South Pacific Regional Fisheries Management Organisation

2nd Meeting of the Scientific Committee

Honolulu, Hawaii, USA
1-7 October 2014

SC-02-JM-08

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Hintzen, N.T., Brunel, T., Dragon, A-C. & Lehodey, P.

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Hintzen[1*], N.T., Brunel[1], T., Dragon[2], A-C. Lehodey[2], P.

[1] IMARES, part of Wageningen UR, Institute for Marine Resources and Ecosystem Studies, PO Box 68, 1970 AB IJmuiden, Netherlands.

[2] Marine Ecosystem Department, Space Oceanography Division, CLS, 31520 Ramonville, France.

[*]Corresponding author: tel: +31 317 489070; fax: +31 317 487326; e-mail: Niels.Hintzen@wur.nl

Abstract

The sustainable exploitation of the Chilean Jack Mackerel (*Trachurus murphyi*) population in the South Pacific is of prime interest to the South Pacific Regional Fisheries Management Organisation (SPRFMO) and its member states' fisheries managers. There is however uncertainty related to the population structure of Jack Mackerel, possibly constitution one single population or multiple population units that may mix during part of the year. Currently, all Jack Mackerel are being assessed as one single stock. This study evaluates the consequences on sustainable exploitation of a potential mismatch between population and management structure. Results indicate that assuming the existence of two separate stocks in the advisory process, while true population structure is unknown, is less likely to result in over exploitation of the Jack Mackerel population.

Keywords

Chilean Jack Mackerel, management strategy evaluation, meta-population, stock structure

Introduction

The sustainable exploitation of the Chilean Jack Mackerel (*Trachurus murphyi*) population in the South Pacific is of prime interest to the South Pacific Regional Fisheries Management Organisation (SPRFMO) and its member states' fisheries managers (FAO, 1999; Reiss et al., 2009). Core to the sustainability goal is to have a correct understanding of the population size and dynamics of the fish resource (Deroba et al., 2014). Stock assessment models, taking catch and survey data into account, are therefore often put into place to assist fisheries managers in setting exploitation targets. These models require users to make a-priori assumptions on population and management structure, often assuming a homogeneously distributed fish resource with a homogenously distributed fishery targeting it.

Uncertainty regarding the population or management unit structure is often disregarded due to the complexity involved when one wants to assess a fish resource with a more complex population structure (Stephenson, 1999; Smedbol et al., 2002) such as potentially is the case for Jack Mackerel (Gerlotto et al., 2012). Stock assessment models that are able to assess, for example, meta-population structures are not widely spread either (Beamish et al., 2009; Goethel et al., 2011; Cunningham et al., 2007). For a number of stock assessment therefore, simplifying assumption about the population structure are made. A mismatch between population and management structure, potentially due to the simplifications in assessments, may however hamper management (Iles and Sinclair, 1982; Stephenson, 1999; Frank and Brickman, 2000; Reiss et al., 2009; Cope and Punt, 2011; Ulrich et al., 2013).

The population structure of Jack Mackerel in the South Pacific is not fully understood yet. Although its distribution stretches over a large area, potentially from the east coast of New Zealand up to the coastline of Chile and Peru, genetic studies did not point towards different population components (Poulin et al., 2004; Cárdenas et al., 2009). Analyses based on otolith chemistry however show potential boundaries between the western and eastern South Pacific Ocean and Chile and Peru (Ashford et al., 2011). The signal in either genetic or otolith structures may be blurred due to exchange of Jack Mackerel between Chilean and Peruvian waters. This exchange may be driven by the El Niño-Southern Oscillation (ENSO) cycle which cause large inter-annual environmental changes in the distribution area (Arcos et al., 2001; Diaz et al., 2000) and alter the migration routes of Jack Mackerel.

Depending on the amount of mixing and migration between northern and southern distributed fish, the population complex may be classified as a single population, a patchy population, a metapopulation or two separate populations (Gerlotto et al., 2012). In accordance, management areas should be defined. Given the uncertainty regarding the population structure, the Scientific Committee of the SPRFMO however assumes, as a working hypothesis for management, that all Jack Mackerels in the SPRFMO convention area and inside the EEZ of Chile, Peru and Ecuador constitute one large population. No Jack Mackerel has been found for a long period along the western side of the distribution area.

Since the 1970s, the majority of Jack Mackerel are caught by Chilean and Peruvian vessels inside their respective EEZs. In the 80's a fishery on the high seas developed as well but diminished in the early 90's. Since the 2000's catches were taken on the high seas again by a large variety of nations such as Belize, China, the European Union, Korea, Vanuatu. The four fleets that are distinguished here, a northern fishery by Peru and Ecuador, a northern Chilean fishery, a southern-central Chilean fishery and a fishery on the high-seas, caught as much as 5 million tonnes in the mid 90's but catches declined to around 450 thousand tonnes in recent years. Due to low recruitment levels and high catches in the early 2000s the Jack Mackerel stock declined substantially and was in 2013 estimated at around 3 million tonnes in spawning biomass. Due to this decline and international ratification of the convention on the long-term conservation and sustainable use of fishery resources in the South Pacific Ocean, attention was raised to recover the Jack Mackerel stock to sustainable exploitation and biomass levels. At the same time, the assumption on population structure in the SPRFMO stock assessment was again challenged.

