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Incorporating Habitat Suitability into Productivity Estimates for Sea Scallops in Scallop Fishing Area 29 West

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ABSTRACT

In 2014, a framework assessment was conducted for Scallop Fishing Area (SFA) 29 West (W) and a new approach for modelling the population dynamics of sea scallop was adopted. This new approach incorporated measures of differing productivity by scallop habitat suitability areas into the Bayesian state-space, size-based model that has been used for the Bay of Fundy, Georges Bank, and Browns Bank scallop assessments. However, the definition of Precautionary Approach (PA) reference points in the context of a habitat based model was not resolved for the 2014 assessment. Further, the problem of how to predict the allocation of effort by the fishery to the different habitat suitability areas to model short term yield for fishing plans and long term yield for the definition of reference points needed to be solved.

A new model for the spatial allocation of fishing effort has recently been developed that links relative fishing intensity to habitat suitability and scallop density. In addition to providing the means to predict the fishing pattern by habitat suitability areas for short and long term yield, the results of fitting this model to SFA 29W scallop showed that reference points were best defined in terms of the productivity of the High suitability areas only. Candidate reference points are proposed here for subareas B, C, and D in SFA 29W, for further discussion by the fishing industry and management.

Intégration des habitats propices aux estimations de la productivité des pétoncles géants de la zone de pêche du pétoncle 29 ouest

RÉSUMÉ

En 2014, une évaluation du cadre de travail pour la zone de pêche du pétoncle (ZPP) 29 ouest (O) a été réalisée et une nouvelle approche de modélisation des dynamiques des populations de pétoncles géants fut adoptée. Cette nouvelle approche a intégré des mesures de différentiation de la productivité en fonction des zones d'habitat propices de pétoncles au modèle bayésien de type état-espace basé sur la taille qui avait été utilisé pour l'évaluation des pétoncles de la baie de Fundy, du banc de Georges et du banc de Browns. Cependant, la définition des points de référence de l'approche de précaution dans le contexte d'un modèle basé dur l'habitat n'a pas été résolu dans le cadre de l'évaluation de 2014. De plus, la question de savoir comment prévoir la répartition des efforts de pêche par différentes zones d'habitats propices à des fins de modélisation a permis, à court terme, de mettre en place des plans de pêche et à long terme, de résoudre le problème de la définition des points de référence nécessaires.

Un nouveau modèle pour la répartition spatiale des efforts de pêche a récemment été élaboré; ce dernier fait le lien entre l'intensité relative de la pêche et les habitats propices et la densité de pétoncles. En plus d'avoir fourni des moyens pour la prévision des profils de pêche en fonction des zones d'habitats propices à court et à long terme, les résultats d'adaptation de ce modèle à la zone de production de pétoncles 29 O a montré que les points de référence étaient mieux définis en fonction de la productivité des habitats propices seulement. Dans le présent document, des points de référence possibles sont proposés pour les sous-secteurs B, C et D de la ZPP 29 O aux fins de discussion par la direction et l'industrie de la pêche.

INTRODUCTION

A new approach to modelling the population dynamics of sea scallops in Scallop Fishing Area (SFA) 29 West (W) was introduced in the Fisheries and Oceans Canada (DFO) Canadian Science Advisory Secretariat (CSAS) framework meeting in February 2014 (Smith et al., 2015), and was used to provide stock assessment advice for the 2014 fishery (Sameoto et al., 2014). This approach incorporated measures of differing productivity by scallop habitat suitability areas as per Brown et al. (2012) into the Bayesian state-space, size-based model that has been used for the Bay of Fundy, Georges Bank and Browns Bank scallop assessments (Hubley et al., 2013; Nasmith et al., 2013). Two issues were left outstanding from the 2014 framework meeting. The first was the definition of reference points for the determination of current stock status within the context of the DFO implementation of the Precautionary Approach (PA)[1]. The usual application of this approach assumes that there is one biomass indicator for stock productivity to be used to define reference points, but the model developed in the framework actually had biomass estimates for each habitat suitability area and it was not clear whether to just use the biomass from one habitat suitability area or from a combination of areas. The second issue was the need to understand how the fishery allocated effort to the different habitat areas that were used in the model to predict long-term yield for the definition of the reference points. The actual spatial allocation of fishing effort is available each year from the Vessel Monitoring System (VMS) data and commercial log data collected from the fishery. However, any determination of long-term productivity needs to be able to predict how effort will be allocated in the future over a range of situations.

Smith et al. (2016) presented a model for the spatial allocation of fishing effort that not only can be used to predict long-term yield but also clarifies how to define the reference points for this fishery. This method is used here to develop proposed reference points for subareas B, C and D in SFA 29W. The data on shell height growth, meat weight yield, mortality and recruitment required for this approach are investigated in terms of how they reflect the varying productivity evident in the stock assessment model results for the different habitat suitability areas. More work is needed on subarea A, as this area has very little of the High habitat suitability areas that exists in the other subareas that is key to the approach presented here. Unfortunately, no results are available for subarea E due to the lack of survey data covering the whole period of the fishery, and this area was not covered by the habitat suitability map.

HABITAT SUITABILITY RELATIONSHIPS

FISHING EFFORT

The locations on the VMS records were matched with the habitat suitability measures binned into 10 intervals of width 0.1. The VMS effort hours were totaled by bin and then standardized by the associated area of the bin since bin areas differed (i.e., hours/km^2). Fishing effort per area, or fishing intensity, was consistently higher in the higher habitat suitability areas for all of the subareas, except subarea A where the extent of the higher habitat suitability areas was limited (Figures 1-4). This pattern of higher fishing intensity in the higher habitat suitability areas continued to be the case even as catches declined over time.

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[1] See A Fishery Decision-Making Framework Incorporating the Precautionary Approach for background documents on precautionary approach for Canadian fisheries (accessed on October 6, 2015).

Most fishery models assume that all individuals of commercial size in the fished population are equally vulnerable to being caught (Beverton and Holt, 1957). Catch is expected to result from the application of a single exploitation or fishing mortality rate to the fished population as a whole. For age-based fishery models, selectivity curves are used to apportion fishing mortality over different age groups that may not be equally at risk, and a similar approach has been suggested for spatial components that have different vulnerabilities to fishing by age (Sampson and Scott, 2011). A selectivity curve approach has not been used for scallops in SFA 29W because the model is stage-based, and not age-based, reflecting only the dynamics of the scallops recruiting to the fishery in the following year and those scallops already of commercial size.

The strong relationship between the VMS effort and habitat suitability presented in Figures 1-4 suggests a different approach to explore modelling spatial patterns of fishery exploitation. Smith et al. (In press) defined three models to describe the spatial pattern of fishing effort over the area being fished. The Area model corresponds to the uniform fishing mortality model described in Beverton and Holt (1957), which predicts that fishing effort at location h ($h, 1, \ldots, H$), E_h, will be proportional to the area (A_h) of that location. That is,

$$\frac{E_h}{A_h} = \frac{\sum_h^H E_h}{\sum_h^H A_h} \tag{1}$$

Therefore, fishing intensity $f_h = E_h/A_h$, is constant at any location h.

The Density model predicts that fishing effort at location h will be proportional to the density, D_h at that location (Caddy, 1975). This model can be expressed as,

$$f_h = \frac{D_h \sum_h^H E_h}{\sum_h^H D_h A_h} \tag{2}$$

In this case, fishing intensity will be proportional to the relative density at location h and will exhibit an increasing linear relationship with increasing relative density.

In SFA 29W, the relative density estimates were obtained from the annual surveys, and the annual spatial coverage of these surveys limited the habitat suitability categories to Low, Medium and High (Smith et al. 2015). The VMS effort data were similarly categorized (Figure 5). Analysis of these fishing intensity and density data suggested the following variant of the Density model referred to as the Habitat model in Smith et al. (2016).

$$f'_{ht} = \begin{cases} \alpha_h\,, \text{ subarea A} \\ \alpha_h + \beta \dfrac{D_{h,t-1}}{\sum_h^H D_{h,t-1} A_h}, \text{ subareas B, C, and D} \end{cases} \tag{3}$$

where $f'_{ht} = f_{ht} / \sum_h^H E_{ht}$, represents relative fishing intensity for year t. Fishing intensity in year t is scaled by total effort for that year to remove the effect of changes in annual total effort due to management measures possibly unrelated to changes in population biomass. The relative biomass density for year $t-1$, which includes both commercial and recruit size scallops, was used as an indicator of the biomass that would be available at the time of the fishery. Relative fishing intensity for subareas B, C, and D was directly related to the relative density present in all habitat suitability areas with an added “habitat” component, α_h. This component indicates that even when relative densities are similar over the three habitat suitability areas, more effort will be directed to the High rather than to the Medium suitability areas, which in turn will receive more effort than the Low suitability areas (Figure 6).

SHELL HEIGHT GROWTH

The relationship between shell height and age is obtained by fitting a von Bertalanffy growth model to shell height and shell annual ring data collected as part of the detail samples during the survey. On average, half of the survey tows in any one year were sampled for shell height and meat weight data. The possible relationship between the parameters of the growth model and habitat suitability was investigated using a nonlinear mixed-effects model with survey tow within years as the grouping factors.

$$H_{ijk} = \left(L_{\infty} - l_{\infty jk}\right)\left(1 - \exp\left(-\left(\exp(K') - \exp\left(k'_{jk}\right)\right)\left(a_{ijk} - \left(T_0 - t_{0jk}\right)\right)\right)\right) \tag{4}$$

where,

H_{ijk} = Scallop shell height for shell *i*, from tow *j* in year *k*

a_{ijk} = Age in years for shell *i*, from tow *j* in year *k*

L_{∞}, $l_{\infty jk}$ = Fixed and random effects parameters for asymptotic shell height

K_0, k_{0jk} = Fixed and random effects parameters for the natural logarithm of the growth rate

T_0, t_{0jk} = Fixed and random effects parameters for the offset for initial shell height

Given that the habitat suitability information has only become available recently, the first 13 years of the survey did not use this information for the survey and sampling design and, as a result, very few detail samples were collected on bottom characterized as High habitat suitability. More detailed samples were obtained in the 2014 survey, which was designed using the habitat suitability data, and there do not appear to be any patterns in the random effects with respect to habitat suitability categories for that year (Figure 7). There was no apparent relationship between random effects and depth, but that was not surprising given that all depths sampled were less than the 90 m depth, at which Smith et al. (2001) identified a significant change in parameter estimates for the same type of growth model applied to the 1996 detailed samples in the Bay of Fundy survey. There were trends in random effects over the years with the last three years indicating slower than average growth (Figure 8).

The fixed effects parameter estimates for the von Bertalanffy growth model, along with the meat weight/shell height relationship (see below), were used to estimate the annual growth for the commercial and recruit biomass in the assessment model (Sameoto et al. 2015).

