Canadian Journal of Fisheries and Aquatic Sciences
Journal canadien des sciences halieutiques et aquatiques

The effect of marine closures on a feedback control management strategy used in a spatially-aggregated stock assessment: A case study based on pink ling in Australia

Journal:	<i>Canadian Journal of Fisheries and Aquatic Sciences</i>
Manuscript ID	cjfas-2016-0017.R1
Manuscript Type:	Article
Date Submitted by the Author:	18-Apr-2016
Complete List of Authors:	Punt, André; University of Washington, School of Aquatic and Fishery Sciences Haddon, Malcolm; CSIRO, Little, Richard; CSIRO Marine and Atmospheric Research, Tuck, Geoff; CSIRO Marine and Atmospheric Research
Keyword:	age-structured stock assessment methods, closed areas, harvest control rules, simulation, spatial structure

SCHOLARONE™
Manuscripts

1 **The effect of marine closures on a feedback control management strategy used in a**
2 **spatially-aggregated stock assessment: A case study based on pink ling in Australia**

3

4 André E. Punt^{1,2}, Malcolm Haddon², L. Richard Little², Geoffrey N. Tuck²

5

6 ¹*School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195-5020, USA*

7 ²*CSIRO Oceans and Atmosphere, Castray Esplanade, Hobart, Tasmania, Australia;*

8 **Abstract**

9 Simulation is used to explore the effect of spatial heterogeneity, and spatial closures, on the
10 ability of feedback-control management strategies to achieve goals relating to conservation
11 and utilization of fishery resources. The operating model underlying the projections is based
12 on pink ling, *Genypterus blacodes*, off southern Australia and assumes that animals are
13 sedentary following settlement. The management strategies are able to move the resource
14 towards the target level in the absence of spatial closures even though assessment results are
15 biased. The probability of reducing the stock below its limit reference point is higher when
16 growth rates vary spatially, but the effect is small. The probability of the stock being above
17 its target reference point is lower when one of the smaller spatial areas is closed. However,
18 performance is markedly different when a larger fraction of the total area is closed, with stock
19 size being substantially larger than the target at the end of the projection period.

20 Keywords: age-structured stock assessment methods, closed areas, harvest control rules,
21 simulation, spatial-structure

22

Introduction

Spatial closures have always been a standard component of the toolbox used to achieve single-species goals in marine fisheries. Closures off the US west coast are used to reduce fishing mortality on stocks that have been declared to be overfished and are in need of rebuilding (Field et al. 2006); and closures in Australia's Northern Prawn Fishery have been introduced to reduce fishing mortality on juvenile prawns (AFMA 2015a). Closures can also be implemented for biodiversity conservation (e.g., Anon 2015), reduction of impacts on threatened and endangered species (e.g., Greenstreet et al. 2006; Daley et al. 2015; AFMA 2012), and to protect habitat (e.g., Field et al. 2006).

Although the number of spatial closures has increased over time, so has their diversity. Some spatial closures are entirely no-take, while others are restricted to gear types such as bottom trawling restrictions on sea mounts (with pelagic gear allowed); still others, such as the closures to protect overfished rockfishes *Sebastes* species off the US west coast, are seasonal. Spatial closures are often capable of achieving single-species and ecosystem goals (Field et al. 2006), but may also increase spatial heterogeneity in population abundance, and size- and age-structure compared to unfished conditions (e.g., Lester et al. 2009; McCook et al. 2010; Aburto-Oropeza et al. 2011).

It is common to ignore closures and associated spatial heterogeneity when conducting stock assessments (Punt et al. 2015), particularly when there is limited movement of animals post-recruitment. Several studies (e.g., Punt and Methot 2004; Babcock et al. 2007; Garrison et al. 2011; McGillaird et al. 2015; Punt et al. 2016) have explored the impact of no-take spatial closures on the ability of stock assessments to provide accurate and precise estimates of management quantities. These studies have generally shown that ignoring spatial structure leads to bias, and this bias is exacerbated by closures. They also show that spatially-structured stock assessments reduce bias in estimates of biomass, at the cost of lower precision (Punt et al. 2015), but may lead to biased estimates of the parameters that govern the probability of animals moving from each spatial region of the model to the others (McGillaird et al. 2015). Ideally, spatially-structured stock assessments should be based on tagging data to inform estimates of movement, but such data are available for very few stocks (exceptions in Australia include the assessment of gummy shark *Mustelus antarcticus*, Pribac et al. 2005, and toothfish *Dissostichus eleginoides*, Day et al. 2015). Consequently, it is common to either ignore spatial structure and instead apply the fleets-as-areas approach, which accounts approximately for spatial structure (Punt et al. 2014; Waterhouse et al. 2014)

56 or use spatial models with no tagging data (McGillaird, et al. 2015; Szuwalski and Punt
57 2015).

58 Although estimates from assessments that ignore spatial structure, or use approximate
59 methods for addressing spatial structure such as the fleets-as-areas approach, are biased (and
60 imprecise), the use of such estimates in harvest control rules may not necessarily lead to an
61 inability to achieve goals of management related to the conservation and utilization of the
62 stock. This is because the feedback nature of harvest control rules mean that assessment
63 errors may be corrected over time. This paper starts to address the question of whether
64 closing areas negatively impacts the ability to achieve management goals by conducting one
65 of the first management strategy evaluations (MSE; Smith 1993, 1994; Punt et al. In press) in
66 which stock assessments that ignore spatial-structure are used to manage a system in which
67 there is a large no-take closed area.

68 Management Strategy Evaluation uses simulation to evaluate the relative performance of
69 different ‘management strategies’ (combinations of data collection schemes, stock assessment
70 methods, and harvest control rules), by applying a candidate management strategy to data
71 generated from an ‘operating model’, where the operating model represents an actual
72 underlying situation being managed. Management actions (in this case catch limits) are thus
73 used to update the stock dynamics underlying the operating model. Outputs from MSE are
74 typically performance metrics that quantify the extent to which a candidate management
75 strategy is able to achieve the management goals (Punt et al. In press). The results help
76 managers by identifying management strategy performance, possible actions that if
77 implemented could lead to undesirable outcomes, as well as data sources that could improve
78 management strategy performance and their cost effectiveness.

79 The simulations are based on pink ling, *Genypterus blacodes*, off southern Australia, a
80 component of Australia’s Southern and Eastern Scalefish and Shark Fishery (SESSF). The
81 SESSF covers the region from southern Queensland, around Tasmania, to Cape Leeuwin in
82 Western Australia, and is one of Australia’s largest and most valuable Commonwealth
83 (federal)-managed fisheries in Australia. Pink ling is appropriate as the basis for the study
84 because it is assessed as two independent stocks, separated east and west at 147°E, and is a
85 species for which there is no evidence of large scale movements. Since 2005, four seasonal
86 closures (from approximately September to November) have been in place to protect the
87 spawning stock and reduce fishing mortality at Maria Island, Seiner’s Horseshoe and Everard
88 Horseshoe in the east, and the Ling Hole in the west (Fig. 1). Closures within these areas
89 have been both voluntary and legislated (SEMAC 2012). These closures are relatively small

in area, but are considered to be located over some the most productive and previously favoured fishing grounds (AFMA, 2015b).

