Hydrography and Jack mackerel stock in the South Pacific – Final report

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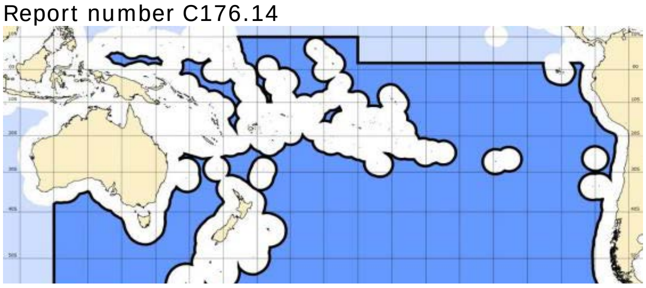

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Executive summary

Jack mackerel in the South Pacific has been exploited by fisheries since the 1970's. Owing to large recruitment influxes in the mid-eighties, the stock grew to approximately 14 million tonnes of spawning biomass, one of largest fish stocks in the world, sustaining catches up to 5 million tons per year. Jack mackerel in the South Pacific is distributed throughout the sub-tropical waters of the South Pacific Ocean, from South America to New Zealand and Australia. Management of Jack mackerel at the high seas is officially organised through the South Pacific Regional Fisheries Management Organisation (SPRFMO) since 2013 and hence does not include the jurisdictional areas of Chile and Peru. In both these areas however the majority of Jack mackerel is observed throughout the year where it migrates from the coastal zones to the high-seas and vice versa.

Total Allowable Catch advice from the Science Committee of the SPRFMO is based on a stock assessment which assumes that Jack mackerel constitute one single stock, hereby taking Jack mackerel inside jurisdictional areas and at the high seas simultaneously into account. Survey, catch, and climatic observations suggest however that more complex stock structures may exist. These observations have resulted in intense discussions among SPRFMO scientists on likely population and stock structure and preparation of TAC advice. In this study, we make a distinction between population structure: the distribution of fish abundance in time and space throughout the year, and stock structure: the abundance, distribution and availability of fish to the fishery in the fishing season. An understanding of population structure is necessary to study stock structure, while a correct understanding of stock structure is necessary to set sustainable management targets.

This study aims (i) to identify the most likely population structure hypotheses of Jack mackerel, (ii) to identify management objectives for Jack mackerel, and (iii) to evaluate sustainable management strategies to achieve these objectives. These three elements were considered through literature review, statistical and population dynamics modelling. Two different conclusions were drawn: a conclusion towards most likely population structure and a conclusion towards most likely stock structure.

In total, six different population structure hypotheses were considered. Information has been collected that clearly shows that Jack mackerel in the South Pacific cannot be considered as a single discrete population, two or multiple discrete populations or a patchy population. No strong evidence was presented to reject the metapopulation hypothesis, assuming two main patches of Jack mackerel. One patch exists off the coast of Peru and one patch exists off Chile migrating onto the high seas. There is substantial exchange of fish between the two patches. Therefore we conclude that the metapopulation structure is most likely for Jack mackerel in the South Pacific.

Considering stock structure required the analyses of fishing patterns in combination with likely population structure. The Jack mackerel inside Peruvian waters is bounded by its habitat during the fishing season from January till May with peak catches in April. Given this bounded habitat, we conclude that Jack mackerel in the Northern area constitutes a separate stock. Jack mackerel inside the Chilean coastal areas is targeted around the same time of the year, with a peak around April. The catches inside the Chilean coastal area however cannot be considered in isolation from the catches at the high-seas, due to migration of Jack mackerel from coastal Chile onto the high seas. The Jack mackerel in the Southern area (off Chile) is considered to constitute another stock, resulting in a two-stock assumption for the entire South Pacific. Given that over years changes in the dynamics of Jack mackerel in the Southern zone affect Jack mackerel in the Northern zone, management of the two areas cannot be considered in complete isolation from each other.

Sustainable exploitation of the Jack mackerel population in the short term will be associated with an F_{MSY} around 0.14. Under more optimistic recruitment scenarios, as expected in the long term, sustainable exploitation can be associated with an F_{MSY} around 0.21 under the single stock hypothesis and between

0.15 – 0.2 for the two stock hypothesis. Any Harvest Control Rule that ensures setting TACs in the short to medium term close to an F_{MSY} of 0.14 can be considered sustainable. In addition, there appears to be little gain in implementing an increase in either mesh size or minimum landing size.