MEAT WEIGHT SHELL HEIGHT RELATIONSHIP

The relationship between meat weight and shell height is used to convert numbers caught in the survey to weights for the stock assessment model. Previous stock assessments (e.g., Sameoto et al., 2014) have noted that this relationship can vary over years, resulting in varying yield usually presented as the expected meat weight for a 100 mm scallop (also referred to as condition), which can in turn result in higher or lower mortality on numbers of scallops for the same catch measured in weight (meats). A generalized linear mixed effects model was used to investigate relationships between the meat weight/shell height relationship and habitat suitability. The model assumes a gamma distribution, log link and linear predictor as follows.

$$E(W_{ij}) = \exp\left((\beta_0 - b_{0j}) + (\beta_1 - b_{1,j})\log(H_{ij})\right) \quad (5)$$

Where,

H_{ij} = Scallop shell height for shell *i*, from tow *j*

W_{ij} = Meat weight for shell *i*, from tow *j*

β_0, b_{0j} = Fixed and random effects for intercept

β_1, b_{1j} = Fixed and random effects for slope.

As with the shell height growth, the low number of samples from the High suitability bottom from 2001 to 2013 is a problem for the analysis of meat weight/shell height. Analysis of the 2014 data does not indicate a strong relationship with the habitat suitability categories (Figure 9). However, there were relationships with depth in many of the years for either or both of the slope and intercept (Figures 10-11). Meat weight at shell height declined with depth (except for 2002 and 2003) in some years more than others (see Table 1). Declining meat weight at shell height with depth is a trend that has been noted for sea scallops in general (e.g., Hennen and Hart, 2012; and references therein).

NATURAL MORTALITY

Clappers (joined empty shells) caught during the survey are used to monitor natural mortality for the scallop assessment model (see Smith and Lundy, 2002). The ratio of clappers to live scallops in a year has been used as a rough first estimate of mortality. Comparisons of total clapper and live scallops by year and habitat type for each subarea in SFA 29W do not indicate a possible relationship between mortality and habitat type (Figure 12) beyond the fact that the ratio of clappers to live will be higher at the higher abundances and the higher abundances tended to occur in the High suitability habitat. However, the lower ratio between low abundance compared to the higher ratio at higher abundances suggests that there may be density dependence effects. The higher mortality rates estimated in the model tended to occur at the beginning of the time series when abundance and biomass were higher (Figure 13).

RECRUITMENT SURVIVAL

While stock/recruitment relationships are necessary for long-term yield calculations, such relationships have been difficult to demonstrate for scallop populations. Hart (2013) used the Beverton and Holt stock/recruitment model, which assumes that density dependence occurs at the larval or early life stages as a function of the density of scallops at these life stages, similar to the thinning noted for scallops during artificial seeding trials (e.g., Barbeau et al., 1996; Fréchette et al., 2013). The other major model that has been used for species other than scallops is the Ricker stock/recruitment curve, which assumes that any density-dependent mortality that may happen does so due to the density of older scallops where the juveniles are settling out onto the bottom.

Reliable quantitative estimates of year-classes that will eventually recruit to the fishery start at about age 3 in the survey and the recruits in the SFA 29W stock assessment model are age 4. These scallops have been exposed to a number of sources of mortality from the planktonic state to the time that they recruit to the fishery which will obscure any indication of year-class strength as a function of spawner abundance. However, it has been observed that for a number of scallop stocks locally and elsewhere, strong year-classes are rarely followed by other strong year-classes even though the high densities may result in higher fertilization rates. In addition, while strong year-classes have occurred during periods of low density, this is usually rare and more often than not recruitment tends to be weak at low densities. Constant average recruitment was assumed for developing reference points from long-term yield calculations for the Bay of Fundy scallop areas but this method may not adequately reflect what may happen at low densities because it assumes that no matter how low the density of scallop gets, production will always result in the mean recruitment.

Possible relationships between the year-class strength in terms of density at age 4, and the density of older animals in the area when this year-class was spawned and settled, was investigated for survey and model estimates by habitat suitability and subarea in SFA 29W. While the time series only has 10 years of data that can be investigated this way because of the lag between recruits and older scallops, there does seem to be some evidence in the survey data for Ricker-like relationships for subareas C and D that indicate that overall recruit survival tends to increase for the higher suitability areas (Figure 14). The fit of the Ricker model to the subarea B data was significant and did reflect the relationship with habitat suitability; however, the lack of data on medium to high densities of spawners resulted in curves with very high recruit levels at the low densities of spawners. This will result in these very low densities having high productivity which, in turn will, suggest that subarea B can be fished at very high exploitation levels contrary to experience to date (e.g., Figure 39 in Sameoto et al., 2015). The fit of the Ricker models to the data in subarea A was not significant. Similar results were obtained from model-based estimates where adults were defined as scallops with shell heights 90 mm and above to correspond to the size ranges used in the model (Figure 15). The results of these model fits are interpreted here to indicate that while all spawners in one or all of the habitat suitability areas contribute to the year-class recruiting to the population, density dependent survival appears to be linked to habitat suitability areas. In addition, low densities tended to occur at the same time in all areas and lead to low production of recruits in most cases. For the purposes of the analysis here, the lack of data on medium and high densities for subarea B were approximated by using curves fit to the data from all of the subareas.

YIELD ESTIMATES

EVALUATING NEXT YEAR’S CATCHES

Forecasting the impact of different levels of catches for the upcoming year (i.e., 2015 in this instance) only requires the results from the model for the current year along with the posterior distributions for the model components. The model was run forward one year using current estimates of biomass, mortality, recruits and growth, with catch determined according to a range of exploitation values. The Habitat model (Equation 3; Smith et al., 2016) was used to apportion fishing intensity over habitat suitability areas based on the current year relative densities. As noted above, condition varies unpredictably from year-to-year and the condition for 2015 is unknown. The current year’s condition is used for the forecast. The impact of assuming the current year condition for the forecast was evaluated in the stock assessment of Sameoto et al. (2015) by comparing forecasts for past years using current year estimates and known condition weights after the fact. Natural mortality is also unknown for the forecast year and currently the average natural mortality for the previous six years is used for the forecast. The results for subarea D presented here in Figure 16 are much improved over those presented in Figure 49 of Sameoto et al. (2014), mainly due to the addition of the Habitat model (Equation 3) and the six-year average natural mortality estimate for the forecast.

LONG-TERM YIELD

The definition of reference points requires the determination of productivity over the long-term, so that the equilibrium biomass and corresponding catch can be determined for a range of exploitation rates. The equilibrium point is determined by running the assessment forward for a number of years (100-years in this paper) until the biomass stabilizes for a specified constant exploitation rate. Currently, this determination is based on posterior mean estimates, and mean growth and yield, and posterior mean estimates of natural mortality for 2009 to 2014. Posterior distributions have not been incorporated into these calculations at time. Fishing in future years was modelled using the Habitat model. The exploitation rate that results in the maximum catch was used to determine the biomass (density) used for establishing reference points.

Results from one such run for subarea D and an exploitation of 0.1 on the High suitability areas for the Habitat density and Density fishing models are presented in Figure 17. The Area model was also used with an exploitation rate of 0.1 everywhere along with the Habitat model with the exploitation rate set to 0.17 on the High suitability areas, which resulted in an exploitation rate of 0.1 overall. The two density-based models with exploitation equal to 0.1 for the High areas resulted in similar catches to the Area model but at a higher biomass and catch rate than the Area model. As noted earlier, the Area model is the default for most stock assessment models but will present misleading expectations if fishing intensity is actually allocated according to the Habitat model. If the former approach is used to set the quota, the latter will result in a lower population biomass and catch than expected for the area approach even though the catch rate and the exploitation over all areas will be the same.

The equilibrium results for a range of exploitation rates including 0.0 for subareas B, C and D are presented in Figures 18-20. The arrows on the figures indicate the exploitation rate on the High habitat suitability areas, which are associated with the biomass density in the High habitat suitability areas associated with the maximum catch in the High suitability areas. Note that the maximum total catch for subarea B peaks at a much higher exploitation rate than for the High area alone, but at a lower total area catch rate than would be expected when fishing at the maximum catch for the High area. The areas associated with the Medium and Low suitability areas in subarea B are twice what they are in the other two subareas leading to a much larger portion of the biomass in this area that could be fished if catch rate was not limiting.

The densities for the maximum catches are similar over the three subareas, ranging from 3.75-4.68 t/km^2 (Table 2). However, the exploitation rates for subareas B and C are lower than for subarea D, indicating lower productivity rates in the first two subareas. Differences in the recruit survival curves (Figure 15) may be having an effect here.

MANAGEMENT SCENARIOS

The DFO Precautionary approach guidelines suggest setting the Lower (or Limit) Reference Point (LRP) and the Upper Stock Reference (USR) point at 40% and 80% of the stock index, respectively, associated with stock productivity. In this case, biomass density in the High suitability areas for the stock index is used, and the resulting LRP and USR are given in Table 3. The High habitat suitability area was chosen to set the exploitation and biomass density reference points for each subarea because the Habitat model ties all of the different suitability areas together into one relationship. Preventing overfishing in the High suitability areas will also do so for the Medium and Low suitability areas, while preventing overfishing in one of the other two areas will result in overfishing of the High suitability areas.

The posterior distributions of biomass densities for 2015, assuming no catch (exploitation equal to 0.0), were used to evaluate stock status in each subarea with respect to these candidate reference points. The commercial size biomass densities for subareas B and C are both below the LRP with high probability, while commercial size biomass densities for subarea D is above the LRP but is below the USR. Comparison of these candidate reference points with the time series for commercial size biomass densities (High) for each of the subareas indicate that the stocks have been in the cautious zone since 2006 in subarea B, 2010 in subarea C, and 2008 in subarea D (Figure 21). Exploitation rates in the High habitat suitability areas have averaged 0.20 for subarea B since 2006, and 0.15 and 0.24 for subareas C and D, respectively, since 2010 (see Figure 39 in Sameoto et al., 2015)[2]. All of these exploitation rates are much higher than the rates corresponding to maximum catch for these areas (Table 2) and, based on the analysis presented here, are not sustainable in the long-term.

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[2] Note: Exploitation was equal to 0 in 2014 for subareas C and D.

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TABLES

Table 1. Meat weight/shell height parameters for the generalized linear mixed effects gamma model fit to survey data for scallops in SFA 29W. Parameters β_0 and β_1 are as defined in text. Log(Depth) was added as a fixed effect only using either a first or second degree polynomial (β_2 and β_3, for linear and quadratic terms, respectively) and an interaction term with the slope and linear ($\beta_{1,2}$) or slope and quadratic ($\beta_{1,3}$) or both. Meat weight by depth predicted for 100 mm shell height. A dash (-) indicates no value.