The MSE allows for three spatial zones (nominally zones 10, 20, and 30 of the SESSF; Fig. 1), one of which (either zone 10 or zone 20) can be assumed to be closed. The stock structure hypothesis for this paper is that there is a single biological stock across the three spatial zones, i.e. the recruitment for each zone is determined by the total spawning biomass across all three zones. The fish populations in these three zones are assumed to be mixed through the settlement of age-0 animals, with animals of age-1 and older not moving between zones. Two fleets (essentially trawl and non-trawl) are assumed to operate in each zone, growth can be assumed to differ among zones, and recruitment is assumed to be stochastic, with spatial variation in the proportion of the total recruitment that settles to each zone, as well as temporal variation in total recruitment. Management for pink ling is based on an Individual Transferable Quota system in which the Total Allowable Catch (TAC) is set based on a Recommended Biological Catch (RBC). A tier system of harvest control rules is available to set the RBCs for all SESSF species (Dichmont et al. in press). Pink ling is a 'tier 1' stock and its RBC is based on applying a harvest control rule to the outcomes from stock assessments (separately east and west of 147°E) implemented using Stock Synthesis (Methot and Wetzel 2013) and CASAL (Bull et al. 2005). TACs are usually set below RBCs to account for discarding and state catches (Smith et al. 2008), but for the purposes of this paper, the TAC is set equal to the RBC.

The analyses of this paper compare the performance of the management system (spatially-aggregated stock assessments and linked harvest control rules) for pink ling when there is heterogeneity in population structure caused by spatial variation in fishing mortality and growth (but no spatial closures) and when the degree of spatial heterogeneity is increased by the introduction of spatial closures. The analyses, which extend earlier explorations of the impact of spatial structure on the estimation performance of stock assessments (Punt et al. 2015, 2016), also explore the sensitivity of the performance metrics to the availability of survey data from the closures, as well as the area that is closed.

The primary aim of the study is to examine whether biases in assessment outcomes caused by spatial heterogeneity in population structure will lead to an inability to achieve management goals.

Methods and Materials

The simulation evaluation is based on specifying a model of the population dynamics and projecting it forward using catch limits based on a management strategy. This ‘operating’ model is assumed to represent the truth for the projections, and is used to generate pseudo data sets. The projections of the operating model assume that the TACs set by the management strategy are taken exactly, i.e. no account is taken of mis-reporting, including catches being taken illegally from the closed area; a satellite vessel monitoring system is used to enforce spatial boundaries within the SESSF.

The operating model

The operating model allows for spatial variation in fishing mortality, growth and in the proportion of the total recruitment that settles by zone. The historical period covered by the operating model is a 43-year period (nominally ‘1970 ‘to ‘2012’), and the projections involve a 20-year period during which catch limits are updated every third year based on applying a harvest control rule to the outputs from a stock assessment. The choice of conducting assessments every third year mimics the 2012 move in the SESSF to less frequent stock assessments, and reduces the computational demands of the analyses.

The three zones each contain a component of the population. The zones are linked through recruitment, which is a function of the total (over zones) spawning biomass. Once animals settle in a zone they never move out of the zone. The three zones represented in the operating model are assumed to receive different time-varying proportions of the total recruitment in an unfished state, with the parameter ϕ^z (see Equation 1) set to achieve average proportions of 0.28, 0.49, and 0.23 respectively for zones 10, 20 and 30 (which reflect roughly the relative amount of habitat for pink ling off south-eastern Australia; Whitten and Punt 2014) and variation in spatial distribution, σ_ϕ , set to 0.7. Given a Beverton Holt stock-recruitment relationship, the recruitment (at age-0) to zone z at the start of year y , R_y^z , is given by:

$$R_y^z = \frac{e^{\phi^z + \eta_y^z}}{\sum_z e^{\phi^z + \eta_y^z}} \frac{4hR_0\tilde{S}_y/\tilde{S}_0}{(1-h) + (5h-1)\tilde{S}_y/\tilde{S}_0} e^{\varepsilon_y - \sigma_R^2/2} ; \quad \varepsilon_y \sim N(0; \sigma_R^2); \quad \eta_y^z \sim N(0; \sigma_\phi^2) \quad (1)$$

where h is the “steepness” of the stock-recruitment relationship (Francis 1992), R_0 is the unfished equilibrium recruitment, $\tilde{S}_y$ is total (over zones) spawning biomass, $\tilde{S}_0$ is the

150 unfished total spawning biomass, and σ_R is the standard deviation among recruitment
 151 deviations in log space. Spawning biomass is defined as:

$$152 \quad \tilde{S}_y = \sum_z \sum_a O_a^z N_{y,a}^{fem,z} \quad (2)$$

153 where O_a is the product of maturity-at-age and weight-at-age and $N_{y,a}^{fem,z}$ is the number of
 154 females in zone z , of age a in year y (see Methot and Wetzel [2013] for details of how O_a is
 155 calculated).

156 The value for h is set to 0.75 and that for σ_R to 0.7 (Whitten and Punt 2014). The stock
 157 assessment method on which management advice is based (implemented in Stock Synthesis)
 158 is assumed to know the correct form of the stock-recruitment relationship, the true value of
 159 steepness and the true value for the extent of variation about the stock-recruitment
 160 relationship. This is to ensure that the focus of the study is on effects of closed areas, given
 161 the well-known difficulty in estimating steepness (Conn et al. 2012; Lee et al. 2012). Punt et
 162 al. (2015) outline the selectivity patterns by gear (assumed to be the same among zones).
 163 Supplementary Figure 1 shows the spatial variation in historical fishing mortality in the
 164 absence of closed areas. The fishery is assumed to have started in zone 10 and then moved
 165 progressively southward over time – reflecting the fact that the fisheries off southeast
 166 Australia started in the mainland ports (and within zone 10). As in Punt et al. (2015, 2016),
 167 the maximum level of fishing mortality is assumed to be the same spatially, while the fully-
 168 selected fishing mortality for the non-trawl fleet is assumed to be half that for the trawl fleet.
 169 For consistency with the actual assessment for pink ling (Whitten and Punt 2014), selectivity
 170 for the trawl fleet is assumed to be a monotonic logistic function of length while that for the
 171 non-trawl fleet is modelled using a unimodal double-normal selectivity function. Selectivity
 172 by fleet and zone is assumed to be stationary.

173 As in Punt et al. (2015, 2016), catch-rate data are only assumed to be available from 1986
 174 (Haddon 2014), while collection of age- and length-composition data is assumed to start in
 175 1975. Catch-rate data are assumed to be available by gear and by zone (when there is
 176 fishing). Catch-rates are assumed to be proportional to zone-specific exploitation biomass and
 177 log-normally distributed with a coefficient of variation of 10%. Catch-rates are actually not
 178 linearly proportional to the exploitable biomass of the population in the assessment model
 179 within the simulation because the data are analysed in the context of an assessment model
 180 that treats all three zones as spatially homogenous.

Between 1975 and 1985, length data are assumed to be available for 5% of the combinations of years, gears and zones, with years selected at random, and gear-zone combinations for the years with samples for data on length selected in proportion to the size of the catch in weight (reflecting that catches are sampled by port samplers and onboard vessels). From 1986 to 1997, length data are assumed to be available for 20% of year-gear-zone combinations, and 70% thereafter. The observed catch length-composition data for a year-gear-zone combination is a Dirichlet sample from the true catch length-composition, with an effective sample size of 100. This is lower than the actual sample sizes for pink ling, but the length-composition data for pink ling are known to be over-dispersed, and the available length-composition data are considerably down-weighted to reflect this when assessments are conducted (Whitten and Punt 2014; Cordue 2015). The length-composition data are assumed to be unsexed, as is the case in reality for pink ling and most fish stocks. The age-length keys for the historical period are assumed to be obtained from a subset of the length-frequencies (56%), with a sample size of 500 for each sex. Age-length keys are assumed to be available for all year-gear-zone combinations in the future. Given a year-gear-zone, the age data are assumed to be a simple random sample from the catches by age and length, for simplicity and to mimic the intent of the sampling program. The age-estimates are not subject to age-reading error for simplicity.