Given that conclusions related to population and stock structure are uncertain, different Harvest Control Rules were tested under a range of population and stock structure hypotheses. Results suggest that management structures assuming two stocks rather than one are less likely to lead to over-exploitation than under a one stock assumption, even when in reality there is only one population unit rather than a population unit off Peru and one off Chile as suggested in this study. It is therefore recommended to consider two-stocks in the South Pacific, each being managed by a separate Harvest Control Rule, though these rules should be co-developed to account for the connectivity between the two main population units.

Future research should focus on, among others, the following elements: 1) tagging of Jack mackerel, to follow their spatial distribution over time and to identify main migration routes and exchange of fish between e.g. Jack mackerel off Peru and Chile, 2) studying how climate change affects the distribution of Jack mackerel and thereby predicting what the future catch potential of fisheries onto the high seas may be, 3) studying how management should change during the rebuilding of Jack mackerel, under the assumption that the spatial distribution of Jack mackerel changes when the population increases.

Context of the study

Jack mackerel in the South Pacific has been exploited by fisheries since the 1970's. Owing to large recruitment influxes in the mid-eighties, the stock grew to approximately 14 million tonnes of spawning biomass, one of largest fish stocks in the world, sustaining catches up to 5 million tons per year. Jack mackerel in the South Pacific is distributed throughout the sub-tropical waters of the South Pacific Ocean, from South America to New Zealand and Australia. Management of Jack mackerel is executed in the framework of the South Pacific Regional Fisheries Management Organisation (see Figure 1). Given its potential for high catches which may contribute substantially to the need for animal proteins, it is important to sustainably manage this fish resource. Joint action of all parties involved in managing the resource is necessary as currently Jack mackerel is in a poor state, with estimated spawning biomass around 2.7 million tonnes in 2014.

Management of Jack mackerel at the high seas is officially organised through the SPRFMO since 2013. Since 2011, scientists already advised the SPRFMO regarding maximum sustainable catches. The SPRFMO area does not include the jurisdictional areas of Chile and Peru, while in both these areas the majority of Jack mackerel is observed throughout the year where it migrates from the coastal zones to the high-seas and vice versa. For this reason, the Science Committee of the SPRFMO provides advice for the entire area, and not only for the high-seas part of it. Chile, a contracting party of the SPRFMO, sets quota in their jurisdictional area in accordance with the SPRFMO agreements. Peru however, who has not ratified the SPRFMO convention, sets quota according to own assessments and observations. However, the total TAC of all countries together did not exceed the Science Committee advised TAC since 2011.

The European Union also has fishing interests in this area, both currently as in the past, with vessels reporting catches in the 1970s and 1980s and more recently from 2005 up to 2014. At the end of the 1970's and beginning of the 1980's Polish vessels targeted Jack mackerel on the high-seas with catches peaking around 80,000 tonnes. More recently, Dutch, German, Polish and Lithuanian vessels caught around 60,000 – 120,000 tonnes per year. In 2011 – 2014, however, catch records range between 0 and 15,000 tonnes.

The recent low catches by the EU fleet follows the decline in Jack mackerel biomass since 2003. This decline in biomass resulted from a series of low recruitments since 2003 and no substantial reduction in catches. The biomass reached a time-series low in 2010 at 1.6 million tonnes. The low biomass was pointed out for the first time in the first joint assessment for the entire distribution area of Jack mackerel in the South Pacific in 2010. Although the stock assessment that was carried out assumed that Jack mackerel constitute one single population, survey, climatic and catch observations suggest that more complex population structures may exist. These observations have resulted in intense discussions among SPRFMO scientists on likely population structure and preparation of TAC advice. Peer-reviewed literature on this topic suggests that sustainable management of the resource may be hampered when inappropriate assumptions are taken regarding population structure.

Scientists have suggested a number of different hypotheses to describe population structure of Jack mackerel. A single homogenously distributed population, the existence of two population units (Northern (off Peru) and Southern (off Chile), and possibly also a population unit at the high seas or coastal and high seas population units), patchy and metapopulation, where a Northern, Southern and potentially high seas population unit are connected through exchange of fish. Especially climatic fluctuations, owing to e.g. El Niño and La Niña, may be important to understand the population structure of Jack mackerel as changes in abiotic conditions (e.g. currents, temperature, oxygen content) and biotic conditions (e.g. prey) impact the habitat and distribution of Jack mackerel. In the end, a good understanding of population structure is crucial to design sustainable management regimes that match biological reality.