Year	**Fixed effects**						**Random effects**		**Residual**	**Meat weight (g)**		
	β_0	β_1	β_2	β_3	β_{12}	β_{13}	σ_{b0}	σ_{b1}	σ_R	**35 m**	**55 m**	**80 m**
2001	2.50	2.98	-0.14	-	-	-	0.04	0.12	0.16	12.6	11.8	11.2
2002	2.27	2.85	-	-	-	-	0.06	0.16	0.15	10.5	10.5	10.5
2003	2.43	2.72	-	-	-	-	0.08	0.16	0.15	11.2	11.2	11.2
2004	2.71	2.76	-0.13	-	-	-	0.06	0.25	0.13	11.3	10.6	10.1
2005	2.71	2.73	-1.17	-1.60	-	-	0.05	0.17	0.16	11.7	11.3	7.3
2006	2.85	2.81	-1.77	-1.32	-	-	0.05	0.11	0.13	12.3	12.8	9.3
2007	2.57	2.98	-1.66	-1.83	-2.99	-4.06	0.05	0.07	0.18	12.3	12.2	8.9
2008	2.75	2.87	-0.39	-	-	-	0.04	0.09	0.15	13.6	11.4	9.8
2009	2.70	2.92	-0.78	-	-	-	0.06	0.07	0.15	16.3	11.5	8.6
2010	2.85	2.76	-0.08	-	-	-	0.06	0.16	0.15	12.7	12.2	11.8
2011	2.78	2.64	-1.27	-0.73	-	-	0.04	0.21	0.15	11.3	10.6	9.5
2012	2.80	2.86	-2.94	-1.56	-2.00	-4.51	0.04	0.10	0.17	13.9	12.3	9.9
2013	2.81	2.97	-3.41	-0.89	-4.35	-5.10	0.08	0.16	0.15	14.5	12.7	10.6
2014	2.55	2.64	-1.24	-2.01	-	-	0.06	0.19	0.17	10.6	10.5	7.7

Table 2. Maximum sustainable catch indicators by subarea based on long-term yield calculations for SFA 29W.

Indicators	**Subarea B**	**Subarea C**	**Subarea D**
Exploitation (High Suitability areas)	0.06	0.06	0.09
Density (t/km2, High Suitability areas)	3.75	4.68	4.32
Catch rate (kg/h, subarea)	29.88	25.46	38.31
Catch (High Suitability areas)	12.50	8.75	21.83
Catch (subarea)	30.41	21.00	42.50

Table 3. Precautionary approach candidate density reference points by subarea based on long-term yield calculations for SFA 29W.

Candidate Density Reference Points	**Subarea B**	**Subarea C**	**Subarea D**
Density 2015 (e=0)	1.42	1.29	2.11
LRP(40%D_{MSY})	1.50	1.87	1.73
Prob($D_{High, 2015}$>LRP)	0.47	0.35	0.64
USR(80%D_{MSY})	3.00	3.74	3.46
Prob($D_{High, 2015}$>USR)	0.14	0.14	0.19

FIGURES

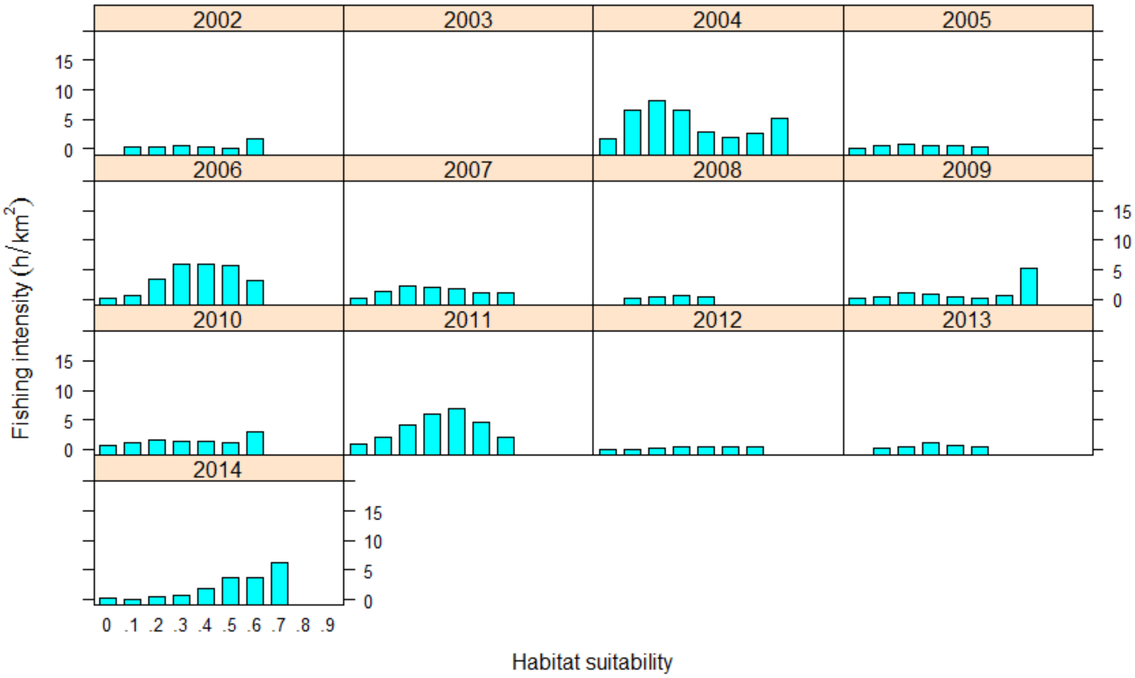

Figure 1. Fishing intensity (h/km^2) derived from VMS data binned by 0.1 categories of habitat suitability probabilities for subarea A in SFA 29W from 2002 to 2014. There were no suitability bins ≥ 0.8 in this subarea.

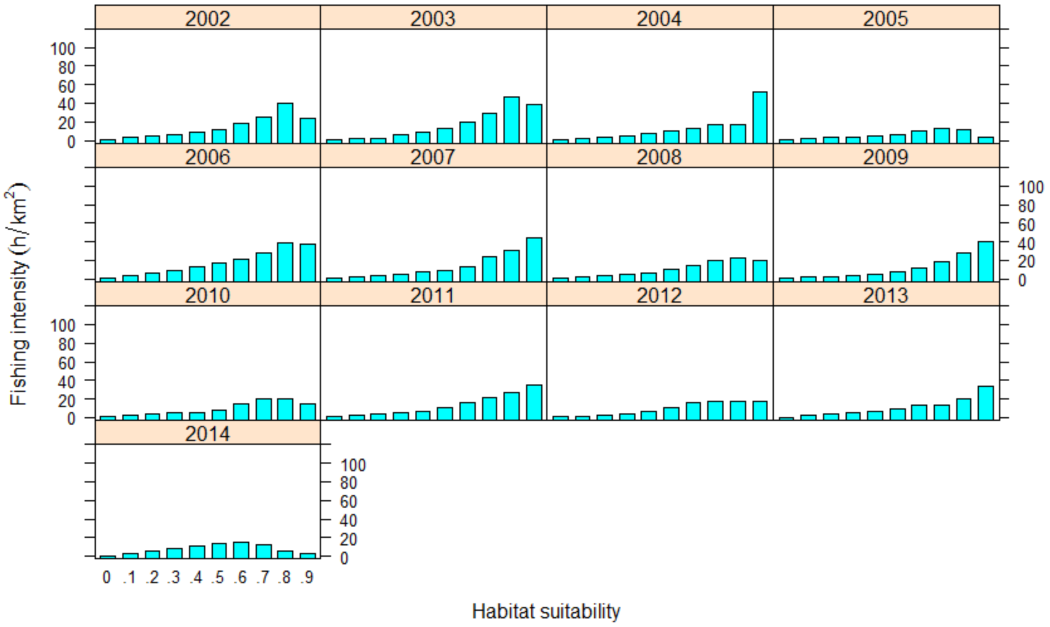

Figure 2. Fishing intensity (h/km^2) derived from VMS data binned by 0.1 categories of habitat suitability probabilities for subarea B in SFA 29W from 2002 to 2014.

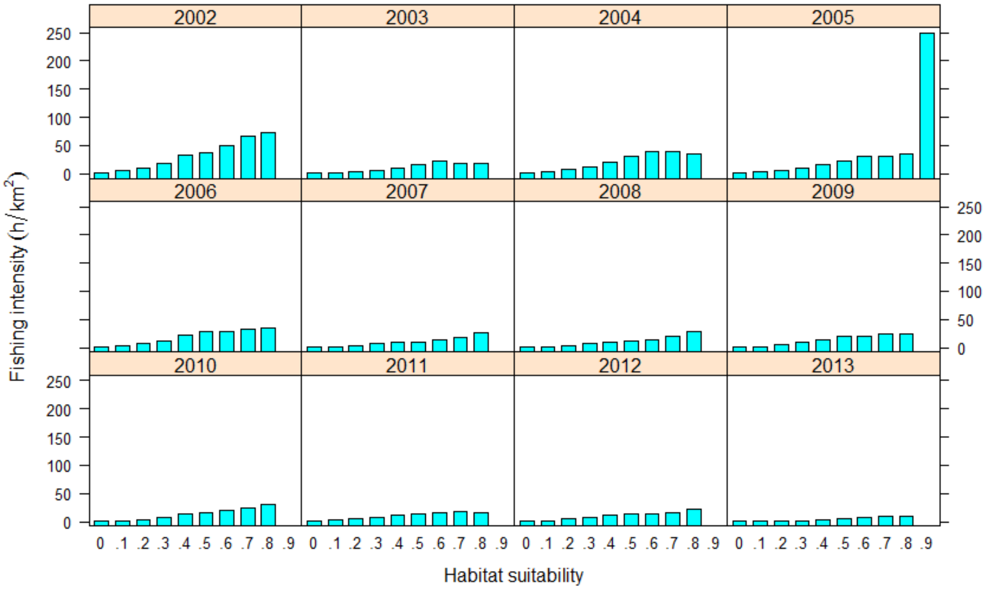

Figure 3. Fishing intensity (h/km^2) derived from VMS data binned by 0.1 categories of habitat suitability probabilities for subarea C in SFA 29W from 2002 to 2013. This area was closed to fishing in 2014 (Sameoto et al., 2015).