Management Strategy Evaluation (Kell et al., 2007; Kraak et al., 2008) can be used in this instance to indicate whether the different views on Jack Mackerel population structure affect its management. Simulating different assumptions on population structure and its fisheries is key in this process and allows managers to assess whether a potential mismatch between population and management structure jeopardizes sustainable exploitation of the fish resource. An important attribute of the MSE framework is the option to simultaneously simulate the Jack Mackerel population structure and dynamics, following best available knowledge (Butterworth et al., 2010), and the stock assessment and advisory process (Hintzen et al., 2014). The assumptions on population and stock structure do not necessarily have to match between the biological part and the stock assessment part of the model. For example, the population may constitute two separate units while in the assessment they are considered as one stock.

In this study we simulate three alternative hypothesis on the Jack Mackerel population structure: a single-unit, two separate units and two separate units with extensive mixing between the units. These designs are combined with two alternative assessment assumptions, assuming a single stock and two separate stocks. Hence, in total six different scenarios are tested using simulations. In each case the performance of the management system, given the underlying biology is evaluated, with respect to estimated biomass trends, expected catches and risk to overexploitation. Through these analyses we show whether accurately accounting for population structure has an effect on sustainable fisheries management and how quantitative results may differ among population and management structures. The results are discussed in the light of these hypothesis and do not consider any other population structure hypotheses.

Material & Methods

The Management Strategy Evaluation (MSE) considers four components. The biological population unit(s) of Jack Mackerel in the South Pacific Ocean [1], the four fisheries targeting the population unit(s) [2], the stock assessment procedure to obtain a perceived status of the population unit(s) [3] which is used to set management targets [4]. The framework includes feedback loops, were over time, the result of setting management targets affect the population unit(s) the year after, and thereby also affect the fisheries and management. In order to reflect the uncertainties related to population dynamics, fisheries dynamics and management implementation, the simulations are run with 200 replicates, each representing a different but likely version of the true dynamics of the population unit(s) and fisheries. The combination of all replicates together indicate the range in outcomes and risk for a given population and management structure assumption. Assessment results from the combined and north – south scenarios is used to condition the model for the years 1970-2013. Simulations were run until 2042. The mathematical framework underlying the simulation model is based on the equations presented in (Hintzen et al., 2014).

[1] Population unit(s)

In the South Pacific Ocean, it is hypothesised that up to two Jack Mackerel units may reside (Ashford et al., 2011). One unit north of 20°S in Peruvian and Ecuadorian waters and one south of 20°S. Under the one-unit hypothesis, the two units mentioned above should be considered as one combined population unit. Jack Mackerel spawns offshore and migrates closer to shore during the winter months to forage. Most of the Jack Mackerels are present in the Chilean EEZ or migrate perpendicular to the Chilean coast onto the high seas. Smaller numbers of Jack Mackerel are found inside the Peruvian, and occasionally in the Ecuadorian EEZ. Juveniles occupy a different habitat than adults and are predominantly located between 20° and 30°S.

Historical dynamics

The output of stock assessment models, assuming either a single stock or two separate stocks, carried out at SPRFMO (Scientific Committee, 2013) were used to populate an age structured (ages 1-12) population models. For each of the 200 replicates new matrices of population unit numbers-at-age and fishing mortality-at-age were drawn from a multivariate normal distribution using the variance-co-variance matrix supplied as output by the assessment models. Weight-at-age in the population units was modelled using an ARMA (auto-regressive moving average) model. The ARMA model was fitted to the observed weight-at-age given in the assessment input to capture the degree of autocorrelation of the variation of the time series. The ARMA models were fitted using the fArma library in R. For each time series, the best model – the optimal set of p and q parameters, being the orders of the autogressive and moving average parts respectively, was obtained by fitting a range of models with varying p and q values and selecting the one with the lowest AIC criteria. Once an ARMA model is fitted to a time series, it can be used to simulate time series with the same characteristics as the original time series. An ARMA model was first fitted to the time series of weights-at-age 1.The growth increment during the second year of the fish (i.e. weight-at-age 2 minus weight-at-age 1) was modelled by another ARMA model. Time series of weight increments from age 1 to 2 were generated for each replicate of the population unit. The weight increments were added to the weights-at-age 1 of the corresponding cohort to generate the weights-at-age 2. Weights-at-age 3 to 12 were generated in the same way. Maturity-at-age and natural mortality-at-age were assumed equal to the assessment settings. The simulated population units are assumed to represent the true dynamics of the population.