Allowance for closed areas and simulation scenarios

The scenarios (Table 1) explore the impact of factors that could impact estimation and management performance:

- Whether there are closures, and if there are closures, they are in zone 10 or zone 20.
- Whether there are spatial differences in growth (see Supplementary Figure 2 for how growth varies spatially; the growth curve when growth is spatially-invariant is set equal to that for zone 20 - this choice was made because the biomass in zone 20 is larger than that in the other zones).
- Whether survey data are available for assessment purposes.

The closures are assumed to be implemented in 2000. When a closed area is implemented in zone 10 or zone 20, to ensure comparability among analyses the exploitation rates in the zones open to fishing are increased so that the ratio of the total (over zones) spawning stock biomass at the start of the projections in 2012 to the total unfished spawning biomass (B_0) is the same (0.4) under deterministic projections (i.e., no spatial variation in settlement and no

variation in recruitment about the stock-recruitment relationship). This is to avoid the impacts of closed areas on performance being confounded with changes in overall population biomass. This assumption means, for example, that zones 20 and 30 will be more depleted when the management strategy is first applied if zone 10 is closed.

The total amount of historical length and conditional age-at-length data is the same among scenarios, i.e. closing one zone will lead to more length and conditional age-at-length data for the other zones. This specification is made to avoid the effects of closures being confounded with the total amount of data available for assessment purposes; although in reality one effect of closures is likely to be that less fisheries data is collected.

Surveys are assumed to be conducted from 2000 (i.e. at the start of the closures). Surveys are assumed to occur every 2nd year. The selectivity of the survey gear is assumed to be the same as that of the trawl fishery. The survey CV for each zone is assumed to be 0.1 and the survey length-frequency data are assumed to be a multinomial sample with an effective sample size 100, while the survey conditional age-at-length data are assumed to be a multinomial sample of size 500. Thus, the simulations are based on a highly informative survey.

The projections are replicated 100 times for each scenario. This is adequate to detect differences among scenarios and management strategies that are consequential at a management level.

The management strategy

The management strategy consists of stock assessment and harvest strategy components. These components are specified to mimic (to the extent possible) how assessments are conducted, and how management advice is provided for pink ling off south-eastern Australia. RBCs are set annually based on the estimated spawning biomass in years that assessments are performed, and on RBC projections from previous assessments in intervening assessment years, although TACs are now set every three years.

The stock assessment

Two assessment methods are examined.

Naïve spatially-weighted aggregated assessment method (NSWA):

The primary stock assessment considered in this work mimics how management advice is currently provided for pink ling. It does not recognize that there are spatial differences in population structure and abundance, and involves conducting a spatially-aggregated

assessment. This assessment method thus involves fitting a population model to data by fleet (trawl and non-trawl) that are combined over the three zones under the assumption that there is a single homogenous population over the region being managed. The data aggregation process is:

- The catch data are summed over zones.
- The catch rate data are aggregated across zones for use in the assessment model, defining the catch-rate for year y as total catch for year y divided by the total effort for year y .
- The annual trawl and non-trawl catch length-frequency data by fleet are pooled over zones, weighting the data for each zone by the annual catch by the zone.
- The annual age-length keys (i.e., the conditional age-at-length data) are summed over zones (without catch weighting). This reflects how age data have been aggregated in actual assessments for pink ling (Whitten and Punt 2014).

The assessment estimates unfished recruitment, natural mortality (assumed to be the same for males and females), growth by sex (five parameters per sex: the parameters that govern von Bertalanffy growth and the CVs of length-at-age for ages of 1 and 20), length-specific selectivity parameters (logistic for the trawl fleet, double-normal for the non-trawl fleet, i.e. based on the correct selectivity patterns), catchability for the CPUE indices, and recruitment for simulated years 1963 onwards. Recruitment estimation includes an initial bias-ramp (Methot and Taylor 2011) to avoid bias when estimating the deviations about the stock-recruitment relationship, given length and CPUE data are only available for the more recent years. The difference between the last year with data and the point at which the bias-ramp declines is always four years. Thus, for the first year of projection (2013) the bias-ramp begins to decline in 2009 and this point is incremented by three years each time a stock assessment is conducted

Fleets-as-areas assessment method (FAA):

This assessment method assumes a single homogenous population and that zones 10, 20 and 30 each contain a separate trawl and non-trawl fleet. Separate selectivity patterns are estimated for the three trawl fleets and for the three non-trawl fleets. Thus, this assessment method makes the same population structure assumption as the spatially-aggregated NSW method, but the catch-rate, length-frequency and conditional age-at-length data for each fleet are kept separate by zone in this method rather than being aggregated spatially. This approach to stock assessment has been applied widely in Australia (e.g., Whitten and Punt

2014; blue grenadier *Macruronus novaezelandiae*, Tuck 2014) and off the US west coast (e.g., petrale sole *Eopsetta jordani*, Haltuch et al. 2013; canary rockfish *Sebastes pinniger*, Stewart 2009).

The harvest control rule

Catch limits are set using the $B_{20}:B_{35}:B_{48}$ harvest control rule (Fig. 2). This harvest control rule, which is the default for data-rich SESSF stocks (Dichmont et al. in press; Smith et al. 2008), sets the catch limit to zero if the stock is assessed to be below the limit reference point of 20% of the unfished spawning biomass, B_{20} (in reality, targeted fishing would cease and only bycatch allowed). If the stock is assessed to be above B_{35} the fishing mortality rate used to determine the catch limit is set to F_{48} , the fishing mortality rate that is estimated to correspond to a depletion of spawning biomass to 48% of its unfished level (B_{48}), with this fishing mortality declining linearly between B_{35} and B_{20} . B_{48} is a proxy for B_{MEY} , the biomass corresponding to Maximum Economic Yield, which is the target biomass for Australian Commonwealth fisheries. The Australian Harvest Strategy Policy (DAFF 2007) allows for the use of proxies for B_{MEY} ($1.2 \times B_{MSY}$), where the proxy for B_{MSY} is taken to be 40% of the unfished spawning biomass, i.e. $0.4B_0$ (Rayns 2007).

The outcomes from the harvest control rule are subject to meta-rules (Stobutzki et al. 2001; Dichmont et al. in press). Specifically, catch limits are not permitted to change by more than 50% from one year to the next. Note that because catch limits are a set of 3-year blocks, the change in catch limit from one time-block to the next can substantially exceed 50%.

The allocation of the catch limit to zone and gear is based on the relative catch by gear and zone in the last year of the assessment period, i.e. the split of the total RBC for all future years equals that for the last year for which catch data are available (2012).

Performance metrics

Two types of performance metrics are reported – those pertaining to the ability of the stock assessment method to estimate spawning biomass adequately and those related to achieving management goals.

The assessment method provides many outputs (Methot and Wetzel 2013). However, the focus for this paper, and following Punt et al. (2015, 2016), are the estimates of initial total (female) spawning biomass¹ (B_0), final (2012) total female spawning biomass (B_{CUR}) and

¹ Total spawning biomass is spawning biomass summed over the three zones.

relative spawning biomass (B_{CUR}/B_0). The results of the projections are summarized by relative error distributions, as well as by the median over replicates of the absolute relative errors (MARE). The relative error for a given quantity is the estimated value of the quantity less its true value divided by its true value and multiplied by 100, i.e. a positive value indicates an overestimate of the quantity and vice versa.

The management-related performance metrics are those used when the management strategies for the SESSF were developed (e.g., Wayte and Klaer 2010; Little et al. 2011; Fay et al. 2011; Klaer et al. 2012):

- the annual probability over the entire projection period that the stock is below the limit reference point of 20% of the unfished spawning biomass;
- the probability that the stock is above the target reference point of 48% of the unfished spawning biomass at the end of the projection period;
- the average catch over the projection period; and
- the annual average variation in catch, i.e.:

$$AAV = \sum_{y=2013}^{2042} |C_y - C_{y-1}| / \sum_{y=2013}^{2042} C_y$$

The Harvest Strategy Policy for fisheries managed by the Australian Commonwealth (federal) government (DAFF 2007) stipulates that the probability of being below 20% of the unfished spawning biomass should not exceed 10% and this is treated as a ‘performance standard’ when evaluating the results of the projections.