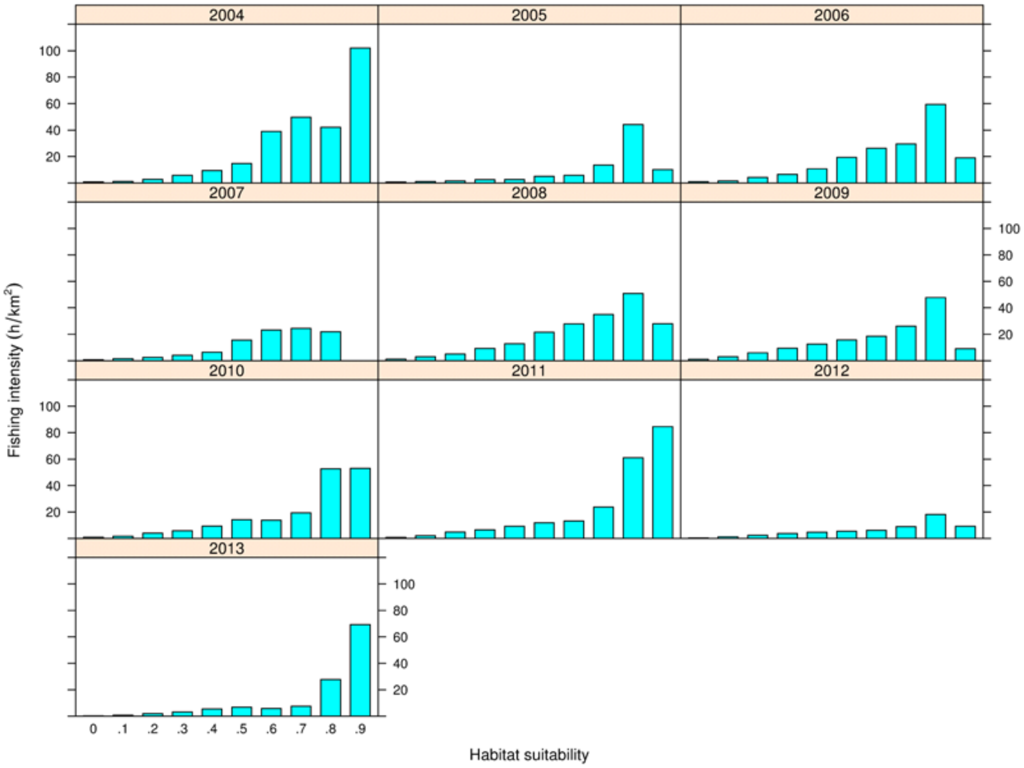

Figure 4. Fishing intensity (h/km2) derived from VMS data binned by 0.1 categories of habitat suitability probabilities for subarea D in SFA 29W from 2002 to 2013. This area was closed to fishing in 2014 (Sameoto et al. 2015).

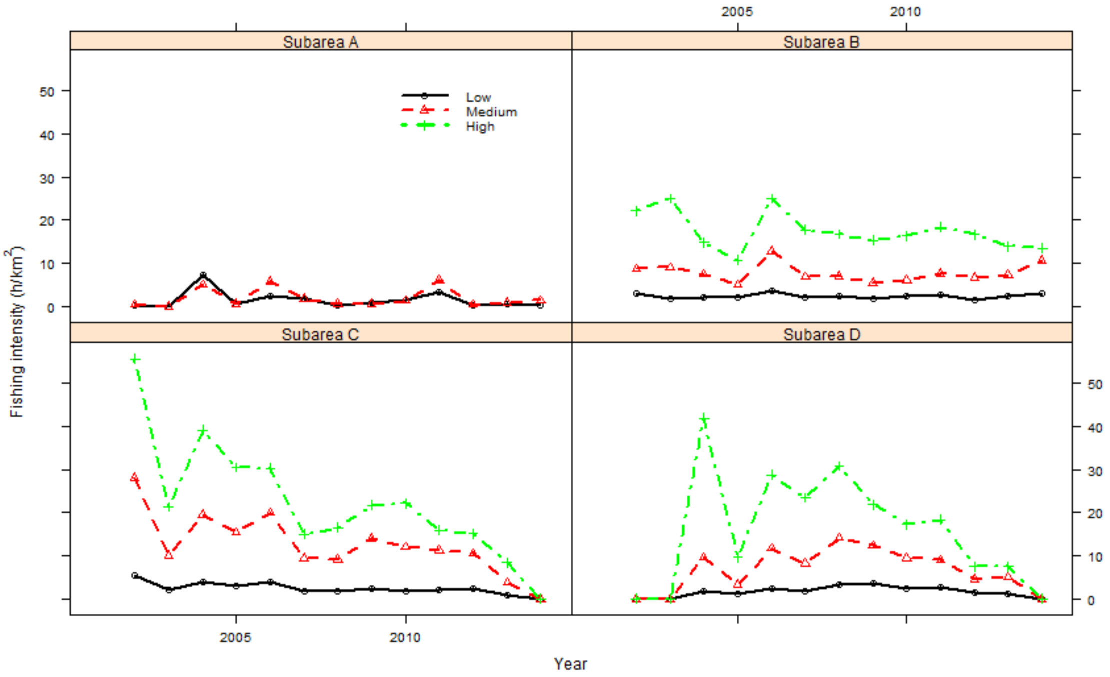

Figure 5. Fishing intensity (h/km^2) derived from VMS data binned by Low [0,0.3), Medium [0.3,0.6) and High [0.6,1.0) areas of habitat suitability probabilities by subarea for SFA 29W.

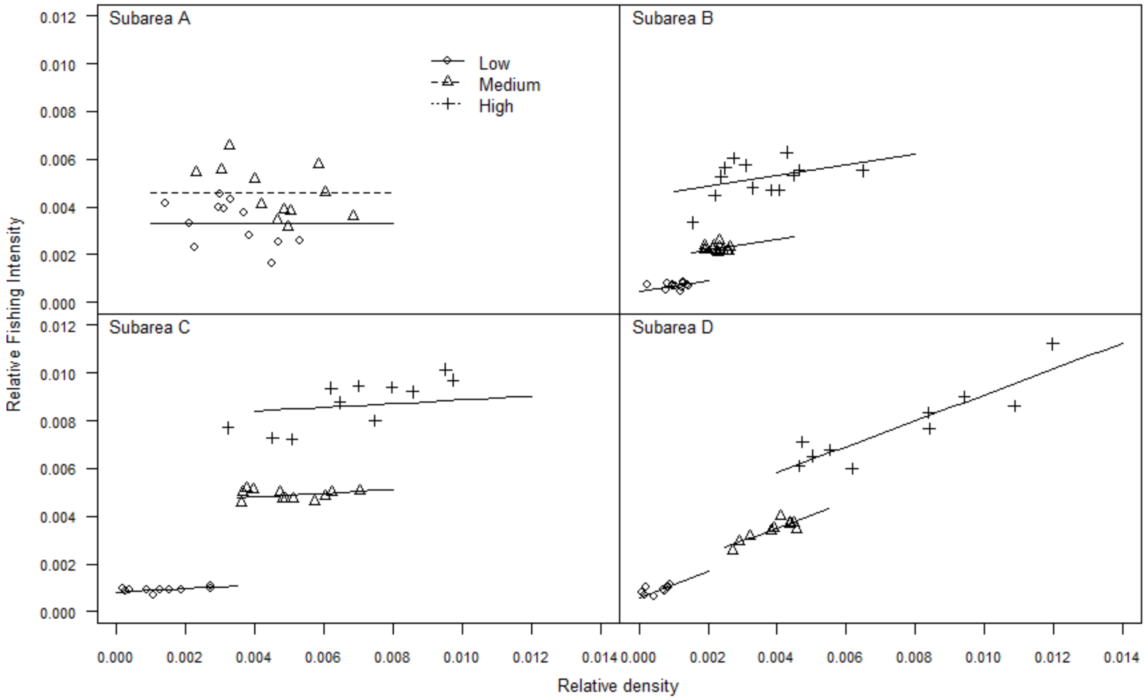

Figure 6. Comparison of relative fishing intensity with relative biomass density estimated from the stock assessment model for scallops in subarea A-D in SFA 29W.

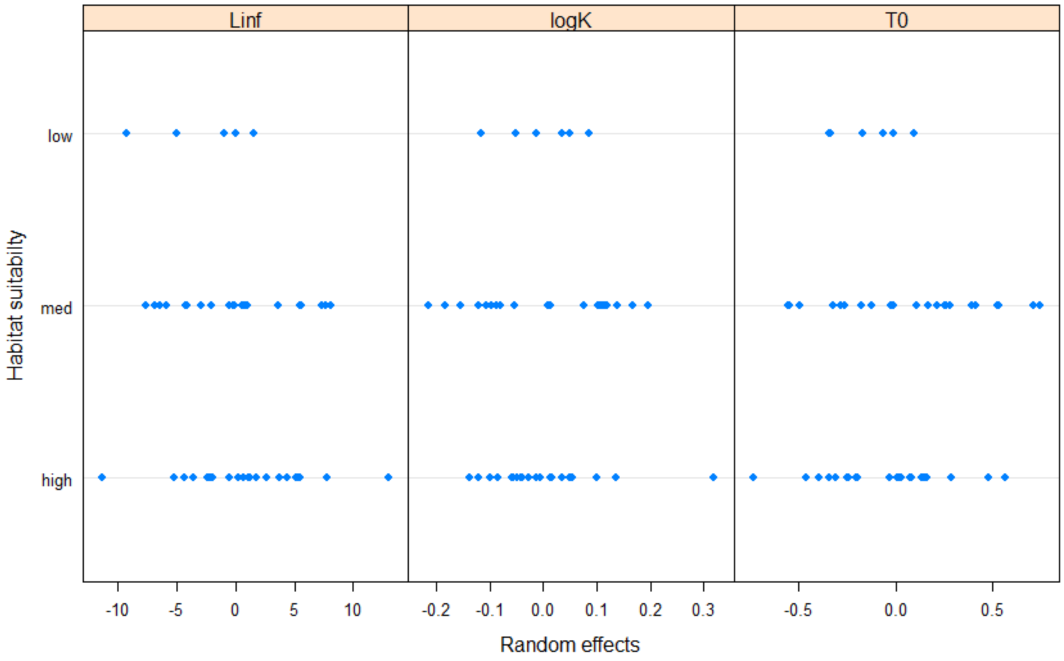

Figure 7. Random effects for von Bertalanffy growth model parameters L_∞, log(k) and t_0 by habitat suitability areas for scallops in SFA 29W in 2014.