Connectivity

Here, connectivity refers to fish moving from one population unit to the other and remaining with the new unit. Connectivity rates were estimates for juveniles (ages 1 and 2) and adults (ages 3-12) separately. The spatio-temporal explicit model (SEAPODYM, (Lehodey et al., 2008)), parameterized for Jack Mackerel, was used to estimate connectivity rates (SPRFMO SC2, Dragon *et al*. 2014). For this reason, 12 different areas were defined where Jack Mackerel has been observed in the past. For each of these areas, their contribution to biomass in any of the other 11 areas was estimated in equilibrium. The contribution of all southern areas to northern areas (as a fraction of the total abundance in the northern area) was used as a connectivity rate from the south unit to the north unit. The rate from north to south was calculated in a similar way. The variability in contribution in the southern and northern areas was taken as an approximation of variability in connectivity rates.

Operating model dynamics

Recruitment is the key component of population productivity. Here, recruitment is simulated to have the same variability as the recruitment observed historically in the period 2003-2013 (low productivity regime), applying a method combining different stock-recruitment functions (Simmonds et al., 2011). Based on a Bayesian estimation of model parameters, a full representation of the uncertainty in the stock-recruitment model is given. Furthermore, fish die from natural or fishing mortality. Based on these mortalities, survivors from one year to the next are calculated. Fish that become older than 12 years build up in the so-called plusgroup and are treated as being 12 years of age. Fishing mortality may be caused by a variety of fisheries, each associated with different selection patterns and catch targets. The fishing mortality encountered by a population unit therefore depends on the availability of the unit to each of the fisheries and the level of mortality each fishery induces. The availability of each unit to the fisheries was estimated by fitting a generalized linear model to proportional catch numbers-at-age by fleet according to:

$$\frac{C^f{}_{a,t}}{C_{a,t}} \sim a \cdot t \cdot f + N_{a,t} + F^f_{a,t}$$

The model described was fitted as a binomial GLM with a, *N* and *F* being integers and *t* and *f* being treated as factors. $C^f{}_{a,t}$ denotes the catch of fishery *f* at age *a* and year *t* and $N_{a,t}$ is presented by numbers-at-age obtained from the combined assessment (Scientific Committee, 2013). $F^f_{a,t}$ denotes the selection pattern of each fishery. Model selection using the AIC criteria was used to select the best model fit among competing model formulations. Competing models were constructed applying similar or less variables with and without interactions. In earlier model selection steps the variables SSB and cohort were excluded.

[2] The fisheries

The four fleets (South-Central Chile, Northern Chile, Offshore and Far North) target the Jack Mackerel population unit(s). Each of these fleets catch fish at different ages following a certain selection-at-age pattern and may have, depending on the scenario evaluated, access to either the southern or northern unit. The four fleets together target

100% of the population. The catch equations according to (Hintzen et al., 2014) apply. Selectivity patterns for the four fleets for the period 2014-2042 were generated as follows. The period that was considered indicative for future selectivity patterns was defined by 1) calculating the mean selection period over the entire historic time-series, being inversely weighted by the distance in years from the most recent year, 2) similar to the mean calculation, the standard deviation of the selection pattern per age was calculated for each of the four fleets, 3) all assessment estimated selection patterns that fell outside two standard deviations from the mean were not included as being indicative for future selectivity. New selectivity values by age, year and fleet were generated by a multivariate normal distribution taking the variance-co-variance structure into account of the yearly change in fleet selectivity pattern observed in the indicative years. The random values had mean 0 and allowed to construct a random walk by summing the randomly drawn values by age and fleet over time. Finally, selectivity patterns were constructed by multiplying the random walks (with mean zero) with the mean selection pattern over the indicative years. Selection patterns were standardized to the mean for each fleet separately. Historical selection patterns were estimated based on landing numbers-at-age as estimated by the assessments and predicted availability of each fishery to the population units.

Similar to the approach to model the growth of the biological operating model, observed fisheries landings weight-at-age have been used together with the ARMA approach to simulate weight-at-age for the period after 2013 for each fishery separate. Observed weights-at-age from the assessment model output were used to generate weight-at-age per fishery in the period 1970-2013.

[3] The assessment procedure

In the simulations, as in reality, management decisions are based on the perception of the stock(s) provided by a stock assessment. Stock assessment gives a perception of the stock which can deviate from the real population unit for a number of reasons : inaccuracy of the catch data, sampling uncertainty, noise in the survey indices, assessment model mis-specification, assessment model fit uncertainty.