Results

Results for a single replicate

Prior to exploring the results for multiple replicates, it is illustrative to examine the results for single replicates. Figure 3 shows results for projections when growth does not vary spatially, when there are no survey data, for cases when there are no spatial closures (Fig. 3a-d), and when zone 10 is closed in 2000 (Fig. 3e-h) (scenarios A and C in Table 1). Each assessment estimate (dashed lines Fig. 3a,e) is based on the same data as the previous assessment, except that an additional three years of data are included in each subsequent assessment. The estimates of spawning biomass from the assessments (dashed lines in Fig. 3a,e) are consequently correlated and often systematically different from the true values for several groups of years. For the two projections considered in Fig. 3, there is an early period when the assessment overestimates recent spawning biomass followed by a period, after the

management strategy is first applied, when spawning biomass is under-estimated (Fig. 3a,e). The estimates of spawning biomass for the years before the first application of the management strategy also differ quite substantially from the true values for both projections, i.e. irrespective of whether there is a closed area. For the projection with a closed area, the estimates of biomass for the early years (1970 to ~1982) are always over-estimated (Fig. 3e).

The time-trajectories of spawning biomass by zone (Fig. 3b,f) differ prior to implementation of the closed area as well as thereafter owing to different (random) allocations of total recruitment spatially as well as differences in catches spatially. The spawning biomass for zone 10 increases to above B_0 when there are closures (Fig. 3f). The trend in zone 10 differs markedly from the trends for the other two zones when there is a closed area (Fig. 3f). The catches (Fig. 3c,d,g,h) in the zones open to fishing (Fig. 3g,h; zones 20, 30) increase after 2012 as the stock is assessed to be above the target biomass of $0.48B_0$ (green horizontal line in the upper left panels of Fig. 3a,e).

Performance of the management strategy in the absence of closed areas

The upper two rows of panels in Figure 4 show distributions for the time-trajectories of total spawning biomass relative to the unfished level and catch when management advice is based on the spatially-aggregated NSW assessment, and there are no closed areas. Spawning biomass is relatively close to the target reference point of $0.48B_0$ throughout the projection period (Fig. 4a,c,e,g; median spawning biomass in 2042 relative to B_0 between 0.43 and 0.49 [Table 2]), with the results not differing substantially depending on whether survey data are available in addition to catch rate data nor whether there is spatial variation in growth. The probability that the total spawning biomass exceeds $0.48B_0$ varies between 0.3 (scenario B) and 0.55 (scenario F) (Table 2). In all cases, catches increase in the first year of the projection period as the stock is assessed to be above the target reference point, but subsequently decline to levels consistent with a spawning biomass of $0.48B_0$. The between-replicate variation in spawning biomass is largely independent of scenario (Fig. 4a,c,e,g). In contrast, between-replicate variation in catch is slightly higher when growth varies spatially (Fig. 4b,d,f,h). Average catches are higher when growth varies spatially, but among-year variation in catch is also higher (Table 2).

There is no apparent benefit of survey data on management performance (contrast the results of scenario B with those for scenario A, and the results for scenario F with those for scenario E; Fig. 4). This is because even though surveys provide an index of abundance that

is linearly proportional to biomass for each zone, the assessment model is mis-specified through it not accounting for spatial structure, and this means that the results remain biased.

Performance of the management strategy when there are closed areas

Spawning biomass equilibrates close to the target level when zone 10 is closed in 2000 and management is based on the spatially-aggregated NSW assessment (Fig. 4i,k,m,o). The total spawning biomass initially rebuilds with correspondingly higher catches, to a level greater than the target reference point; given the higher catches the biomass then declines to below the target biomass. This pattern is most evident when growth varies spatially (Fig. 4m,o), with the probability that the total spawning biomass is below the limit reference point being higher than when growth does not vary spatially (roughly 2% of all years for scenarios G and H compared to less than 1% for scenarios A-E; Table 2). Average catches are again higher when growth varies spatially, but unlike the case when there were no spatial closures, catch variation (AAV) is highest when there are no survey data (Table 2). Consequently, as was the case when there were no spatial closures, the availability of survey data only leads to a limited impact on management performance.

Assessments based on the fleets-as-area approach

The time-trajectories of spawning biomass relative to the unfished level and catch are similar for the two assessment methods (NSW and FAA) when there are no spatial closures (Figs 4 vs 5). However, the results differ between the two assessment methods when zone 10 is closed. Specifically, spawning biomass is consistently above the target reference point (but does eventually reach $B_{48\%}$) when growth does not vary spatially and zone 10 is closed if the assessment is based on the fleets-as-areas approach (Fig 5e). The pattern of results when zone 10 is closed and growth varies spatially (Fig 5g,h) is close to that when assessments are based on the NSW assessment method (Fig 4m,n). Inter-annual catch variation (AAV) is lower when management advice is based on the FAA assessment method (Table 2).

Closing zone 20 instead of zone 10

Qualitatively, the time-trajectories of spawning biomass and catch are markedly different, both historically and into the future, when zone 20 rather than zone 10 is closed in 2000 (Figs 4 and 6). The difference in the historical period is most evident for the catches between 2000 and 2012, which are much lower when zone 20 is closed than when zone 10 is closed. This occurs because the biomass in zone 20 is much larger than in zone 10 and the assessment is negatively biased when zone 20 is closed (see below) so future TACs are consequently lower

(contrast Figs 4 and 6; Tables 2a and 2b). One implication of this is that the total spawning biomass stabilizes above the target level of $B_{48\%}$ (Fig. 6, Table 2b).

Results by zone

The time-trajectories of spawning biomass differ among zones even when there no closures (Scenarios A, E), primarily because of the way catches have been taken historically (greater depletion between 1980 and 2000 for zone 10 than zone 20 and particularly zone 30) (Fig. 7a-f; Supplementary Fig. 3a-f). Zone 10 is depleted to below the limit reference point when there are no closures, given the assumption that future catches are taken spatially in proportion with the spatial distribution of historical catches (Fig. 7a,d). The other zones are close to the target level when the management strategy is first applied when there are no closures (Figs 7a-f). When zone 10 is closed in 2000, the biomass in zone 10 starts the projection well above the target reference point (green line, Figs 7g,j) and recovers to close to the unfished level when it is closed (Figs 7g,j). Zone 20 however, starts at the target biomass and is depleted to close to the limit reference point (Figs 7h,k). The depletion of zone 20 is more extreme when growth varies spatially. Thus, the spatially-aggregated results differ from those by zone.

Error estimating biomass

The estimates of total spawning biomass from the spatially-aggregated NSW assessment method are biased (the median error differs by zone) prior to the first application of the management strategy irrespective of whether or not there are closures, with the bias larger when growth varies spatially (Fig. 8 a,c,e,g,i,k). These biases are due to spatial heterogeneity in the abundance index as well as the length- and conditional age-at-length data that cannot be addressed using a spatially-aggregated assessment model such as NSW (Punt et al. 2016). The extent of bias changes between the 3rd and 5th assessments (those conducted in 2018 and 2024), although the effects are more marked when zone 10 is closed (Fig. 8a,c,e,g,i,k). The assessment leads to negatively biased estimates of biomass towards the end of the projection period irrespective of whether zone 10 is closed or not. Thus, the additional 30 years of data does not improve the ability to estimate trends in spawning biomass. There is also considerable among-replicate variation in errors in estimating spawning biomass (Fig. 8, columns 2 and 4). The relative errors of the estimates of total spawning biomass exhibit the same general patterns irrespective of whether zone 10 or zone 20 is closed, but the estimates are negatively biased when zone 20 is closed (and for scenario J show extreme variation

among replicates, in particular the possibility exists of occasional highly positive biased estimates of total spawning biomass).