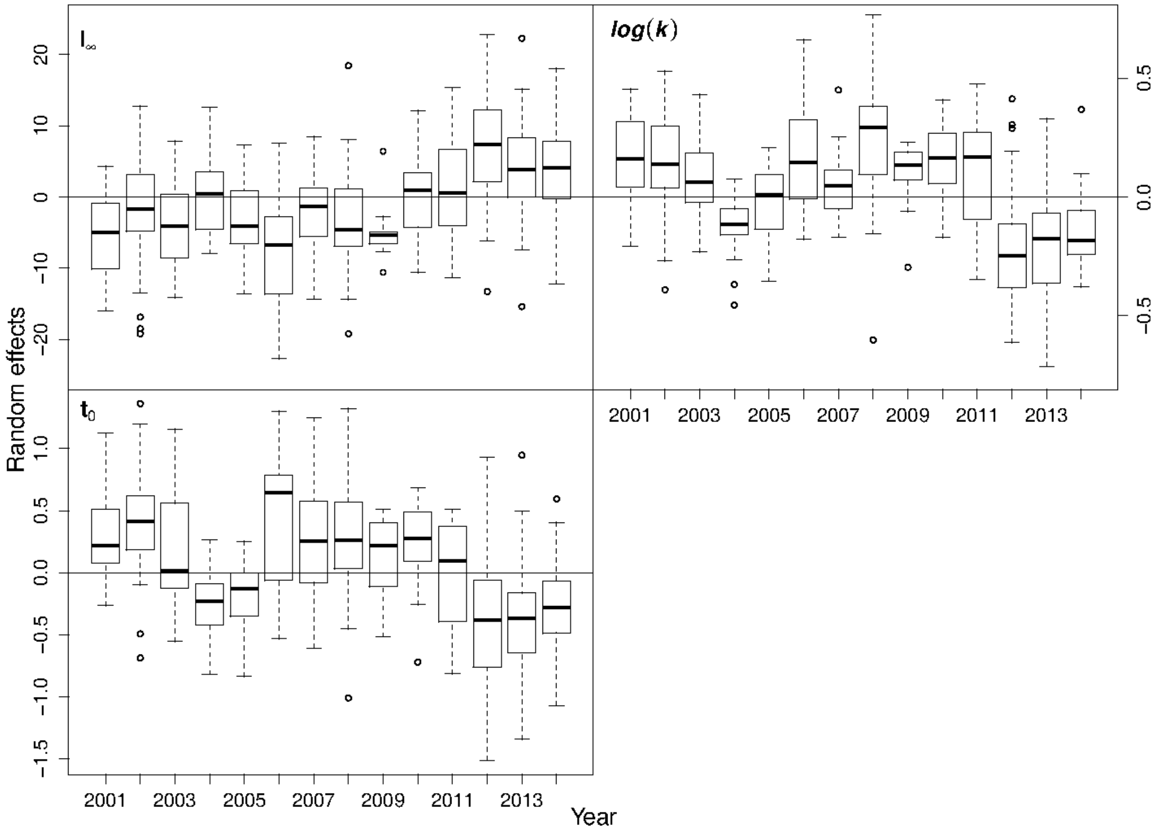

Figure 8. Random effects for von Bertalanffy growth model parameters L_∞, log(k), and t_0 by year for scallops in SFA 29W.

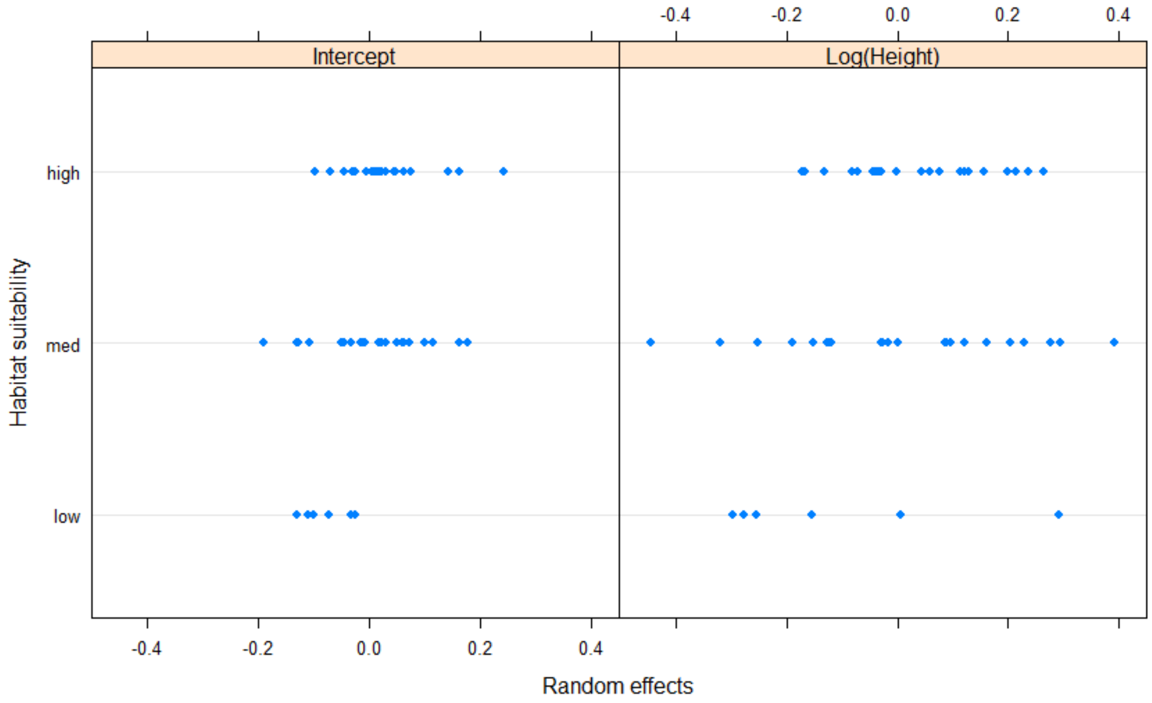

Figure 9. Random effects from meat weight/shell height model for the intercept term (b_{0j}) and slope (b_{1j}) by habitat suitability for scallops in SFA 29W in 2014.

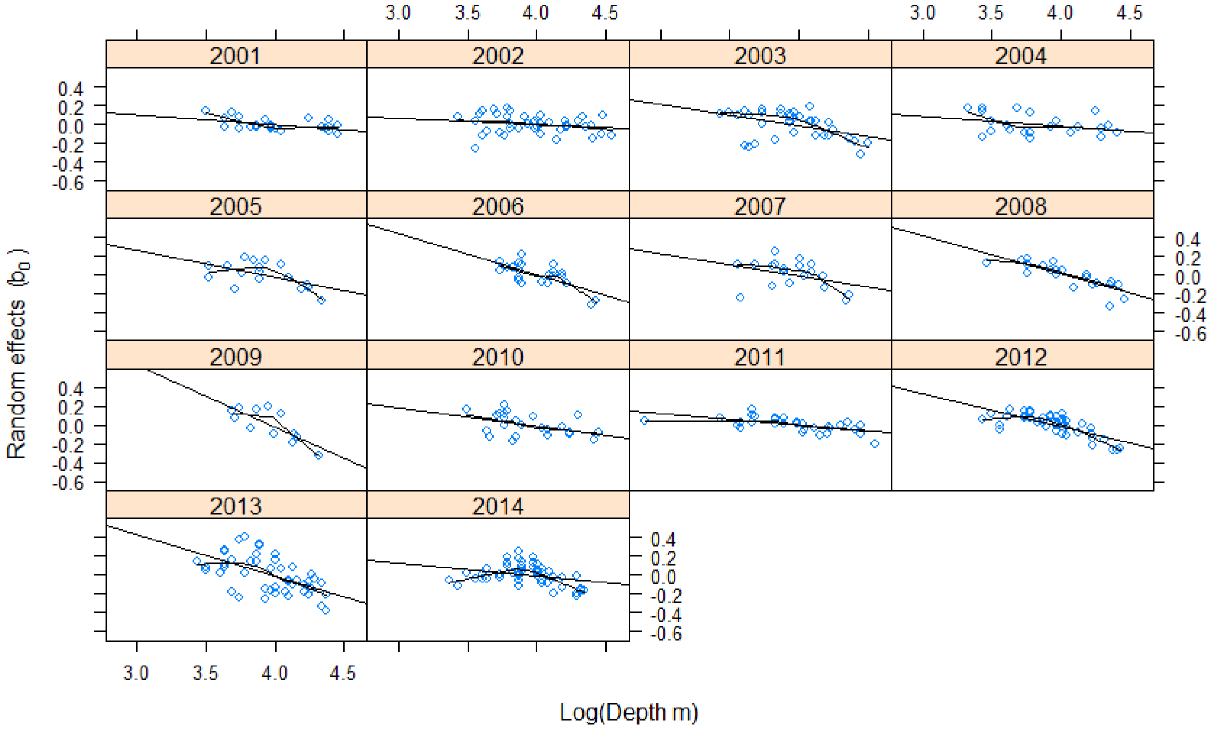

Figure 10. Random effects from meat weight/shell height model for b_{0j} vs. log(Depth) for scallops in SFA 29W.

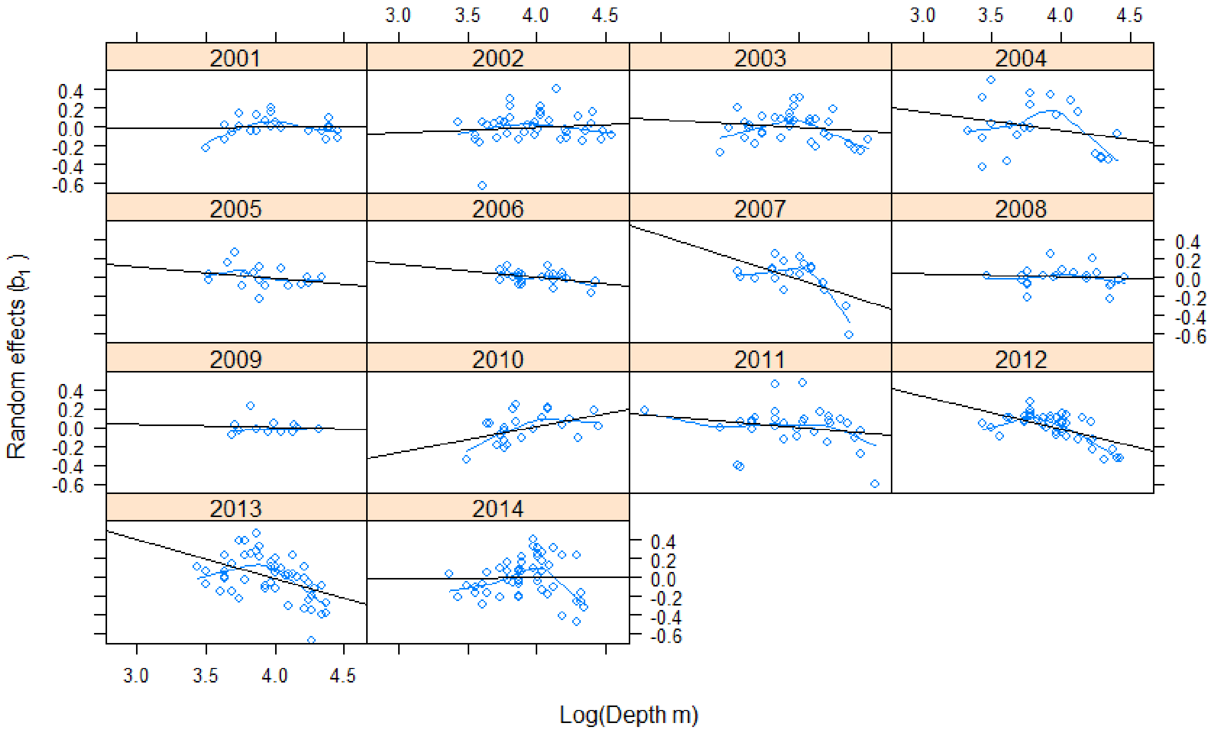

Figure 11. Random effects from meat weight/shell height model for b1j vs. log(Depth) for scallops in SFA 29W.