TAC advice for Jack mackerel is currently based on the single stock assessment results, from which projections are made for the near and intermediate future assuming constant fishing pressure. The future fishing pressure is assumed to be equal to 2014 or a fraction of that. This procedure does not necessarily result simultaneously in all desirable management objectives for Jack mackerel, i.e. rebuilding of the stock, long term sustainable catches and limited variability in the TAC from year to year. The SPRFMO Science Committee, supported by this EU project on Jack mackerel, have designed and evaluated potential exploitation strategies (so called Harvest Control Rules) that should result in sustainable fisheries an improve acceptance of the proposed TACs in the future.

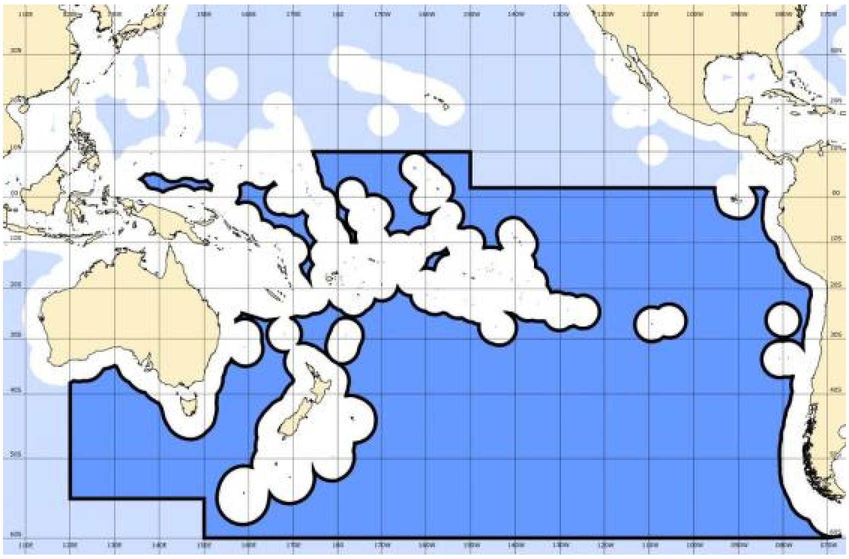

Figure 1: South Pacific Regional Fisheries Management Area. Dark blue represent international waters.

Population versus Stock structure

In this study a distinction is made between population structure and stock structure. The population structure entails the biological spatio-temporal organisation of Jack mackerel throughout the South Pacific, potentially driven by the highly dynamic Humboldt Current system and South Pacific gyre. Stock structure entails the abundance, distribution and availability of Jack mackerel to the fishery in the fishing season. In other words, stock structure entails the perceived view on the spatial organisation of Jack mackerel throughout the South Pacific from a fisheries management perspective.

To illustrate the difference, a theoretical scheme is presented (Figure 2). The black circles represent the population units and the yellow squares represent the fishery. On the left-hand side, parts of the population migrate to separate spatial locations during several months of the year where fisheries target it. In this case, the population structure can be considered as one homogenous unit, while from a fisheries perspective there would be two stocks. In the middle panel, a similar population structure is presented with similar migration, only the fishery now targets the population during the time when all fish reside in the same area. This would result in assuming a one-single stock. In the right-hand side panel, two populations are shown being targeted by one fishery. In this instance, only one stock would be considered. In this study we focus first on population structure and thereafter on stock structure.