The estimates from the FAA method are less biased compared to the NSW method (and the pattern in bias is quite different for scenario C than for the other scenarios) (Fig 8m-p). However, and consistent with Punt et al (2016), the among-replicate variation in errors estimating spawning biomass is larger for the FAA method (e.g. Fig 8b vs 8n).

Discussion

Several studies have explored the behaviour of stock assessment methods in the face of spatial heterogeneity in population structure, including when a portion of habitat is closed (e.g. Punt 2003; Punt and Methot 2005; Garrison et al. 2011; Guan et al. 2013; McGilliard et al. 2015). It is well known that attempting to manage two (or more) stocks as one can lead to an inability to achieve conservation and utilization objectives (e.g. Hilborn 1985; Fu and Fanning 2004). However, management strategy evaluation has not previously evaluated the ability of management strategies to achieve management goals in the face of spatial heterogeneity and spatial closures when there is a single stock (i.e. simulating the assessment method rather than setting a fishing mortality rate). Punt and Hobday (2009) explored the performance of a management strategy for rock lobsters that was based on a size-structured population dynamics model when the region to be managed contained multiple stocks, but they did not examine the consequences of spatial closures, while Fay et al. (2011) explored the performance of an empirical management strategy, again in the absence of spatial closures.

The results of this paper confirm the results of earlier studies that spatial heterogeneity in abundance and age structure will lead to bias for assessments based on spatially-aggregated population dynamics models, irrespective of whether the NSW or FAA methods are applied. They further confirm that the extent of bias in estimates of total spawning biomass is exacerbated in the presence of spatial closures. Although the simulations involved closures that were in operation for more than 50 years, there was no evidence that biases that arise due to spatial closures (or even spatial heterogeneity in population structure) reduce over time, even when high precision survey data are available for assessment purposes.

However, biased estimates of total spawning biomass do not necessarily lead to a complete inability to achieve management goals. While the time-trajectories of catches and biomass are substantially more variable than would be expected had a single stock been managed, the stock tends (in median terms) to be fairly close to the target level at the end of

the projection period, with a low probability of being depleted below the limit reference point, at least in the absence of closures and for closed areas that are up ~25% of the stock area². Larger closed areas lead to lower catches and stock sizes in excess of the target level. The extent to which the stock is above the target level depends on the size of the closed area and the target level. In the context of scenarios I and J, the target is 48% of the unfished level and close to 50% of the stock biomass (in an unfished state) is contained in the closed area. Consequently, it is not unexpected that the stock is well above the target biomass.

There was a notable impact of spatial variation in growth rates on the performance of the management strategy, seen as bias of the assessment. The bias arises because the estimated growth curve in the assessment does not match those used when the data (particularly the length-frequency data) are generated.

The management strategies considered in this paper are based on one harvest control rule and two assessment methods, and are actually used for pink ling off southern Australia where recent management advice has been based on the NSW method (Whitten and Punt 2014; Cordue 2015). However, there are many other types of harvest control rules that could be used to determine catch limits (see the review of harvest control rule formulations in Deroba and Bence 2008), while the input for applying harvest control rules could be obtained from many types of assessment method. In principle, some of the biases associated with spatial heterogeneity could be removed by using a spatially-explicit stock assessment method, but the extent to which this would be the case depends on how accurately the spatial model underlying the assessment method matches reality (Punt et al., 2016). An additional complication associated with management strategies based on spatially-explicit models is that they tend to be very imprecise (Punt et al. 2015, 2016), which would lead potentially to high between-year variation in assessment outcomes and catches.

Several jurisdictions, including Australia, have adopted empirical rather than model-based management strategies for some fished species (e.g., Plagányi et al. 2007; Smith et al. 2008). Empirical management strategies tend to lead to more variable catch limits than model-based approaches (Butterworth and Punt 1999), but may be less biased as they do not attempt to interpret monitoring data in the context of an incorrect population dynamics model. Whether empirical management strategies outperform model-based management strategies in the face of spatial heterogeneity should form the basis for future work. This may be the case when there is spatial heterogeneity in abundance trends as well as in trends in age

² The approximate size of zone 10

and length data because empirical methods do not attempt to analyse all available data using a model that would be mis-specified.

The operating model on which this study was based was simple compared to reality by including only three areas and not allowing adult movement. The assumption of no movement should have increased spatial heterogeneity, as movement tends to reduce the effects of the spatial variation in fishing mortality. Other areas where future work should focus include (a) changing the number of areas and how assessment regions match population structure, (b) conducting projections where catch limits are not taken in proportion to the spatial distribution of the catch in 2012 (fishers are to some extent place-based and hence likely to continue to use the same gear and fish in the same zone, but this can and will change over time), (c) basing the simulations on operating models that include plausible source-sink dynamics or size-based habitat preferences and (d) considering performance metrics related to catch-rates as well as to catches (which will, all things being equal, be lower in the presence of a large closed area).

Although the results of this study are case-specific (in common with all simulation studies), several general conclusions can be drawn:

- Assessment outcomes will be biased in the face of unmodelled spatial heterogeneity, and these biases are unlikely to disappear given additional data, and are exacerbated by spatial closures.
- Biased assessments due to unmodelled spatial heterogeneity do not necessarily lead to an inability to achieve management goals.
- The ability to achieve management goals is negatively affected by closed areas, with the effects larger for large closed areas.
- Survey data from within the closed area do not necessarily improve management outcomes.

Some of the assumptions on which the analyses are based would be optimistic for many cases (e.g. the low survey and CPUE observation error CV, perfect knowledge of the form and parameters of the stock-recruitment relationship, stationary selectivity pattern). Less precise (or biased) data and (further) mis-specification of the model on which the assessment is based could lead to the changes to the second and fourth conclusions above, and should be the focus for future studies.

Spatial heterogeneity and closed areas have always been a reality for fisheries management (Field et al. 2006). However, the results of studies such as the present one

highlight that effective management may require sampling programs and assessment frameworks designed to support management strategies tailored to there being closed areas. Such programs could involve tagging programs as well as sampling of age structure in closed areas. Frameworks such as those outlined in this paper could be used to evaluate the extent to which alternative management strategies can outperform current approaches.

Acknowledgements

The draft was improved by comments from Dale Kolody (CSIRO) and two anonymous reviewers.

References

- Aburto-Oropeza, O., Erisman, B., Galland, G.R., Mascarenas-Osorio, I., Sala, E., and Ezcurra, E. 2011. Large recovery of fish biomass in a no-take marine reserve. *PLoS ONE*, **6**: e23601. doi:10.1371/journal.pone.0023601
- AFMA 2012, Upper-Slope Dogfish Management Strategy AFMA-managed Fisheries October 2012, Australian Fisheries Management Authority. Canberra, Australia. <http://www.afma.gov.au/wp-content/uploads/2014/12/Upper-slope-Dogfish-Management-Strategy-14December-2012-FINAL.pdf> (last accessed 4 January 2016).
- AFMA 2015a, Northern Prawn Fishery Directions and Closures 2015, Australian Fisheries Management Authority. Canberra, Australia. <http://www.afma.gov.au/wp-content/uploads/2014/08/NPF-Directions-and-Closures-2015.pdf> (last accessed 3 January 2016).
- AFMA. 2015b. *Southern and Eastern Scalefish and Shark Fishery Management Arrangements Booklet 2015*, Australian Fisheries Management Authority. Canberra, Australia. <http://www.afma.gov.au/fisheries/southern-and-eastern-scalefish-and-shark-fishery/> (last accessed 10 April 2016) http://www.afma.gov.au/wp-content/uploads/2014/08/SESSF_Management_Arrangements_Booklet_2015.compressed.pdf
- Anon., 2015. Commonwealth Marine Reserves. <http://www.environment.gov.au/topics/marine/marine-reserves> Department of the Environment, Australian Government.
- Babcock, R.C., Phillips, J.C., Lourey, M., and Clapin, G. 2007. Increased density, biomass and egg production in an unfished population of Western Rock Lobster (*Panulirus cygnus*) at Rottne Island, Western Australia. *Marine and Freshwater Research* **58**: 286-292.
- Bull, B., Francis, R.I.C.C., Dunn, A., McKenzie, A., Gilbert, D.J., and Smith, M.H. 2005. CASAL (C++ algorithmic stock assessment laboratory): CASAL user manual v2.07-2005/08/21. NIWA Technical Report 127.
- Butterworth, D.S., and Punt, A.E. 1999. Experiences in the evaluation and implementation of management procedures. *ICES J. Mar. Sci.* **56**: 985–998.
- Conn, P.B., Williams, E.H., and Shertzer, K.W. 2010. When can we reliably estimate the productivity of fish stocks? *Can. J. Fish. Aquat. Sci.* **67**: 511–523.