At each new year in the simulation, a new perception of the stock is generated, in a way that mimics as closely as possible the uncertainty related to stock assessment. The approach taken here consists in adding an error term to the assessment output – abundance and fishing mortality at age - of the biological and fisheries operating model. This error term was defined as the product of cohort-specific normally distributed deviations and an error amplitude proportional to the assessment uncertainty of the corresponding estimate. The cohort specific deviations were generated by sampling a random number from a standard normal distribution for each cohort of the projection period, and propagating this value to all the ages for each cohort. One matrix of cohort-specific normal deviations was generated for each replicate of the stock. The amplitude of the error on numbers and fishing mortality at age was calculated from the 200 replicates of the population unit(s) at the start of the simulation. These replicates were generated by resampling parameters from the stock assessment based on the variance covariance matrix and therefore the inter-replicate variability of a given estimate represents the uncertainty in the assessment output. A matrix of CV representing the amplitude of the assessment uncertainty was calculated for numbers and fishing mortality at age by computing the standard deviation of a given estimate (N or F at a given age, for a given number of years before the terminal assessment year) across all 200 replicates and dividing by the mean. The final error was calculated by multiplying the cohort specific deviations by the uncertainty variance, calculated as square of the product between the CV and the estimate from the biological model.

Under a number of scenarios evaluated the population structure does not match the management structure, e.g. simulating two population units with only one stock assessment. In those cases, population unit numbers are either combined (from two units to one stock assessment) or split (from one unit to two stock assessments) according to the availability of the units to the different areas. For the assessment, it is assumed that catches from the Far North are used for the northern unit while the catches of the remaining three fisheries are used for the southern unit.

[4] Management

Every year, a TAC advice is formulated based on the results of the latest assessment. In a given year y, the TAC advice is given for the following year y+1, based on a perception of the stock in the previous year y-1. In order to give a TAC advice, a short term projection of the stock is necessary to get the stock abundance in the advice year y+1. The short term forecast is based, as in reality, on the perceived stock and not on the abundance in the population unit(s). Here, the survivors at the start of the current year, y, are projected forward to the start of the next year, y+1, using the assumption that the catch of the current year y is equal to the TAC for the same year y. Then, based on the numbers at age at the start of the year y+1, a fisheries target is applied: this rule gives the value of the fishing mortality which should be applied in the year y+1. The advised TAC in year y+1 is calculated based on this fishing mortality. Management targets are set in agreement with fishing at F_{MSY} where F_{MSY} is internally estimated within the stock assessment models (Scientific Committee, 2013). In the MSE, it is assumed that the actual catch in a given year is equal to the advised TAC, i.e. that the quotas are fully used and not overshot. Table 1 shows the scenario design and respective fishing mortality targets used.

Scenario description

In total six different scenarios are evaluated, combining three assumptions on population structure with two assumptions on stock assessment structure.

(i) The base scenario: simulating the Jack Mackerel population as one unit and assessing it as one combined stock with contributions of all four fisheries. Fishing targets are set at $F_{MSY}=0.25$

(ii) The two stocks scenario: simulating the Jack Mackerel population as one unit but assessing it in two separate stock assessments. The Far North fishery contributes to the northern stock and the remaining three fisheries contribute to the southern stock. The TAC following from the northern stock is only caught by the Far North fishery while the TAC following from the southern stock is shared among the remaining three fisheries. In the latter case, the fishing mortality-at-age ratios among the three fisheries are maintained in defining the TAC split. Fishing targets are set to 0.2 for the northern stock and to 0.25 for the southern stock.

(iii) The two unit scenario: simulating the Jack Mackerel population as two units (north and south) but assessing it as one combined stock. Fishing target is set to 0.25 for the combined stock. The TAC is shared among the fisheries, whereby the fishing mortality-at-age ratios among the fisheries are maintained.

(iv) The two unit match scenario: simulating the Jack Mackerel population as two units (north and south) and assessing it as two stocks (north and south). The Far North fishery contributes to the northern stock and the remaining three fisheries contribute to the southern stock. The TAC following from the northern stock is only caught by the Far North fishery while the TAC following from the southern stock is shared among the remaining three fisheries. In the latter case, the fishing mortality-at-age ratios among the three fisheries are maintained in defining the TAC split. Fishing targets are set to 0.2 for the northern stock and to 0.25 for the southern stock.

(v) The meta scenario: simulating the Jack Mackerel population as two units (north and south) including migration between the units. The population units are assessed as one combined stock. Fishing target is set to 0.25 for the combined stock. The TAC is shared among the fisheries, whereby the fishing mortality-at-age ratios among the fisheries are maintained.

(vi) The meta match scenario: simulating the Jack Mackerel population as two units (north and south) including migration between the units. The population units are assessed as two stocks (north and south). The Far North fishery contributes to the northern stock and the remaining three fisheries contribute to the southern stock. The TAC following from the northern stock is only caught by the Far North fishery while the TAC following from the southern stock is shared among the remaining three fisheries. In the latter case, the fishing mortality-at-age ratios among the three fisheries are maintained in defining the TAC split. Fishing targets are set to 0.2 for the northern stock and to 0.25 for the southern stock.