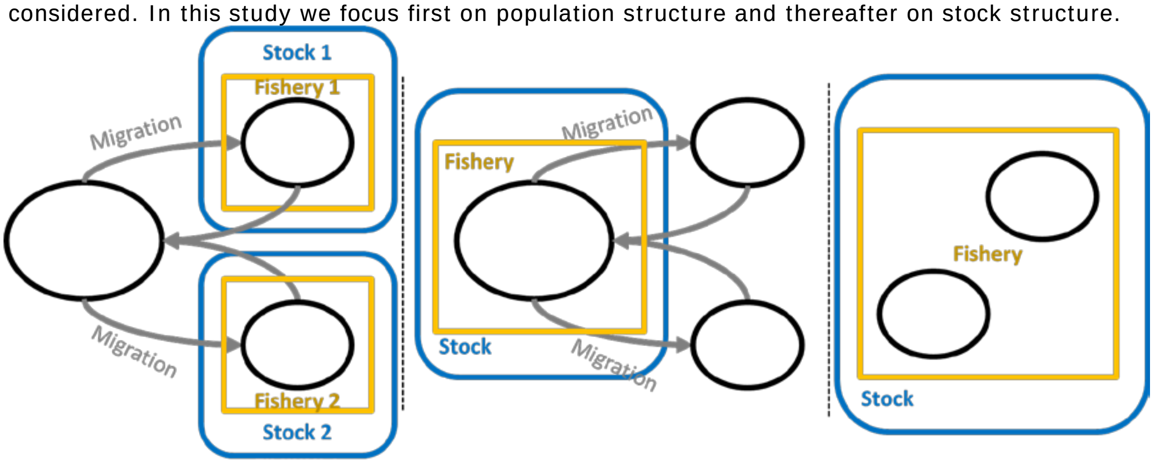

Figure 2. Theoretical illustration of the interaction between population structure (black circles with grey migration routes) and the fishery (yellow squares). The left-hand panel illustrates how one single population may distribute over two patches during part of the year and being targetted by two different fisheries on those times. The middle panel illustrates the same population structure but with a fishery targetting at a different time the population when it is structured into one patch. The right-hand side panel illustrates one fishery targetting two populations at the time.

The population structure of Jack mackerel may have changed considerably over time at millennial (Cardenas et al., 2009) to decadal scales (Kawahara et al. 1988, Gerlotto et al. 2012). Figure 3 shows a conceptual model adapted from a basin model framework (see MacCall 1990 and Bertrand et al., 2008) according to which the population structure may have changed under good and poor conditions. Given that population structure may have changed over time, the analyses of population and stock structure are in this project considered in the light of the most recent state of the population, at a time-series low in abundance.

