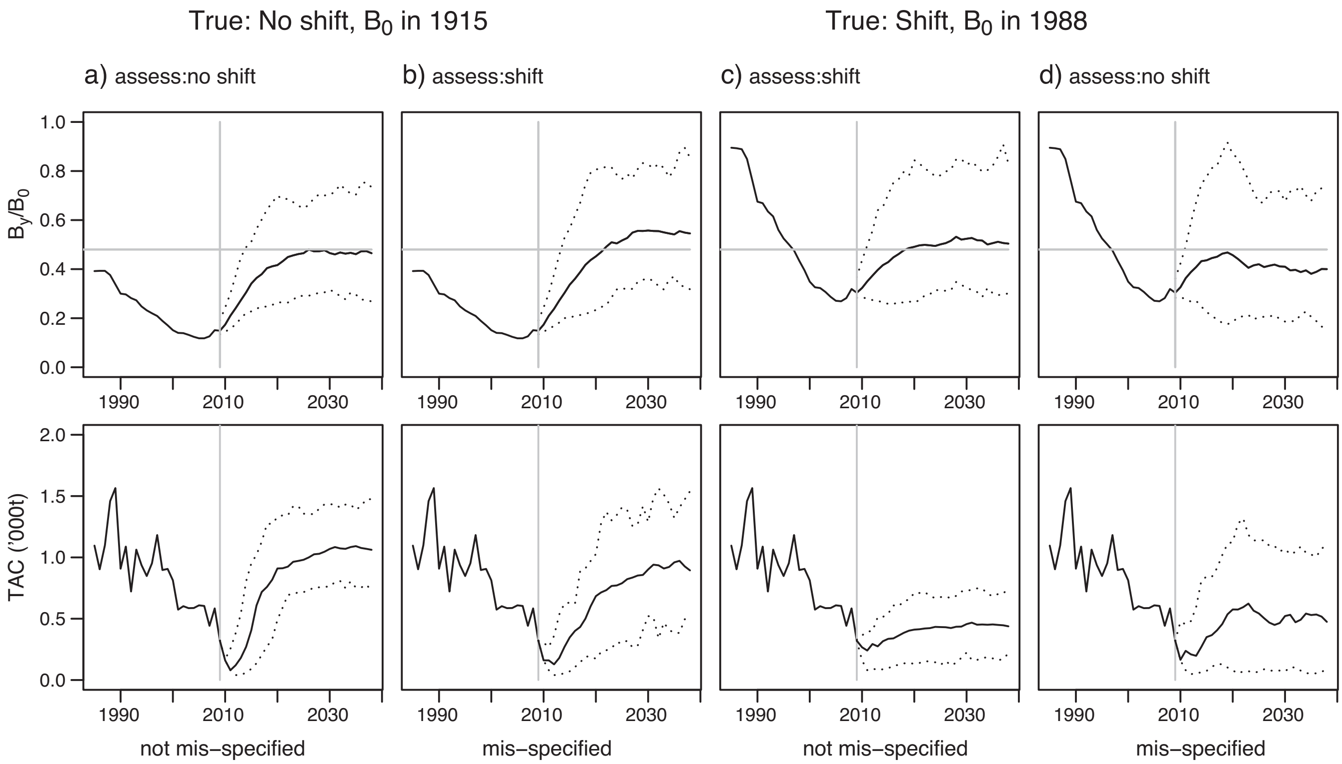

Fig. 5. Time-trajectories (median, and 2.5 and 97.5 percentiles over 100 simulations) of 'true' stock status (B_y/B_0) and TAC for the four MSE scenarios (see Table 1 for scenario description). Only the final 23 years of the historic period are shown. The horizontal gray line shows the target stock status, and the vertical gray line indicates the start of the projection period.