Table 1. Scenario descriptions and fishing mortality targets under different assumptions of population and management structure

		Management structure			
		1 stock assessment	2 stock assessments	1 stock F target	2 stocks F targets
Population structure	1single population unit	Base scenario	Two stock scenario	0.25	0.2 / 0.25
	2 fully separated population units	Two unit scenario	Two unit match scenario	0.2	0.2
				0.25	0.25
	2 separate population units with connectivity	Meta scenario	Meta match scenario	0.2	0.2
				0.25	0.25

Results

The results of the six scenarios are presented in Figure 1 for the period 2020-2040 and are given in relation to their reference points, as obtained from the 2013 SPRFMO stock assessment model runs (Scientific Committee, 2013). As starting conditions for the scenarios are different, the period 2014-2019 has been used as a 'burn-in' time frame. Under the '***Base scenario***' (black line + C, see Figure 1), SSB increases to just below 4000kt SSB with associated catches of around 750kt. The quota set yearly according to a fishing mortality target of 0.25 and resulting estimated fishing mortality match well. The '***Two stock scenario***' (red line + C, see Figure 1), reaches SSB levels lower than under the 'Base scenario' at around 3300kt. Landings are, on average, higher too at around 800kt and are associated with a fishing mortality onto the population of 0.25 per year. This is higher than the target set at 0.2 for the Northern stock and 0.25 for the Southern stock combined. The '***Two unit scenario***' (green lines + N & S, see Figure 1) provides indicators for both population units. Under this scenario, the Southern component reaches SSB levels of around 3500kt and the Northern component around 335kt. Combined, this adds up to around 3900kt, just below the 'Base scenario'. Landings of the Southern component is comparable to the 'Base scenario' and 'Two stock scenario' at around 800kt. The catches of the Northern component add up to 150kt per year. Combined, this results in catches of around 950kt per year which is higher than reported under the 'Base scenario'. The fishing mortalities encountered by both the Southern and Northern component are above target, at 0.26 and 0.7 for the Southern and Northern component respectively. Especially the 0.7 for the Northern component is well above the 0.25 target. Under the '***Meta scenario***' (blue lines + N & S, see Figure 1) the SSB of the Southern and Northern component are markedly different. SSB of the southern component resides at levels around 2600kt while the Northern component increases to around 1600kt, well above the estimated B_{MSY} for this unit. Catches are therefore different too with high catches for the Northern unit, even higher than the Southern unit. The selection of the Far Northern fleet is tailored towards juvenile fish due to net movement of fish from south to north, compared to the 'Two unit scenario', catches increase. This net movement of fish also results in a reduction in F for the Northern component. Under the '***Two unit match scenario***' (orange lines + N & S) the SSB of the Southern component reaches levels up to 3600kt and the Northern component up to around 1000kt, summed together being markedly higher than the 'Two unit scenario' which summed to 3900kt. Catches under this scenario are higher than the 'Two unit scenario' too with especially higher catches from the Northern Unit. Encountered fishing mortality is in line with targets set for these fisheries of 0.25 for the Southern unit and just below target at 0.18 for the Northern unit. The final '***Meta match scenario***' (purple lines + N & S) shows similar behaviour as the 'Meta scenario' in terms of SSB, however, in this case, the Northern component is larger than the Southern component and therefore the catches from both units are rather similar summing to 1100kt. Under this scenario, the Southern component is fished at higher levels than was set under the management regime (at 0.27) but the Northern component is fished below target at 0.14.