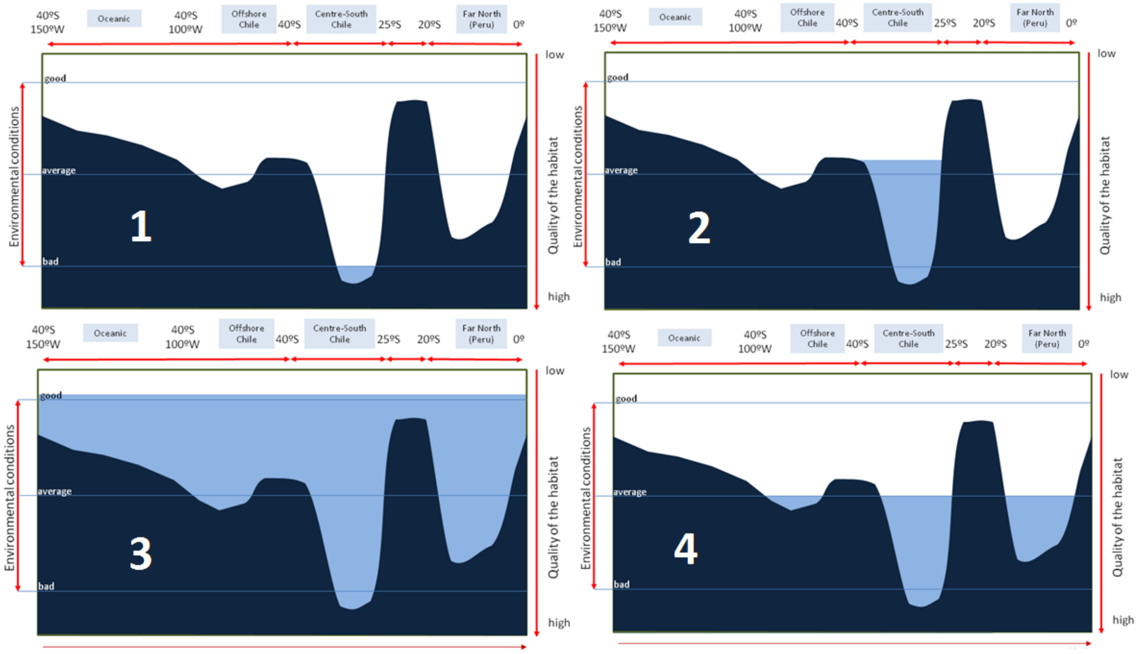

Figure 3. Description of population dynamics using McCall's Basin model as an example. The five main steps of the dynamics are presented.
1 bad environmental conditions. The only location of a source population is found in the deepest part of the basin (representing the only part of the habitat where fish can survive under these hard environmental conditions). The level is lower than the bottom of the other pits where no fish could survive.
2 improving conditions. The source niche is filled, but the level is not high enough to allow the colonization of the secondary niches that are empty despite their compatibility with life.
3 optimal conditions. The whole potential habitat is filled with fish, and the entire ecosystem is colonized. All the sub-areas are connected and there is only one large population visible.
4 back to average conditions. All the niches are occupied but the conditions do not allow exchanges between them. If these average conditions last long enough, the different sub-populations may eventually diverge.
5 rather bad conditions (not displayed, similar to I). The only niches where fish are found are those in the areas with the most favourable habitat. Some sub-populations are already extinct. If the conditions are still degrading, stage I will be reached and the only surviving sub-population will be a source.

Within the literature and during South Pacific RFMO working group meetings the population structure of Jack mackerel has been discussed extensively. So far, there is no consensus among scientists on the most likely population structure. The hypotheses are:

- **H1**: one discrete population
- **H2**: two discrete populations; one in Peruvian waters and one off Chile extending onto the high seas
- **H3**: two discrete populations; one in the coastal areas of Peru and Chile combined and one on the high seas
- **H4**: three or more discrete populations; one in Peruvian waters, one in the Chilean coastal zone and multiple discrete populations in the high seas
- **H5**: patchy population; with multiple patches of fish being highly connected to each other
- **H6**: metapopulation; with multiple patches of fish being moderately connected to each other