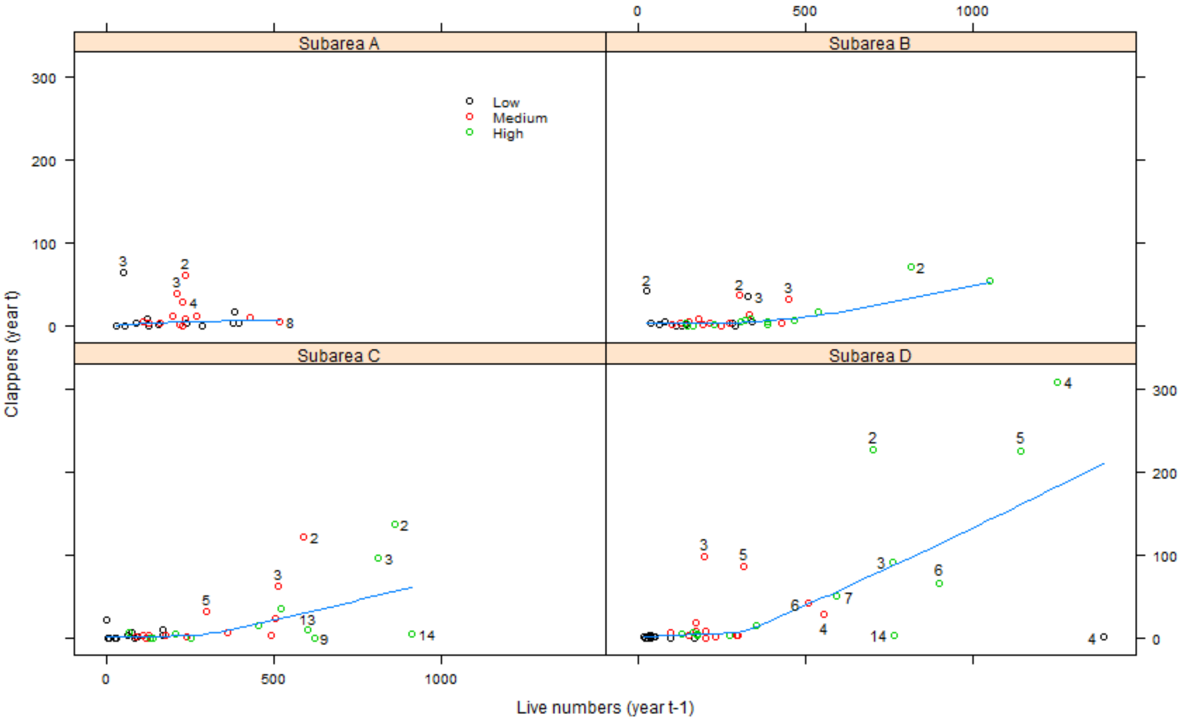

Figure 12. Clappers in year t vs. live numbers of scallop in year t-1 from the survey (all sizes) by habitat suitability areas in SFA 29W. Year of survey indicated for a number of estimates (e.g., 2002 = 2).

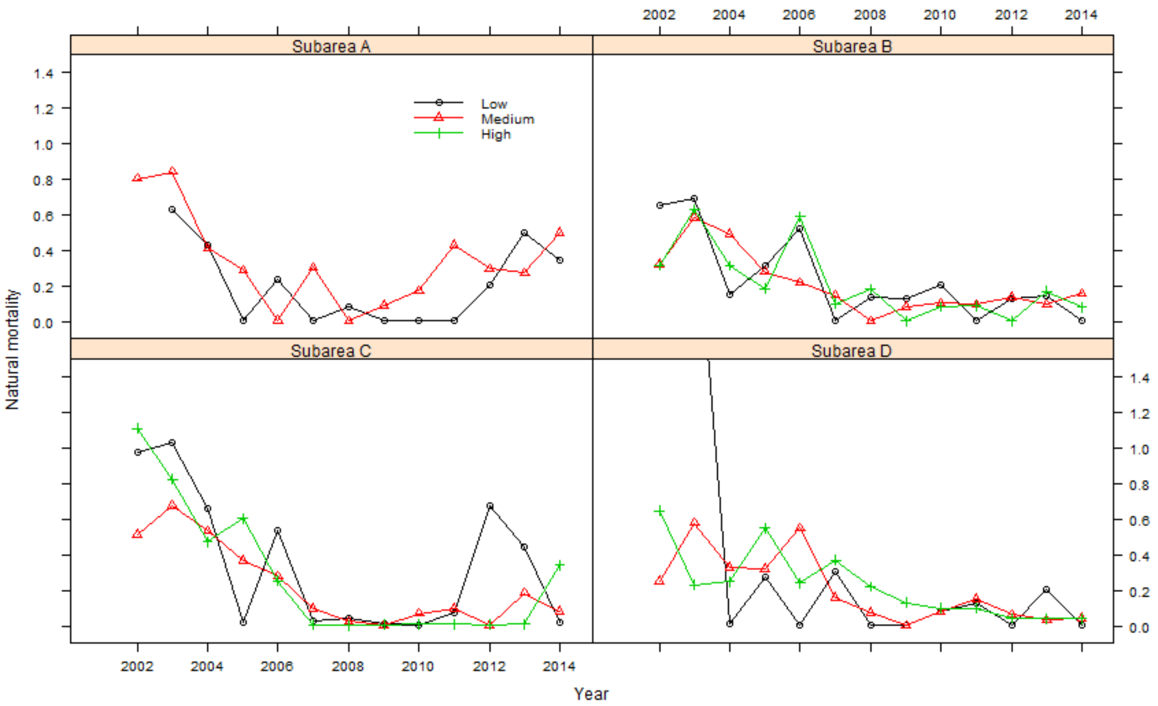

Figure 13. State-space model estimate of natural mortality for commercial size scallops by Low [0, 0.3), Medium [0.3, 0.6) and High [0.6, 1.0) habitat suitability probabilities for subareas A-D in SFA 29W. Estimates were 2.4 for 2002, 2003 in the Low habitat in subarea D.

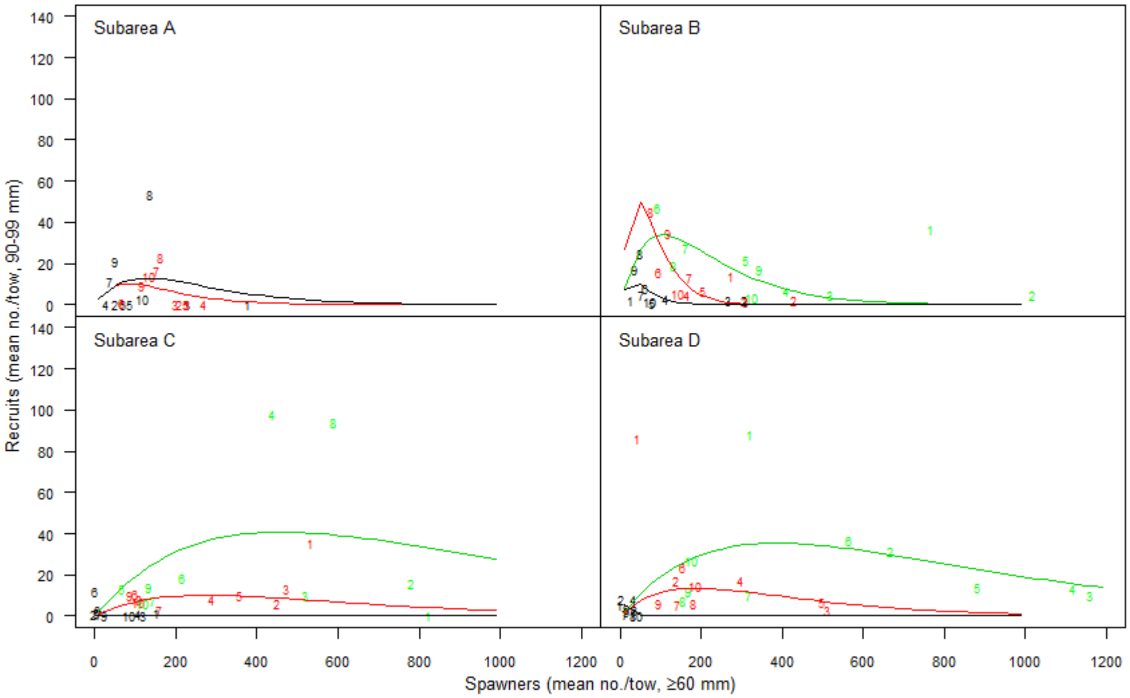

Figure 14. Recruit (90–99 mm) numbers per tow vs. adult (60+ mm, lag = 4 years) numbers per tow by habitat suitability from the survey for subareas A-D in SFA 29W. The numbers labelling the points in the panels refers to the year (e.g., 2001 = 1) that the recruits were spawned.