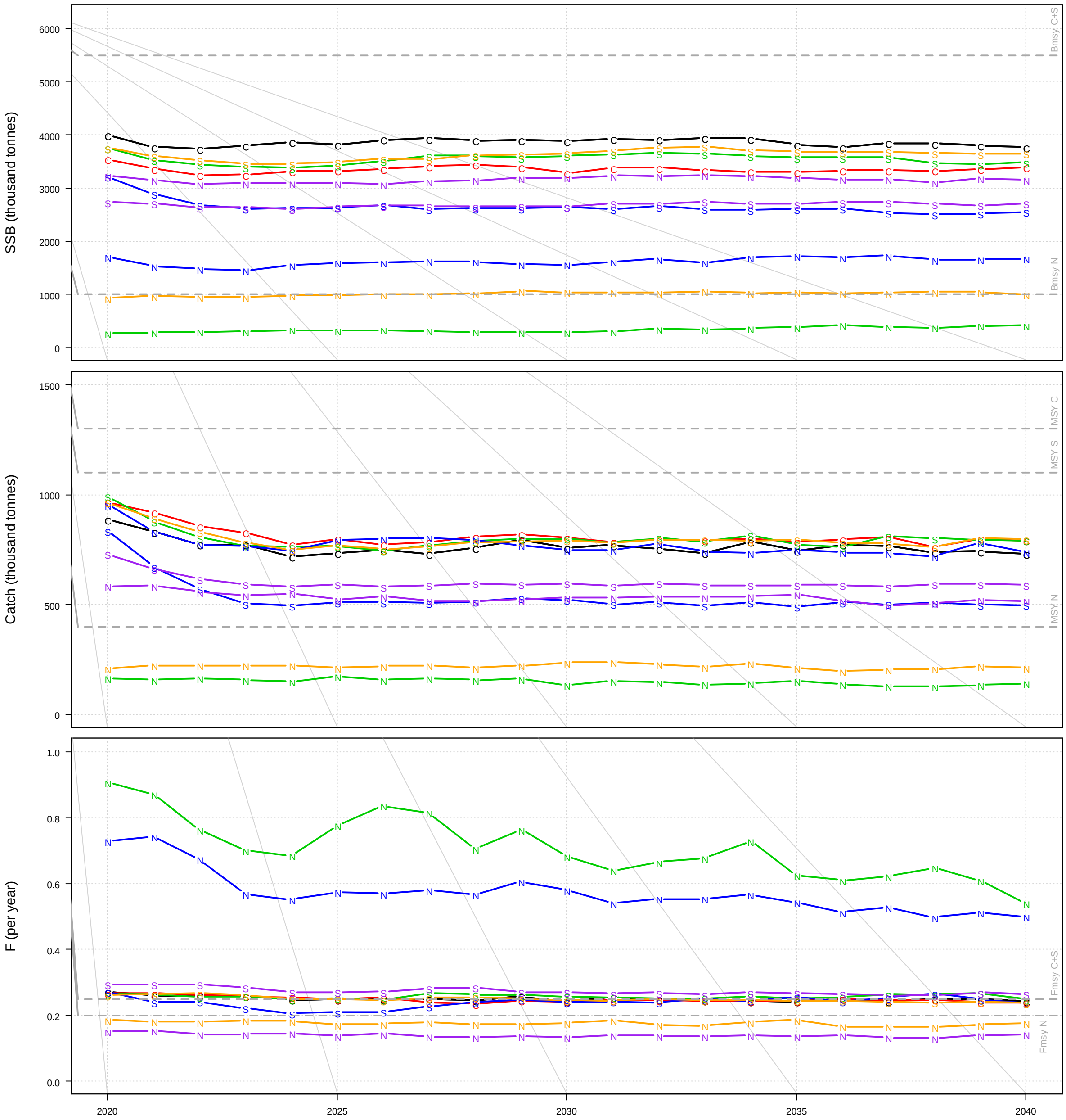

Figure 1. Panels of SSB (top), catch (middle) and Fishing mortality (bottom) under each of the six scenarios evaluated. Black lines correspond to the Base scenario, red lines to the Two stock scenario, green lines to the Two unit scenario, blue lines to the Two unit match scenario, the orange lines to the Meta scenario and the purple lines correspond to the Meta match scenario. In case the scenario simulated two population units, lines contain the letters N or S to denote the Northern or Southern unit. In all other cases, the scenario simulated only one population unit denoted by a C (combined). Biomass MSY, MSY and fishing mortality MSY values are given by grey dashed lines.

Figure 2 shows the risk under each of the scenarios to not reach B_{MSY}. Most of the units will not increase to B_{MSY} or beyond. Only under the 'Meta match scenario' does the size of the Northern unit increase to SSB levels above 1000kt. Under most scenarios, the risk to not reach B_{MSY} is substantially lower for the Northern component than for the Southern component that in only a few instances increase to B_{MSY} or above. The low productivity regime used in these analyses won't allow a rebuild to B_{MSY} or above for most population units.