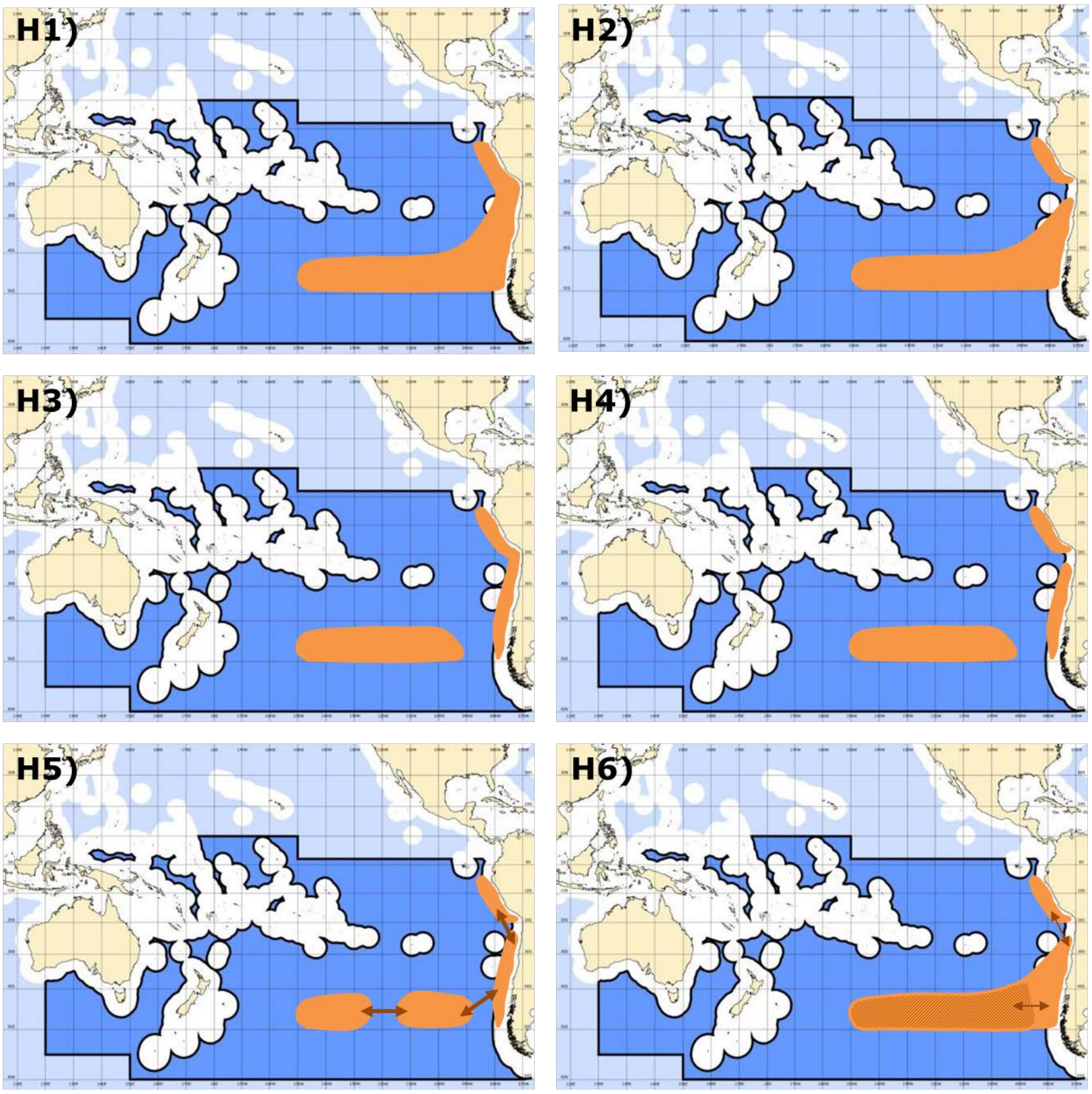

Figure 4. Illustration of the six hypotheses on population structure. The orange area shows the assumed distribution and connectivity of Jack mackerel. Separated patched denote different population units which may or may not be connected through mixing (arrows). Thicker arrows indicate higher exchange rates of fish than thinner arrows.

Project objectives

The project aims to provide insight into the most likely population structure as deducted from a comprehensive study using data analyses, literature review, statistical modelling and mechanistic modelling. Results indicate where there is substantial agreement and disagreement among the methods applied. Provided that uncertainty in each of these methods is apparent, using simulation modelling, we investigate the risks to jeopardize sustainable management, explicitly taking the uncertainty in population and stock structure into account.

The objectives of the project can be summarized in three over-arching topics:

1) Identify the most likely population and stock structure hypotheses of Jack mackerel
2) Considering the most likely population structure, identify management objectives for Jack mackerel
3) Evaluate sustainable management strategies to achieve these objectives

General approach

Six main activities were undertaking to meet the objectives. The interaction between activities is given in Figure 5. A short description of each of the activities is given below to illustrate how these contribute to addressing the objectives. More information can be found in the methodology description further on in this report and in the annexes. The following colour coding is used to identify where further information can be found in the annexes.

Annex A – WP1 | **Annex A – WP2** | **Annex A – WP3** | **Annex A – WP4** | **Annex A – WP5**

i. To perform all these analyses, the availability of data is crucial. A specific work package was devoted to collecting high resolution environmental, survey and catch data from as many countries and fleets as possible.

   Annex A – WP1

ii. **Literature study to list existing population structure hypotheses and key factors that determine population structure**

   Annex A – WP2, D2.1

   Most of the scientific work on Jack mackerel has been published in internal reports and local not-peer-reviewed publications, which means that no exhaustive synthesis was available at the beginning of this project. The main objective of this literature study was to provide a comprehensive basis of biological and ecological information as a starting point to define the existing population structure hypotheses. The literature review focussed on among others: life cycle migrations; reproductive strategies, in specific timing of the spawning seasons and spawning location; indications on population structure as studied using biological markers; the response of Jack mackerel in its distribution to changes in environmental conditions, and trophic interactions such as predator-prey interactions that may play a role in the dynamics of Jack mackerel. This study was used to list the hypotheses published on population structure, and to find out which arguments were available supporting or argue against any of the six major population structure hypotheses.

iii. **Modelling the 3D habitat of Jack mackerel, providing insight in potential separation of population units**

   Annex A – WP3, D3.1

   Studying the population structure of Jack mackerel and the ability to reveal the most likely population structure requires an in-depth understanding of the Jack mackerel habitat and environment. We first explored how environmental conditions shape the habitat (both its distribution in space as its position in the water column, i.e. 3D habitat) of Jack mackerel.