- 572 Cordue, P.L. 2015. Stock assessment results for eastern pink ling: new base model. Post-meeting Draft report to
573 the RAG meeting of 29th October 2015.
- 574 DAFF. 2007. *Commonwealth Fisheries Harvest Strategy Policy Guidelines*. Australian Government Department
575 of Agriculture, Fisheries and Forestry, Canberra, Australia, pp. 55.
576 http://www.agriculture.gov.au/fisheries/domestic/harvest_strategy_policy (last accessed 3 January 2016).
- 577 Daley, R.K., Williams, A. Green, M., Barker, B. and Brodie, Pamela. 2015. Can marine reserves conserve
578 vulnerable sharks in the deep sea? A case study of *Centrophorus zeehaani* (Centrophoridae), examined with
579 acoustic telemetry. *Deep Sea Research II*. **115**: 127-136.
- 580 Day J., Haddon M., and Hillary R. 2015. Stock Assessment of the Macquarie Island fishery for Patagonian
581 toothfish (*Dissostichus eleginoides*) using data up to and including August 2014. Report to SARAG 51,
582 24 February 2015. CSIRO, Australia.
- 583 Deroba, J.J., and Bence, J.R. 2008. A review of harvest policies: Understanding relative performance of control
584 rules. *Fish. Res.* **94**: 210–223.
- 585 Dichmont, C.M., Punt, A.E., Dowling, N., De Oliveira, J.A.A., Little, L.R., Sporcic, M., Fulton, E., Gorton, R.,
586 Klaer, N., Haddon, M., and Smith, D.C. In press. Is risk consistent across tier-based harvest control rule
587 management systems? A comparison of four case studies. *Fish. And Fish.* **00**: 00–00.
- 588 Fay, G., Punt, A.E., and Smith, A.D.M. 2011. Impacts of spatial uncertainty on performance of age structure-
589 based harvest strategies for blue eye trevalla (*Hyperoglyphe antarctica*). *Fish. Res.* **110**: 391–407.
- 590 Field, J.C., Punt, A.E., Methot, R.D., and Thomson, C.J. 2006. Does MPA mean “Major Problem for
591 Assessments?” Considering the consequences of place-based management systems. *Fish and Fish.* **7**: 284–
592 302.
- 593 Francis, R.I.C.C. 1992. Use of risk analysis to assess fishery management strategies: A case study using orange
594 roughy (*Hoplostethus atlanticus*) on the Chatham Rise, New Zealand. *Can. J. Fish. Aquat. Sci.* **49**: 922–
595 930.
- 596 Fu, C.H., and Fanning, L.P. 2004. Spatial considerations in the management of Atlantic cod off Nova Scotia,
597 Canada. *N. Am. J. Fish. Manage.* **24**: 775–784.
- 598 Garrison, T.M., Hamel, O.S., and Punt, A.E. 2011. Can data collected from marine protected areas improve
599 estimates of life-history parameters? *Can. J. Fish. Aquat. Sci.* **68**: 1761–1777.
- 600 Greenstreet, S.P.R., Armstrong, E., Mosegaard, H., Jensen, H., Gibb, I.M., Fraser, H.M., Scott, B.E., Holland,
601 G.J., and Sharples, J. 2006. Variation in the abundance of sandeels *Ammodytes marinus* off southeast
602 Scotland: an evaluation of area-closure fisheries management and stock abundance assessment methods.
603 *ICES Journal of Marine Science.* **63**: 1530 – 1550.
- 604 Guan, W., Cao, J., Chen, Y., and Cieri, M., 2013. Impacts of population and spatial structures on fishery stock
605 assessment. *Can. J. Fish. Aquat. Sci.* **70**: 1178–1189.
- 606 Haddon, M., 2014. Catch rate standardizations for selected species from the SESSF (data 1986 – 2012). In *Stock*
607 *Assessment for the Southern and Eastern Scafish and Shark Fishery 2013, Part 2. Edited by G.N. Tuck*
608 *Australian Fisheries Management Authority and CSIRO Marine and Atmospheric Research.* pp. 57-275.
- 609 Haltuch, M.A., Ono, K., and Valero, J. 2013. Status of the U.S. petrale sole resource in 2012. Pacific Fishery
610 Management Council, 7700 Ambassador Place NE, Portland, OR 970220. [http://www.pcouncil.org/wp-](http://www.pcouncil.org/wp-content/uploads/Petrade_2013_Assessment.pdf)
611 [content/uploads/Petrade_2013_Assessment.pdf](http://www.pcouncil.org/wp-content/uploads/Petrade_2013_Assessment.pdf) (last accessed 3 January 2016).