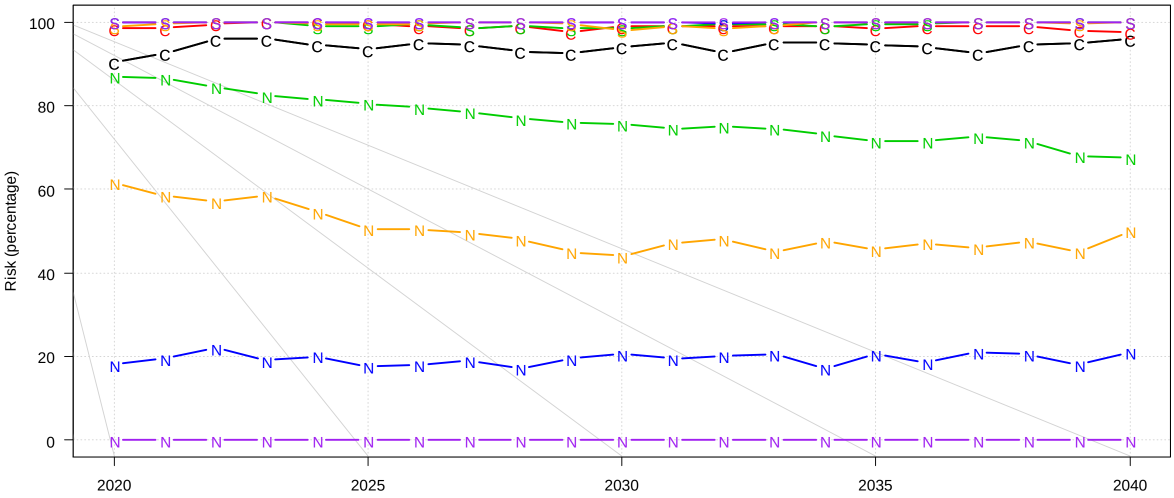

Figure 2. Risk to not reach B_{MSY} under each of the six scenarios. Black lines correspond to the Base scenario, red lines to the Two stock scenario, green lines to the Two unit scenario, blue lines to the Two unit match scenario, the orange lines to the Meta scenario and the purple lines correspond to the Meta match scenario. In case the scenario simulated two population units, lines contain the letters N or S to denote the Northern or Southern unit. In all other cases, the scenario simulated only one population unit denoted by a C (combined).

Figure 3 shows the risk to overexploitation, i.e. encountered fishing mortality greater than F_{MSY}. In theory, units will in approximately 50% of the time encounter fishing mortality higher than F_{MSY} and in 50% of the time encounter fishing mortality lower than F_{MSY}. For this reason, the risk to overexploitation is given as the percentage above or below 50%. The results indicate that under all but the 'Meta match scenario' the combined or Southern unit is fished at target (3% more than expected above target). The Northern unit however is at risk to be either heavily over or under exploited under the 'Two unit scenario' (over exploited), 'Meta scenario (over exploited)', 'Two unit match scenario' (under exploited) and 'Meta match scenario' (under exploited). In the latter scenario, the Southern unit has an increased risk to be over exploited too.

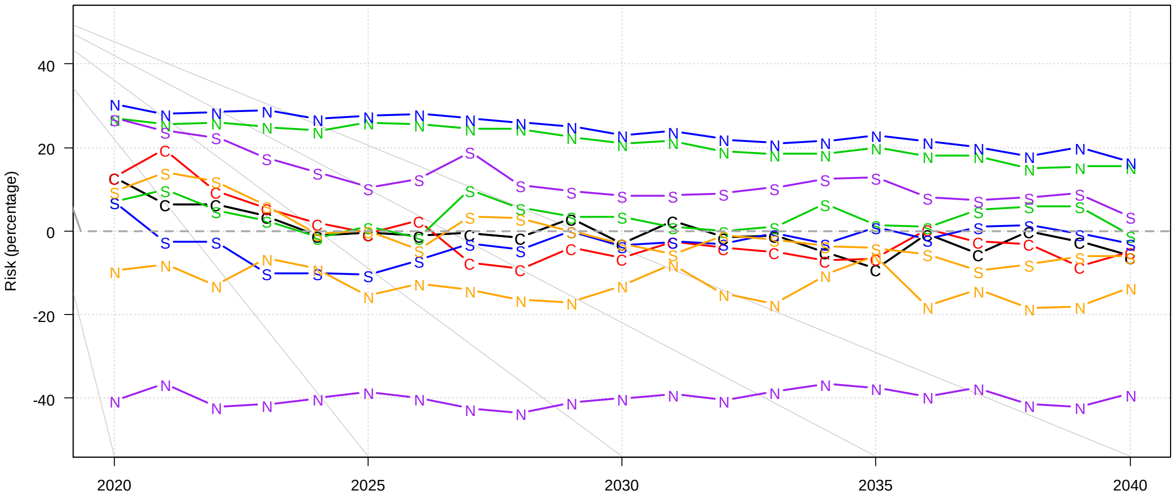

Figure 3. Risk to overexploitation under each of the six scenarios. Black lines correspond to the Base scenario, red lines to the Two stock scenario, green lines to the Two unit scenario, blue lines to the Two unit match scenario, the orange lines to the Meta scenario and the purple lines correspond to the Meta match scenario. In case the scenario simulated two population units, lines contain the letters N or S to denote the Northern or Southern unit. In all other cases, the scenario simulated only one population unit denoted by a C (combined).

Discussion

Mismatch between population and management structure

The population of Jack Mackerel in the South Pacific Ocean may constitute one unit, two, a hybrid meta-population structure or hold even another structure. Although genetics did not indicate towards multiple units (Poulin et al., 2004; Cárdenas et al., 2009), otholith chemistry did show the likelihood of a Northern and Southern unit (Ashford et al., 2011). A mixture of both findings could be interpreted as a meta-population structure, as suggested by Gerlotto (Gerlotto et al., 2012). The analyses performed in this study show that, from a management perspective, there is an increased risk to overploitation when the true, unobserved, structure would consist of two units but is being managed as one stock ('Two unit scenario'). This is in agreement with the findings of Kell et al. (Kell and Bromley, 2004) who showed that 'lumping' units poses additional risks to sustainable management goals. In this instance, the Northern unit would be fished at F's between 0.4 and 0.9, well above sustainable targets at 0.2 – 0.25. This fishing mortality is induced by the fisheries that operate on, among others, a TAC system. Under these scenarios, TACs in all areas increase or decrease equally, which cause problems for the Northern unit as the productivity of the Northern unit is lower compared to the Southern unit. A population unit with a lower productivity, requires a lower fishing mortality for a sustainable fishery too. As the Southern unit, which is markedly larger in size, drives the setting of a TAC and is associated with a higher productivity, the Southern unit is not overexploited. These problems do not arrise under the compareble 'Base scenario' where population and management stucture match.