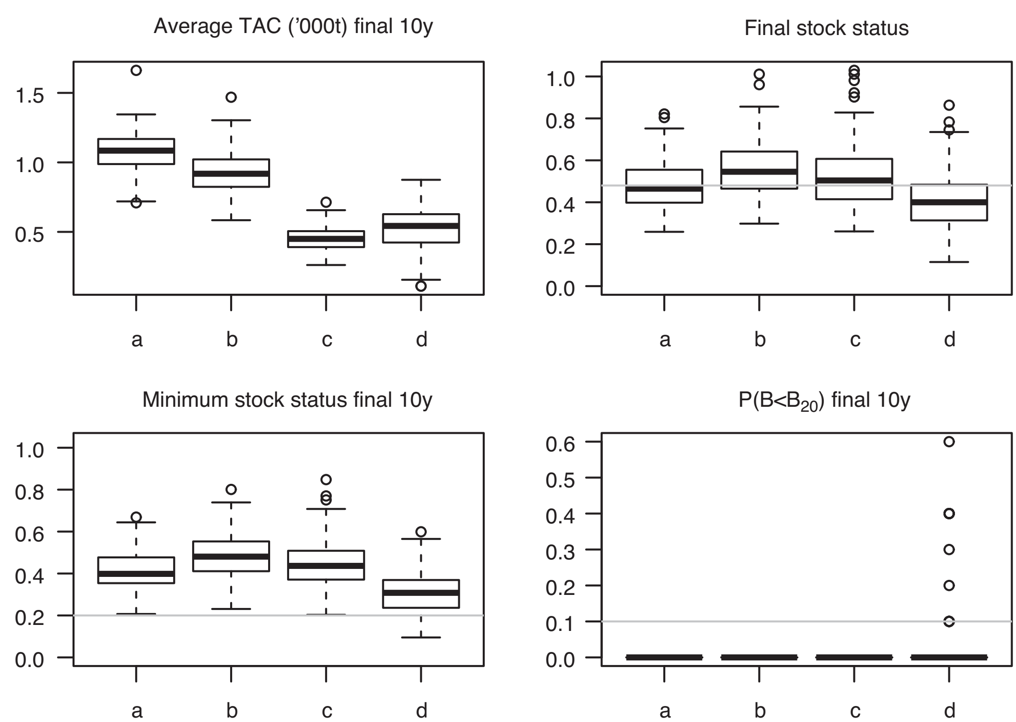

Fig. 6. Box plots of performance statistics for the four MSE scenarios (see Table 1 for scenario description). The top left plot shows the average TAC in the final 10 years of the projection period. The top right plot shows the 'true' stock status in the final year of the projection. The gray horizontal line is the target stock status. The bottom left plot shows the minimum 'true' stock status in the final 10 years of the projection period. The gray horizontal line is the limit stock status. The bottom right plot shows the probability of 'true' stock status being below 20% in the final 10 years of the projection. [For each scenario, the dark horizontal line shows the median value. The bottom and top of the box show the 25th and 75th percentiles, respectively. The vertical dashed lines show either the maximum or minimum values, or, if there are outliers in the data, they correspond to approximately two standard deviations. Outliers are plotted individually.]

initially, and the stock recovers to the target after about 20 years. However, if the assessment is mis-specified and assumes a shift has occurred (scenario b), the TAC does not drop as much initially (because the assessment sees the stock as less depleted), but the median long-term TAC is slightly lower than in scenario a, so the 'true' biomass stabilizes above the target at a median level of about 55% of 'true' $B_0{}^{1915}$ after about 15 years. Alternatively, if a recruitment shift *has* occurred in 'reality' (Fig. 5, right-hand plots), and the assessment is consistent with this (scenario c), the 'true' stock recovers to the target after about 10 years. If the assessment is mis-specified and assumes the shift has not occurred (scenario d), the TAC is low initially and the 'true' stock approaches the target, but subsequent TACs are higher than they should be if the recruitment shift has happened in 'reality', so the stock does not recover to the target, but stabilizes at about 40% of 'true' $B_0{}^{1988}$ after about 15 years, with catches slightly higher on average, although much more variable, than for the scenario where the model is not mis-specified (scenario c).

For all scenarios the median minimum 'true' stock status in the final 10 years of the projection (after the stock has stabilized) is above the 20% limit, and the median probability of the 'true' SB falling below the limit reference point is lower than 10% (Fig. 6). When the assessment model is mis-specified the 'true' biomass stabilizes either above (scenario b) or below (scenario d) the target biomass level (Fig. 6).

5. Discussion

The MSE results show that both the scenarios where the assessment model is mis-specified (scenarios b and d) meet the risk criteria of the Commonwealth Harvest Strategy Policy, but do not meet the target biomass criterion. Examination of the MSE results allows an explicit consideration of the trade-offs and risks of adopting the recruitment shift model in the assessment. The assessment results alone may initially seem counter-intuitive, given that the 'recruitment shift' assessment assumes that recruitment has shifted to a lower level, but estimates a larger 2012 RBC than the 'no shift' assessment. On the other hand, the long-term RBC for the 'recruitment shift' assessment is about half that for the 'no shift' assessment (488 t vs. 1053 t; Table 2); so managers may fear that catches in the future may be reduced unnecessarily if the recruitment shift hypothesis is accepted, and then recruitments return to former levels. The MSE shows that if in 'reality' there has been no shift, and the assessment assumes there has been a shift, there is no increased risk to the stock, and only a small loss of future catch, as compared to correctly assessing without the shift (compare scenarios b and a; Fig. 6). This is because the harvest control rule allows catches to be greater than the long-term TAC if the stock is assessed to be above the target level. Conversely, if the recruitment shift has occurred in 'reality', and the assessment assumes the shift has not occurred, the stock does not reach the target, and there is some chance it may fall below the limit, even though the median catch is only slightly greater than if the assessment made the correct assumption (compare scenarios d and c; Fig. 6). Thus the MSE shows that the consequences of mis-specifying the assessment model are greater if the assessment continues to assume that no recruitment shift has occurred, and the more precautionary approach for management wishing to meet all aims of the Harvest Strategy Policy is to assume that the recruitment shift has occurred.