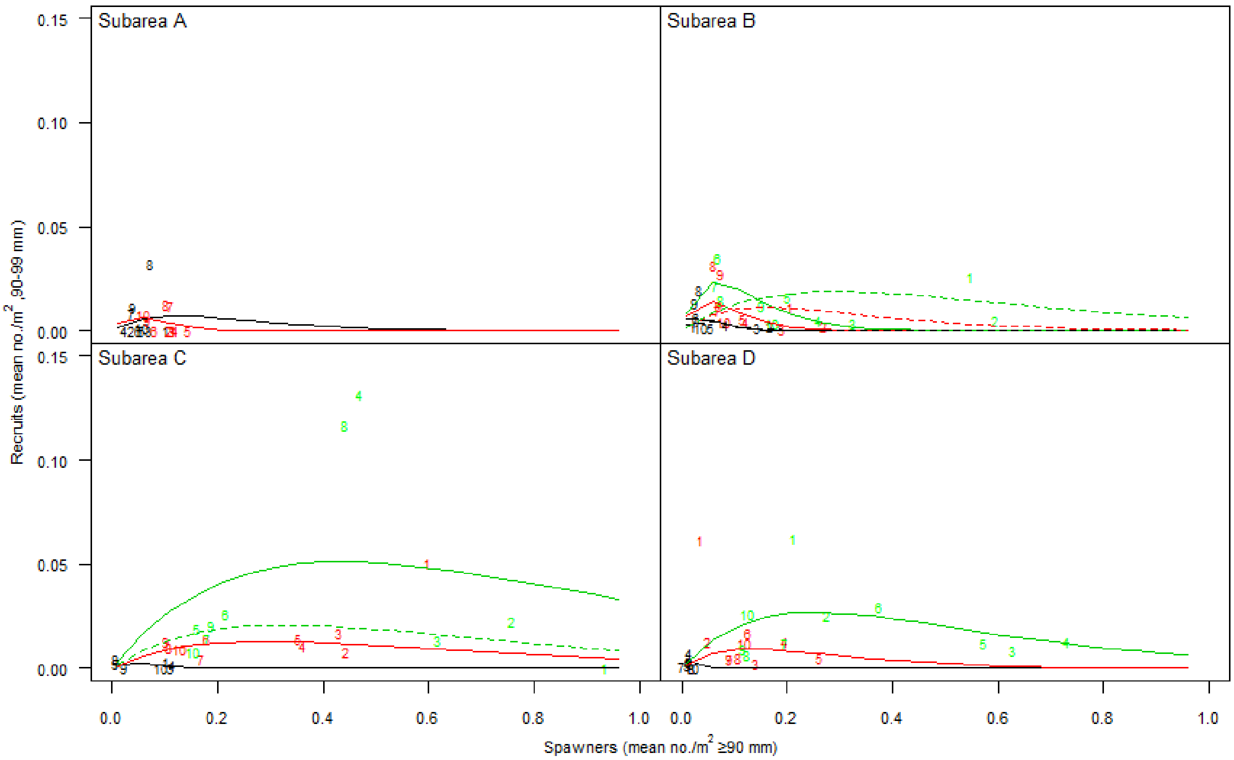

Figure 15. Recruit (90–99 mm) density (numbers/m^2) vs. adult (90+ mm, lag = 4 years) density (numbers/m^2) based on model estimates for subareas A-D in SFA 29W. The numbers labelling the points in the panels refers to the year (e.g., 2001 = 1) that the recruits were spawned. The dashed lines in the subarea B panel indicate that fit of Ricker curves to all of the data for subarea B, C, and D. The dashed green line in the subarea C panel indicates the fit when 2004 and 2008 data points are ignored.

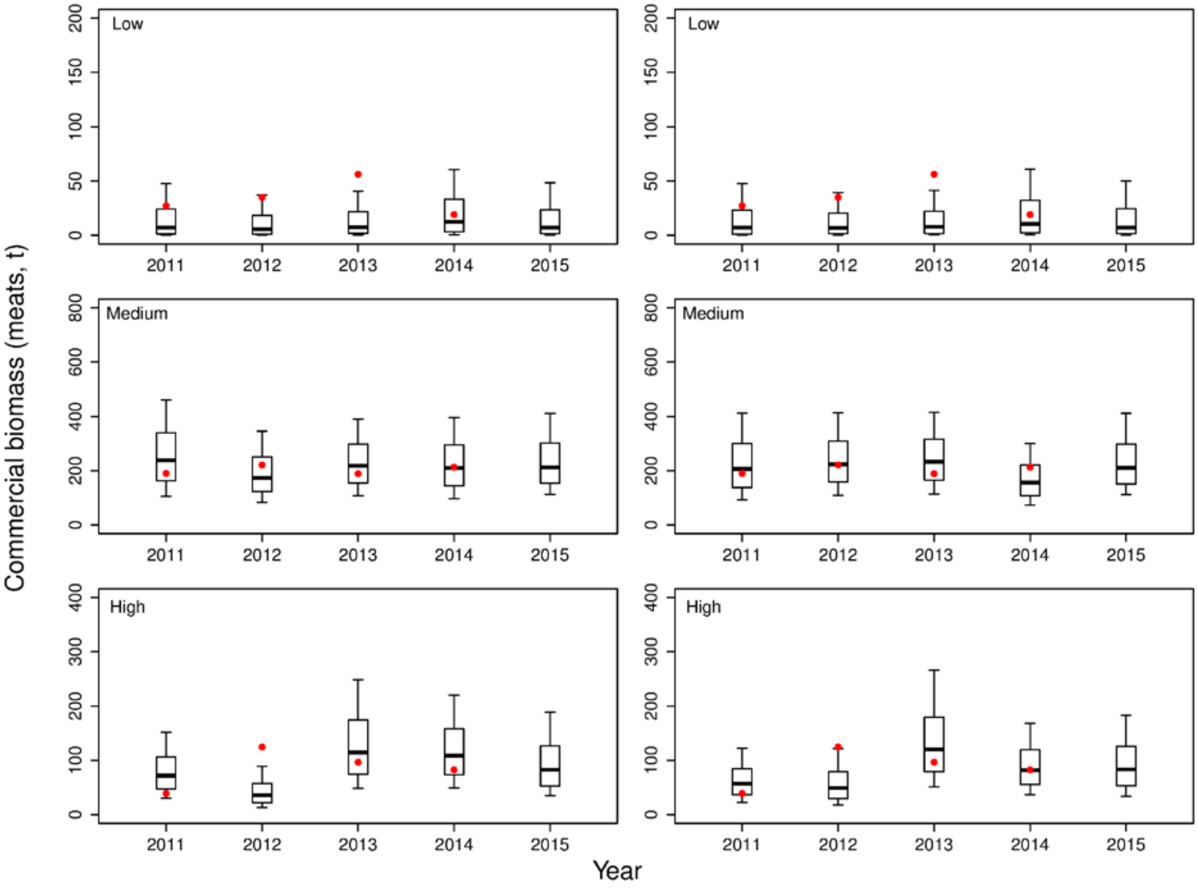

Figure 16. Evaluation of the model projection performance by Low ([0, 0.3)), Medium ([0.3, 0.6)) and High ([0.6, 1.0)) categories of habitat suitability probabilities in subarea D. Box and whisker plots summarise posterior distribution of commercial size biomass in year t based on model fit to year t-1 (e.g., 2011 predictions based on data up to 2010). The upper and lower edges of the box represent the 0.25 and 0.75 quantiles while the upper and lower whiskers indicate the 0.1 and 0.9 quantiles. The horizontal line in the box indicates the median. The red dots represent the estimate of the biomass in year t using data up to and including year t, from the Bayesian state-space assessment model. Left panel predictions made using condition estimates from previous year and right panel predictions were made using the actual condition estimates for the predicted year. Predictions for 2015 assume condition to be the same as in 2014 and a catch of 54 t.

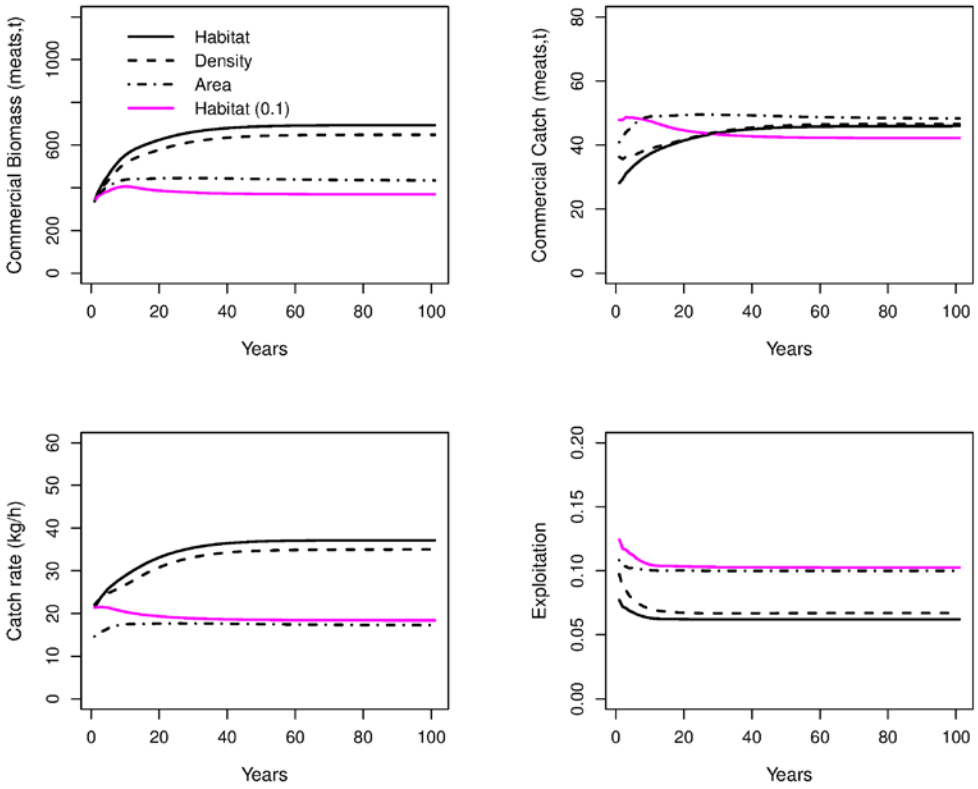

Figure 17. Comparison of long-term yield calculations for different fishing models. The assessment model was run forward 100 years starting with the most recent estimates for subarea D. Fishing models were designated as Habitat model, Density model, and Area model. For the first two models, exploitation was set to 0.1 for the High suitability area only while exploitation was set to 0.1 in all suitability areas for the Area model. Habitat (0.1) denotes the habitat model with the High area set to exploitation 0.17 resulting in an overall exploitation rate of 0.1. The lower right panel refers to the exploitation rate over all habitat areas.

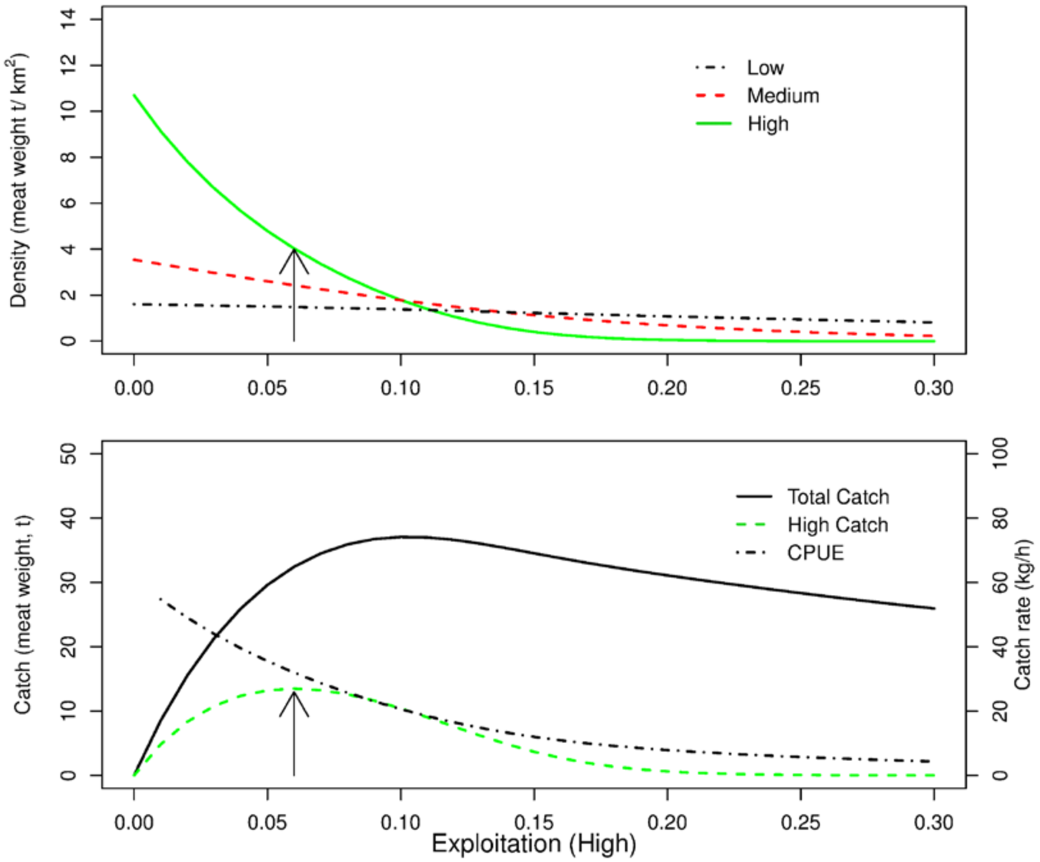

Figure 18. Long-term yield estimates of density (top panel) in SFA 29W subarea B by habitat suitability, and catch for the High suitability areas and total catch (bottom panel) over a range of exploitation rate for the high suitability area. Catch rate is for the whole area for each exploitation rate. Exploitation for the maximum sustainable catch for the High suitability area is indicated by arrows.