Key environmental factors determining Jack mackerel distribution were identified based on literature review. Combining fisheries and survey data with hydrographical data we characterized the environmental conditions where Jack mackerel had been observed in the South Pacific region. Several relationships between physical, chemical and trophic interactions were used to describe the habitat of Jack mackerel. The analyses allowed to determine the Jack mackerel habitat boundaries and most favourable areas within these limits according to temperature, dissolved oxygen, depth and food availability.

The favourable habitat of Jack mackerel was thereafter predicted using the environmental conditions mentioned above and maps were created that reflect favourable habitat in space and time. Inspection of these maps provided insights on whether Jack mackerel is distributed continuously in one large area or is separated into distinct areas, including during different climate and oceanographic conditions. The spatial distribution of the potential habitat and its temporal variations provided information on different hypotheses on population structure. In particular, we tested if the habitat conditions (e.g. oxycline depth) constrained the population structure (range of distribution, spawning area, development of meta-populations) when the oxygen minimum zone declines, resulting in a smaller favourable area in the Northern area off Peru.

iv. **Spatial and temporal modelling of Jack mackerel that provides insight in migration of fish and overlap of potentially different population units over time and space**

Annex A – WP3, D3.2

A spatial model of Jack mackerel population dynamics was designed to estimate migration routes of adult mature fish from and to the spawning grounds (SEAPODYM). The model simulates the age structured population of Jack mackerel in relation to environmental conditions, e.g., the drift of larvae with currents and the active movements of fish searching favourable conditions for feeding or spawning. To ensure that the modelled dynamics are realistic, acoustic survey and geo-referenced catch data were used in a statistical framework to estimate model parameters. The model was then applied to reconstruct distribution and migration of Jack mackerel over the past decades, but also to forecast future distribution and migration.

The amount of available geo-referenced (catch and survey) data available in the model optimization was relatively small (less than 10% of total nominal catch for all the population dynamics), and the estimation of some key parameters controlling the population dynamics are still uncertain.

Spatial structure of the population was analysed through inspection of SEAPODYM predicted feeding and spawning habitat distributions, migration routes, distributions of fish cohorts over the years and the rate of exchange of fish between population units.

v. **Designing and testing a candidate management plan**

Annex A – WP4, D4.1

Management can be formalized using Harvest Control Rules (HCR). These rules stipulate how fishing pressure should change under changing stock biomass. Such rules have been efficient to sustainably manage fish stocks elsewhere, partly by providing a transparent basis to set TACs. What such rules should look like and whether they are appropriate for achieving policy objectives for specific fish stocks, needs to be evaluated. Harvest control rules use reference points to indicate, for example, the maximum sustainable fishing mortality and the lowest sustainable biomass. Within this study, analyses were undertaken to estimate a set of reference points for Jack mackerel under two main hypotheses: the single-stock and two-stock hypotheses. The single stock hypothesis refers to Jack mackerel being targeted as a single structure for the whole South Pacific Ocean, while the two stocks hypothesis refers mostly to a stock centred on the

Centre-South Chile area with extensions in Northern Chile and the high seas, and a stock centred in Peruvian jurisdiction waters. There was a strong focus on F_{MSY}, the fishing mortality that is associated with Maximum Sustainable Yields. In our estimations of F_{MSY}, uncertainty regarding exploitation patterns of the fishery and population life-history characteristics such as growth were explicitly taken into account. In addition, B_{MSY} and B_{lim} (biomass under which recruitment may be impaired) were estimated. Current stock parameters may be compared with these reference points to evaluate if a stock is exploited sustainably or not.

The reference points also form a starting point to design different Harvest Control Rules. Based on stakeholder workshops and SPRFMO requests, a variety of HCR designs were formulated and evaluated. To test which of these rules lead to sustainable exploitation, a simulation model was used that projects stocks into the future under different HCRs. Model results were analysed and converted into key indicators informing stakeholders on expected catch levels, catch variability, rebuilding potential of the stock etc.