Conclusive proof of a link between the observed oceanographic changes and jackass morwong recruitment would be very difficult to obtain, especially as the drivers of post-larval survival of morwong are undoubtedly complex. Nevertheless, for the recruitment shift hypothesis to be accepted by managers, it is still necessary to provide a plausible mechanism based on the observed oceanographic changes and knowledge of fish larval requirements. The 'ocean triad' of processes that combine to provide favorable reproductive habitat for many types of fish is described by Bakun (1998): enrichment processes (e.g. upwelling and mixing) which lead to nutrient availability; concentration processes (e.g. ocean fronts, water column stability) so that a dense concentration of food particles is available, and larvae are concentrated in the same area as their food supply; and retention processes, so that larvae are not lost from the area. All three of these processes are likely to have become weaker in the area of ocean in which the south-eastern Australian jackass morwong post-larvae spend 9–12 months. Firstly, nutrient availability will be lower because the East Australian Current (EAC; Fig. 3) is nutrient-poor in comparison to subantarctic water masses (Harris et al., 1987), and the southward shift of westerly winds will result in less incursion of nutrient-rich subantarctic water and less mixing of the water column (Harris et al., 1988). Thompson et al. (2009) report a long-term decrease in dissolved silicate concentrations in south-east coastal waters, primarily driven by the poleward transport of warm, low-silicate EAC water. They anticipate that this reduction in silicate concentrations will lead to a reduction in primary productivity in the area. Secondly, concentration processes in the area may have declined as the boundary between the EAC and the Subtropical Front (Fig. 3) has moved south (Ridgway, 2007b). Thirdly, larval retention rates have been shown to decline with increasing strength of the EAC (Condie et al., 2011).

The regime shifts studied in the northern hemisphere typically affect the abundance of multiple species (e.g. Polovina, 2005; Beamish et al., 1999), and there is increasing evidence that the shifts in large-scale oceanography in south-eastern Australia have led to changes in the marine system in this region. Last et al. (2011) and Johnson et al. (2011) have presented evidence to show that the increased southward incursion of the EAC has led to ecological changes observed across a range of marine taxa in eastern Tasmania in recent decades. Southern rock lobster (*Jasus edwardsii*), which also have a lengthy pelagic post-larval stage (up to 2 years), have also shown a consistent decline in recruitment in south-eastern Australia in recent years (Linnane et al., 2010). The same recruitment decline is not seen in other demersal quota species in south-eastern Australia; however the larvae of these species do not have the same extended offshore early life history as jackass morwong, and settle at a considerably smaller size (all less than 25 mm compared to 70–90 mm for jackass morwong (Neira et al., 1998)). These factors presumably make them less susceptible to the changes in offshore oceanographic conditions.

The choice of 1988 as the start of the lower recruitment regime, although chosen objectively by the Rodionov and Overland (2005) sequential regime shift detection method, is somewhat arbitrary. It is more likely that the oceanographic changes would have caused a gradual decline in jackass morwong recruitment levels. The year 1988 is, however, broadly consistent with the timing of the breakdown of the recruitment deviation correlation with the westerly wind index, and as well as this, a time-series of temperature data measured at a location off south-eastern Tasmania shows a clear increase from this year (Johnson et al., 2011). Another approach could be to choose the start date of the new regime based on model fits to the data, thus allowing the data to inform the choice of model structure. Polovina (2005) showed that a regime-specific harvest rate performs well when applied with a delay of several years, thus it is not necessary for managers to identify the exact time of the regime shift. Alternatively, a date for the recruitment shift would not be necessary if, instead, an acceptably robust environmental driver for recruitment could be found and used as if it was a survey of annual recruitment deviations (e.g. Schirripa et al., 2009). This method is simple to implement in Stock Synthesis, and could have been used for jackass morwong if the westerly wind correlation had stood the test of time. One of the approaches examined by A'mar et al. (2009) would also obviate the need for choosing a precise year for the recruitment shift. They estimated biological reference points based on an average of recruitment during the 25 years prior to the year for which the recommended catch was required.

The evidence for alteration of the ocean circulation off south-eastern Australia is clear (Cai et al., 2005), irrespective of whether this alteration is a result of anthropogenic climate change or natural multi-decadal environmental variability. The alteration, nonetheless, is consistent with climate models which also predict that these changes will continue into the future (Hobday and Lough, 2011). Plagányi et al. (2011) present examples to show that fishery responses to climate change can affect resources on time-scales relevant to the provision of short-term, tactical management advice. Due to the difficulties of including ecosystem effects into fisheries stock assessment models, they suggest that a pragmatic solution can be the use of approaches such as that implemented here for jackass morwong, where the impact of climate change is modeled as a recruitment shift for a single species and evaluated using MSE.

The flexibility of the Stock Synthesis stock assessment software has greatly facilitated the testing of the alternative model assumptions, by providing multiple options to easily explore different ways of including environmental information into a stock assessment. Use of a general model such as this facilitates such exploration, as the assessment author can concentrate on questioning and testing model assumptions, rather than the time-consuming (and possibly error-prone) task of developing their own code. Use of a general software package also means it is easier for stock assessment practitioners to keep up with best practice in the use of stock assessment models, as the SS developers are active researchers in the field, and the software is under continual improvement and review (Methot and Wetzel, 2013).

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