- Hilborn, R. 1985. Fleet dynamics and individual variation: why some people catch more fish than others. *Can. J. Fish. Aquat. Sci.* **42**: 2–13.
- Klaer, N.L., Wayte, S.E., and Fay, G. 2012. An evaluation of the performance of a harvest strategy that uses an average-length-based assessment method. *Fish. Res.* **134-136**: 42–51.
- Lee, H-H, Maunder, M.N., Piner, K.R., and Methot, R.D. 2012. Can steepness of the stock–recruitment relationship be estimated in fishery stock assessment models? *Fish. Res.* **125-126**: 254–261.
- Lester, S.E., Halpern, B.S., Grorud-Colvert, K., Lubchenco, J., Ruttenberg, B.I., Gaines, S.D., Airame, S., and Waners, R.R. 2009. Biological effects within no-take marine reserves: a global synthesis. *Mar. Ecol. Prog. Ser.* **384**: 33–46.
- Little, L.R., Wayte, S.E., Tuck, G.N., Smith, A.D.M., Klaer, N., Haddon, M., Punt, A.E., Thomson, R., Day, J., and Fuller, M. 2011. Development and evaluation of a cpue-based harvest control rule for the southern and eastern scalefish and shark fishery of Australia. *ICES J. Mar. Sci.* **68**: 1699–1705.
- McCook, L.J., Ayling, T., Cappo, M., Choat, J.H., Evans, R.D., De Freitas, D.M., Heupel, M., Hughes, T.P., Jones, G.P., Mapstone, B., Marsh, H., Mills, M., Molloy, F.J., Pitcher, C.R., Pressey, R.L., Russ, G.R., Sutton, S., Sweatman, H., Tobin, R., Wachenfeld, R.E., and Williamson, D.H. 2010. Adaptive management of the Great Barrier Reef: A globally significant demonstration of the benefits of networks of marine reserves. *Proc. Natl. Acad. Sci. U.S.A.* **107**: 18278–18285.
- McGilliard, C.R., Punt, A.E., Methot, R.D., and Hilborn, R. 2015. Accounting for marine reserves using spatial stock assessments. *Can. J. Fish. Aquat. Sci.* **72**: 262–280.
- Methot Jr., R.D., and Taylor, I.G. 2011. Adjusting for bias due to variability of estimated recruitments in fishery assessment models. *Can. J. Fish. Aquat. Sci.* **68**: 1744–1760.
- Methot, R.D., and Wetzell, C.R. 2013. Stock Synthesis: a biological and statistical framework for fish stock assessment and fishery management. *Fish. Res.* **142**: 86–99.
- Pribac, F., Punt, A.E., Walker, T.I., and Taylor, B.L. 2005. Using length, age and tagging data in a stock assessment of a length selective fishery for gummy shark (*Mustelus antarcticus*). *J. Northw. Atl. Fish. Sci.* **35**: 267–290.
- Plagányi, É.E., Rademeyer, R.A., Butterworth, D.S., Cunningham, C.L., and Johnson, S.J. 2007. Making management procedures operational—innovations implemented in South Africa. *ICES J. Mar. Sci.* **64**: 626–632.
- Punt, A.E. 2003. The performance of a size-structured stock assessment method in the face of spatial heterogeneity in growth. *Fish. Res.* **65**: 391–409.
- Punt, A.E., and Hobday, D. 2009. Management strategy evaluation for rock lobster, *Jasus edwardsii*, off Victoria Australia: accounting for uncertainty in stock structure. *NZ J. Mar. Freshw. Res.* **43**: 475–609.
- Punt, A.E., and Methot, R.D. 2004. Effects of Marine Protected Areas on the assessment of marine fisheries. *Am. Fish. Soc. Symp.* **42**: 133–154.
- Punt, A.E., Haddon, M., and Tuck, G.N. 2015. Which assessment configurations perform best in the face of spatial heterogeneity in fishing mortality, growth and recruitment: A case study based on pink ling in Australia. *Fish Res.* **168**: 85–99.
- Punt, A.E., Butterworth, D.S., de Moor, C.L., De Oliveira, J.A.A., and Haddon, M. In press. Management Strategy Evaluation: Best Practices. *Fish and Fish.* **00**: 00–00.

- 652 Punt, A.E., Haddon, M., Little, L.R., and Tuck, G.N. 2016. Can a spatially-structured stock assessment address
653 uncertainty due to closed areas? A case study based on pink ling in Australia. *Fish. Res.* **175**: 10-23.
- 654 Punt, A.E., Hurtado-Ferro, F., and Whitten, A.R. 2014. Model selection for selectivity in fisheries stock
655 assessment. *Fish. Res.* **158**: 124–134.
- 656 Rayns, N. 2007. The Australian government's harvest strategy policy. *ICES J. Mar. Sci.* **64**: 596–598.
- 657 SEMAC, 2012. Minutes of the South East Management Advisory Committee (SEMAC) 08. 30-31 January,
658 2012. Australian Fisheries Management Authority, Canberra.
- 659 Smith, A.D.M. 1993. Risks of over- and under-fishing new resources. *In* Risk Evaluation and Biological
660 Reference Points for Fisheries Management. *Edited by* S.J. Smith, J.J. Hunt, and D. Rivard. Canadian
661 Special Publication of Fisheries and Aquatic Sciences 120. pp. 261–267.
- 662 Smith, A.D.M. 1994. Management strategy evaluation – The light on the hill. *In* Population Dynamics for
663 Fisheries Management. *Edited by* D.A. Hancock. Australian Society for Fish Biology Workshop
664 Proceedings, Perth 24-25 August 1993. Australian Society for Fish Biology, Perth. pp 249-253
- 665 Smith, A.D.M., Smith, D.C., Tuck, G.N., Klaer, N., Punt, A.E., Knuckey, I. Prince, J., Morison, A., Kloser, P.,
666 Haddon, M., Wayte, S., Day, J., Fay, G., Pribac, F., Fuller, M., Taylor, B. and Little, L.R.. 2008.
667 Experience in implementing harvest strategies in Australia's southeastern fisheries. *Fish. Res.* **94**: 373–379.
- 668 Stewart, I.J. 2009. Status of the U.S. canary rockfish resource in 2009 (Update of 2007 assessment model).
669 Pacific Fishery Management Council, 7700 Ambassador Place NE, Portland, OR 970220.
670 http://www.pcouncil.org/wp-content/uploads/2009_canary_updated_assessment_SAFE_version.pdf (last
671 accessed 3 January 2016).
- 672 Stobutzki, I., Vieira, S., Ward, P., and Noriega, R. 2011. Southern and Eastern Scalefish and Shark Fishery
673 overview. *In* Fishery Status Reports 2010: Status of fish stocks and fisheries managed by the Australian
674 Government *Edited by* J. Woodhams, I. Stobutzki, S. Vieier, R. Curtotti and G.A., Begg. Australian
675 Bureau of Agricultural and Resource Economics and Sciences, Canberra. Pp 114-124.
- 676 Szuwalski, C.S., and Punt, A.E. 2015. Can an aggregate assessment reflect the dynamics of a spatially structured
677 stock? Snow crab in the eastern Bering Sea as a case study. *Fish. Res.* **164**: 135-142.
- 678 Tuck, G.N. 2014. Stock assessment of blue grenadier *Macraronus novaezelandiae* based on data up to 2012. *In*
679 Stock Assessment for the Southern and Eastern Scalefish and Shark Fishery 2013. Part 1. *Edited by* G.N.
680 Tuck. Australian Fisheries Management Authority and CSIRO Marine and Atmospheric Research. pp 61 –
681 115
- 682 Waterhouse, L., Sampson, D.B., Maunder, M., and Semmens, B.X. 2014. Using fleets-as-areas selectivity to
683 model spatial fishing: Asymptotic curves are unlikely under equilibrium conditions. *Fish. Res.* **158**: 15–25.
- 684 Wayte S., and Klaer N., 2010. An effective harvest strategy using improved catch-curves. *Fish. Res.* **106**, 310–
685 320.
- 686 Whitten, A.E., and Punt. A.E. 2014. Stock Assessment of pink ling (*Genypterus blacodes*) using data up to
687 2012. *In* Stock Assessment for the Southern and Eastern Scalefish and Shark Fishery 2013, Part 1. *Edited*
688 *by* G.N. Tuck. Australian Fisheries Management Authority and CSIRO Marine and Atmospheric Research,
689 Hobart. pp. 116-142.

690 **Acknowledgements**

691 This work was partially supported by funding from the FRDC (project 2011/032) on behalf of
692 the Australian Government and by the Joint Institute for the Study of the Atmosphere and
693 Ocean (JISAO) under NOAA Cooperative agreement No. NA10OAR4320148. This paper is
694 JISAO Contribution No. XXX.

695

696

Draft

697 Table 1. The scenarios considered in the analyses of this paper
698

Scenario	Closures	Spatial variation in growth	Survey data	Rationale
A	No	No	No	Explores the impact of model mis-specification due to spatial structure in the absence of closed areas
B	No	No	Yes	Examines the benefits of surveys in the absence of spatial closures
C	Zone 10	No	No	Explores the consequences of additional spatial heterogeneity due to spatial closures
D	Zone 10	No	Yes	Examines the benefits of surveys in the presence of spatial closures (and hence no catch-rate or catch length-and age-composition data in the spatial closures)
E	No	Yes	No	Explores the consequences of growth as well as population age-composition differing among zones
F	No	Yes	Yes	Examines the benefits of surveys relative to scenario E
G	Zone 10	Yes	No	Explores the combined effects of spatial variation in growth and spatial closures
H	Zone 10	Yes	Yes	Examines the benefits of surveys relative to scenario H
I	Zone 20	No	No	Explores the consequences of additional spatial heterogeneity due to spatial closures, when the closure is larger than for scenarios C, D, G and H.
J	Zone 20	Yes	No	Explores the consequences of growth as well as population age-composition differing among zones when there are large spatial closures.