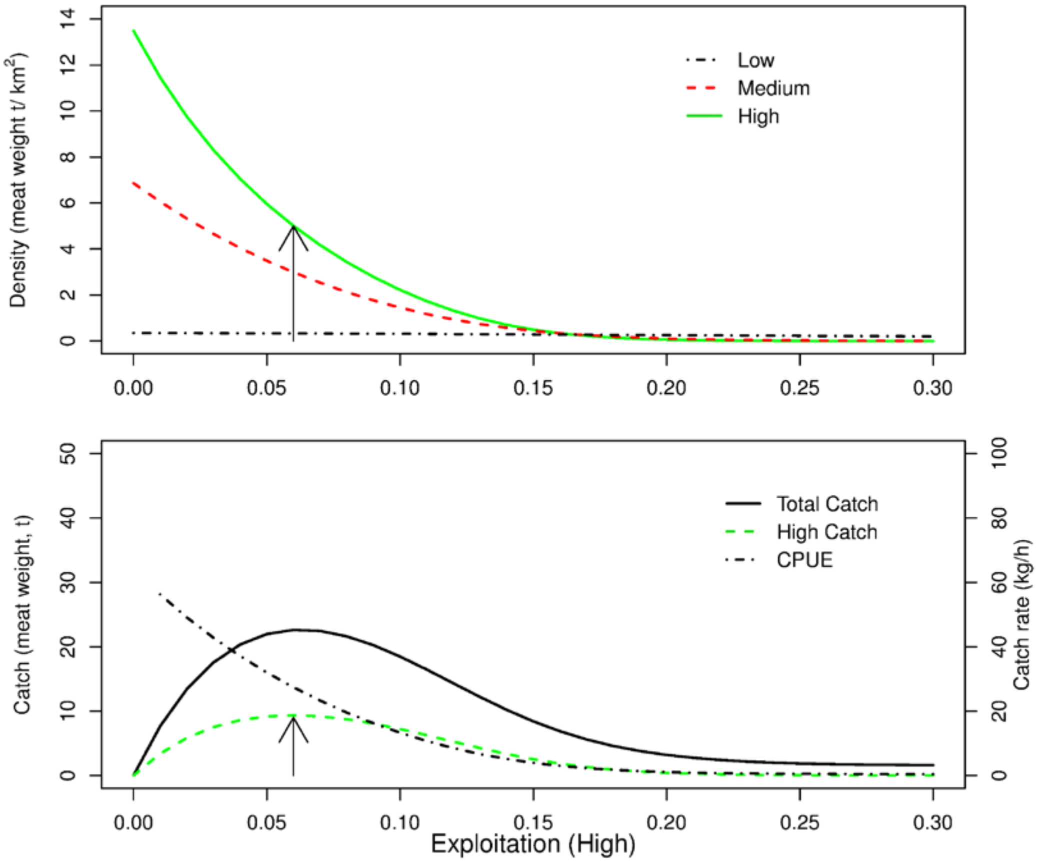

Figure 19. Long-term yield estimates of density (top panel) in SFA 29W subarea C by habitat suitability, and catch for the High suitability areas and total catch (bottom panel) over a range of exploitation rate for the high suitability area. Catch rate is for the whole area for each exploitation rate. Exploitation for the maximum sustainable catch for the High suitability area is indicated by arrows.

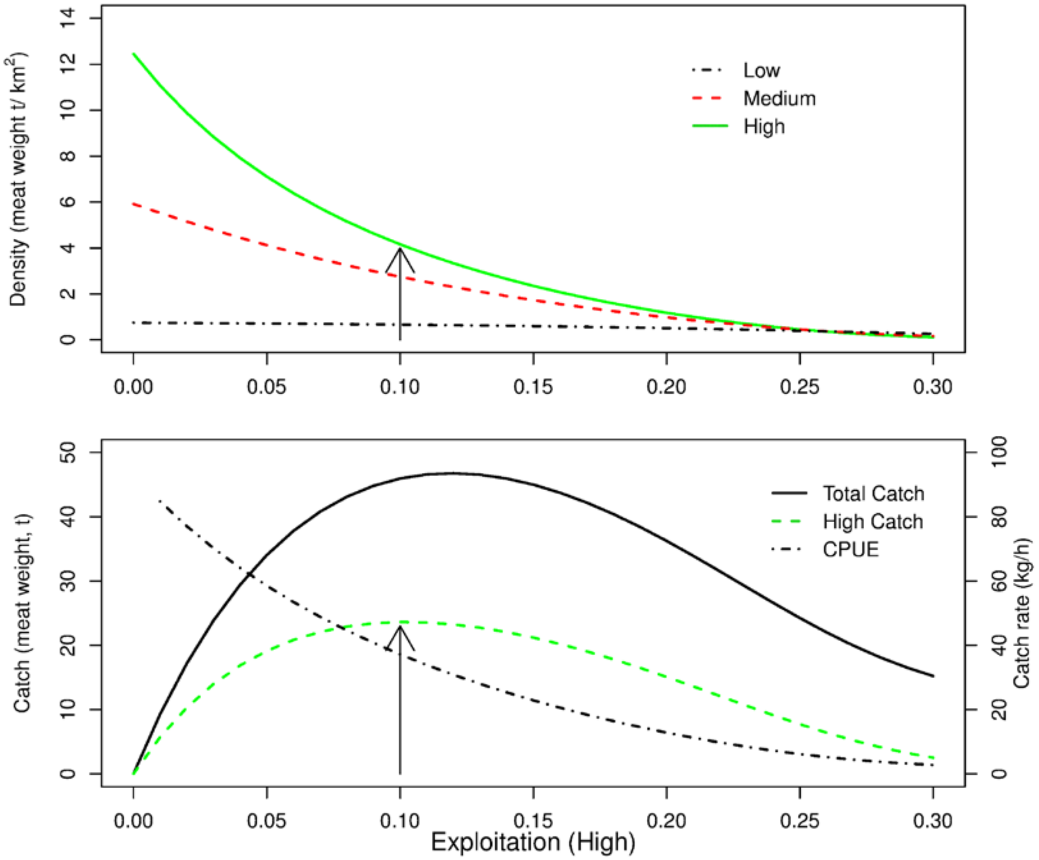

Figure 20. Long-term yield estimates of density (top panel) in SFA 29W subarea D by habitat suitability, and catch for the High suitability areas and total catch (bottom panel) over a range of exploitation rate for the high suitability area. Catch rate is for the whole area for each exploitation rate. Exploitation for the maximum sustainable catch for the High suitability area is indicated by arrows.

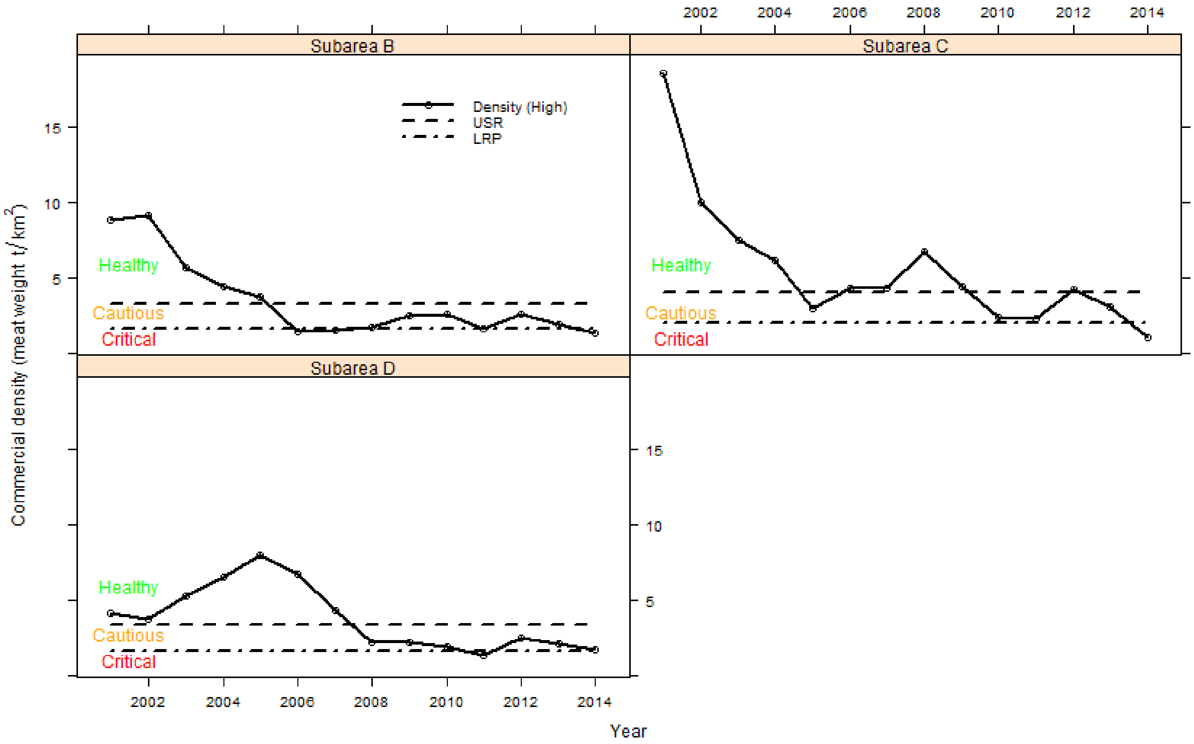

Figure 21. Comparison of the times series for commercial densities (meat weight, t/km^2) for the High suitability areas in SFA 29W for subareas B, C, and D with the proposed candidate reference points in Table 3.