Even so when the population constitutes one unit but under management the stock is divided into two separate elements ('Two stock scenario'), this has consequences for management. In this case however, fishing mortality is not markedly different from the target, thereby not posing a risk for overexploitation. The risk to not reach B_{MSY} is very high however, higher than when population and management structures match. The difference in management structure, setting separate TACs for the Northern and Southern zone, ensure that the relative importance of the Northern fleet increases. The Far North fleet however has a markedly different fleet selectivity, targeting predominantly younger fish, and thereby reducing the potential of the total population to increase in biomass. Comparing the 'Two unit scenario' with the 'Two unit match scenario' we observe that in the latter case, both units are managed on target and result in relatively high change to rebuild to B_{MSY} too. Under the 'Two unit scenario' however, the Northern unit is heavily overexploited and has the lowest chance to rebuild to above B_{MSY} from all scenarios where the Northern unit was simulated.

Management implications related to mixing

Under the scenarios where fish migrate from one to another unit, there is a clear net flow of fish from south to north. This because the Southern unit is larger in size but is associated with a similar migration rate as the one going from north to south. The migration has a positive effect however on the Northern unit, increasing productivity and thereby potential to rebuild biomass. A phenomena also described by (Frank and Brickman, 2000) and (Hintzen et al., 2014). The net flow of fish from south to north also results in an under exploitation of the Northern unit ('Meta match scenario') but overexploitation of the Southern unit. These results indicate that not accounting for migration may cause additional risks for sustainable fisheries even though the right population structure is accounted for. Considering the population as discrete units, as is common in stock assessments (Stephenson, 1999), is then inappropriate (Hart and Cadrin, 2004). In the instance that both the right management structure and migration is not accounted for ('Meta scenario'), the risk to overexploit either of the units is less than when units do not mix, similar to the findings by (Porch et al., 1998). In this case, the net flow of fish from south to north prevents the smaller stock from higher over exploitation. In case the net flow of fish would be the other way around, the risk to over exploit the units however, would be higher.

Interpretation of the results under model uncertainties

The availability of fish to the different fisheries was difficult to estimate, though is one of the core assumptions in this study. The GLM modelling approach takes fisheries dependent information and derivatives of the stock assessment results into consideration to estimate the population spatial distribution. There is however a certain degree of circular reasoning involved in this estimation as fisheries behaviour, rather than unbiased observations, now determine the availability of Jack Mackerel to the fisheries. Fisheries independent surveys, such as acoustic or tagging experiments, could play an important role to estimate the spatial distribution and availability of Jack mackerel to the fisheries. Only in a few cases has such data been used in simulation studies to improve sustainable management (Simmonds, 2009; Hintzen et al., 2014).

Management in the light of the current SPRFMO assessment design

The assumption on management structure currently taken in the Science Committee of the SPRFMO is most similar to the 'Base scenario' or 'Two unit scenario'. In case the latter scenario is closest to the unobserved reality, the Jack Mackerel population in the Northern area is at risk to be overexploited. The risk for overexploitation of the unit in the Southern area is low. The alternative hypothesis explored by the same committee, close to the 'Two stock scenario' or 'Two unit match scenario' poses less risk to overexploitation compared to the 'Two unit scenario'. Also, when migration of fish between two units exists, considering a two stock management approach can be considered risk adverse. Concluding that under all population structure hypothesis investigated, a management structure assuming two stocks is less likely to over exploitation than under a one stock assumption, even when in reality there is only one population unit.

Sustainably managing the Jack mackerel population in the South Pacific is one of the key tasks of the SPRFMO and its member states. Without understanding the full population structure though, over exploitation of potential separate units is a real possibility (Frank and Brickman, 2000; Kell et al., 2009). This because reference points me not be determined appropriately, as is suggested in a similar study by Heath *et al*. (Heath et al., 2008). Through the use of simulation modelling, we can assess these risks and investigate the role of spatial structures and connectivity to improve management decisions (Kerr et al., 2010). It stands out here that if the population is build up of two separate units, the potential Northern unit may be at risk of overexploitation and management action may be desired to manage according to the most vulnerable unit (Reiss et al., 2009).

Acknowledgements

This research was supported through the EU Open call for tenders No MARE/2011/16 Lot 1. The article does not necessarily reflect the views of the European Commission and does not anticipate the Commission's future policy in this area.

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