699 Table 2. Performance measures (probability of being below the limit reference point, probability of being above the target reference point, final
700 relative spawning biomass, average catch, and AAV) for the two assessment methods and the various scenarios.

701

702 (a) Zone 10 closed

Scenario	$\tilde{S}_{Fin} / \tilde{S}_0$					Average catch			AAV		
	P <		Low 5	Median	Up 5	Low 5	Median	Up 5	Low 5	Median	Up 5
	LRP	P > TRP									
Spatially-aggregated NSW assessment											
A*	0.001	0.37	32.7	43.3	68.9	307	525	727	0.040	0.277	0.670
B*	0.002	0.30	31.8	41.9	61.7	312	524	780	0.043	0.275	1.177
E*	0.002	0.51	32.2	48.1	71.5	386	660	973	0.037	0.352	1.100
F*	0.003	0.55	31.2	49.4	72.3	393	646	979	0.013	0.362	0.934
C	0.002	0.36	32.8	38.9	63.4	283	538	764	0.014	0.180	1.248
D	0.003	0.43	32.5	44.5	66.8	279	535	776	0.012	0.213	0.884
G	0.016	0.39	30.4	40.7	71.3	409	755	1036	0.017	0.339	0.899
H	0.018	0.44	30.8	45.2	69.6	415	739	1081	0.016	0.126	0.840
Spatially-aggregated fleets-as-areas assessment											
A*	0.002	0.32	29.2	41.4	71.1	161	509	744	0.009	0.093	0.805
E*	0.006	0.37	28.0	44.3	67.6	394	713	1073	0.015	0.169	1.032
C	0.000	0.54	36.2	49.1	74.7	160	421	603	0.013	0.120	0.792
F	0.019	0.48	30.6	47.6	66.8	423	735	1101	0.006	0.307	1.350

703 *No closures

704

705 (b) Zone 20 closed

Scenario			$\tilde{S}_{Fin} / \tilde{S}_0$			Average catch			AAV		
P <											
	LRP	P > TRP	Low 5	Median	Up 5	Low 5	Median	Up 5	Low 5	Median	Up 5
Spatially-aggregated NSW assessment											
I	0.000	1.000	54.0	63.6	77.5	106	256	397	0.001	0.363	1.166
J	0.000	0.980	50.3	66.9	77.8	137	292	485	0.000	0.179	1.374

706

707

Figure 1. Schematic map of SESSF reporting blocks 10 – 50, with the fine blue lines representing block boundaries. The locations of Sydney, Melbourne, and Hobart are indicated by black squares from top to bottom. The east stock of pink link is found in zones 10, 20 and 30; the line between zones 30 and 40 is at 147°E. The real world closures for pink ling include M, Maria Island; S, Seiners Horseshoe; E, Everard Horseshoe, and L, the Ling Hole; other closures occur in zones 10, 20, and 30 but they are not aimed at pink ling.

718 Figure 2. The B_{20} : B_{35} : B_{48} harvest control rule.

Draft

719

720 Figure 3. For single replicate simulations along each row of panels: (a,e) true time-trajectory of total spawning biomass (thick solid line) and the
 721 estimates of the time-trajectories of spawning biomass each time an assessment is conducted (thin dashed lines), (b,f) true time-trajectory of
 722 spawning biomass by zone, (c,g) time-trajectory of non-trawl catches by zone, and (d,h) time-trajectory of trawl catches by zone. The vertical
 723 red line denotes when the management strategy is first applied, and the red and green horizontal lines in panels (a,e) are respectively the limit

724 and target reference points. Results are shown in (a-d) when there are no spatial closures and in (e-h) when there is a closure in zone 10 starting
725 in 2000. The assessments are based on the spatially-aggregated NSW method.

Draft

Figure 4. Time-trajectories of total spawning biomass relative to unfished spawning biomass (columns 1 and 3) and catch (columns 2 and 4). Results are shown when there are no closed areas (scenarios A, B, E, and F) and when zone 10 is closed (scenarios C, D, G and H). There are survey data for scenarios B, D, F and H. Growth does not vary spatially for scenarios A, B, C and D, but does vary for scenarios E, F, G and H. The solid line is the distribution median, the dark shading covers the central 50% of the distributions and the light shading 90% of the distributions. The vertical red line denotes when the management strategy is first applied, and the red and green horizontal lines are respectively the limit and target reference points. Management advice for the analyses in this figure are based on the spatially-aggregated NSW approach.

738

739

740

741

742

743

744

745

746

Figure 5. Time-trajectories of total spawning biomass relative to unfished spawning biomass (left columns) and catch (right columns) when management advice is based on the FAA method and there are no survey data. Results are shown in the upper two rows when there are no spatial closures (scenarios A and E) and when zone 10 is closed in 2000 (scenarios C and G). Growth does not vary spatially for scenarios A and C, but does vary for scenarios E and G. The solid line is the distribution median, the dark shading covers the central 50% of the distributions and the light shading 90% of the distributions. The vertical red line denotes

747 when the management strategy is first applied, and the red and green horizontal lines are
748 respectively the limit and target reference points.

749

Draft

Figure 6. Time-trajectories of total spawning biomass relative to unfished spawning biomass (left columns) and catch (right columns) when zone 20 is closed in 2000 and the assessment is based on the spatially-aggregated NSW method and there are no survey data. Results are shown in the upper row when growth does not vary spatially (scenario I) and the lower row when growth varies spatially (scenario J). The solid line is the distribution median, the dark shading covers the central 50% of the distributions and the light shading 90% of the distributions. The vertical red line denotes when the management strategy is first applied, and the red and green horizontal lines are respectively the limit and target reference points.

760

761

762

763

764

765

766

767

768

769

770

771

Figure 7. Time-trajectories of spawning biomass relative to unfished spawning biomass by zone (10, 20 and 30, left, center, and right columns). Results are shown in the upper two rows when there are no spatial closures (scenarios A and E) and when zone 10 is closed in 2000 (scenarios C and G). Growth does not vary spatially for scenarios A and C, but does vary for scenarios E and G. The solid line is the distribution median, the dark shading covers the central 50% of the distributions and the light shading 90% of the distributions. The vertical red line denotes when the management strategy is first applied, and the red and green horizontal lines are respectively the limit and target reference points. The results in this figure are based on the spatially-aggregated NSW method with no survey data.

Figure 8: Median relative errors in spawning biomass for 1st, 3rd, 5th, 7th and 10th assessments and the 95% simulation intervals for the relative errors for these assessments. Results are shown for management based on the NSW method in (a, b) for scenario A, in (c, d) for scenario E, in (e, f) for scenario C, in (g, h) for scenario G, in (i, j) for scenario I, and in (k, l) for scenario J and for the FAA method in (m, n) for scenario A, and in (o, p) for scenario C.

1

2

3

4

Supplementary Fig. 1. Fishing mortality rates by gear and zone in the absence of closures.

5

Supplementary Fig. 2. Growth rates by zone.

1

2

3 Supplementary Fig. 3. Time-trajectories of spawning biomass relative to unfished spawning
 4 biomass by zone (10, 20 and 30, left, center, and right columns). Results are shown when
 5 growth does not vary spatially (scenarios A and C) and when growth varies spatially
 6 (scenarios E and G). The solid line is the distribution median, the dark shading covers the
 7 central 50% of the distributions and the light shading 90% of the distributions. The vertical
 8 red line denotes when the management strategy is first applied, and the red and green
 9 horizontal lines are respectively the limit and target reference points. The results in this
 10 figure are based on the FAA assessment method.