Furthermore, the effects of changes in fleet selectivity due to changes in mesh size or minimal landing size were investigated. The same model framework as applied under the HCR evaluations was used. Results show SSB, F and yield trends in the future.

vi. **Evaluating candidate management plans under different assumptions of population and stock structure**

Annex A – WP5, D5.1

The discussion on population structure is likely to recur, particularly when population structure changes as a result of variations in the size of the population. It is therefore important to test the HCRs designed, under a variety of population and stock structure hypotheses. These hypotheses resulted from the analyses as described under i-iii. In total three population structure hypotheses were evaluated. Per population structure hypothesis, two stock structure assumptions were made, bringing the total number of scenarios to six. For each of the six scenarios, six HCRs were tested. These six HCRs were part of the designs proposed under iv, and selected by the Scientific Committee meeting in 2014.

A simulation model was designed that allows the different population structure hypotheses to be evaluated in combination with different Harvest Control Rules. Many components of the model are identical to the methods applied under iv to ensure that simulations provide similar results regardless of the model used. The results from the single stock assessment and the North & South stock assessments of the SPRFMO Scientific Committee were used to parameterize the models. Results from the SEAPODYM modelling exercise were used to estimate exchange rates of fish between multiple population units under those scenarios where exchange of fish between population units was present. This is especially important because exchange rates may be affected by changing environmental conditions. Model results were analysed and converted into key indicators informing stakeholders especially on probability for overexploitation under the evaluated HCRs and population structure hypotheses. With these results it is possible to define sustainable management regardless of population structure assumption, and shows also the trade-offs of not considering the most likely population structure.

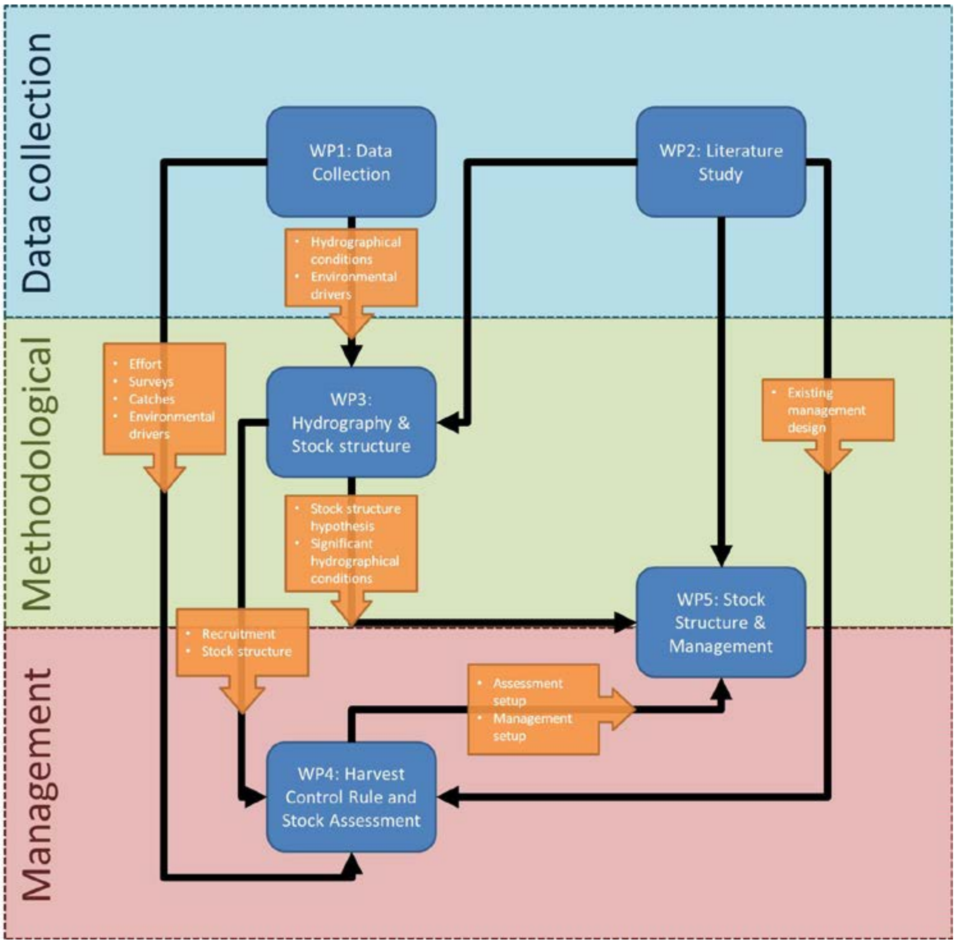

Figure 5. Project structure, including work packages and their interactions.

Conclusions & methodology on project objectives

1) Identify the most likely population and stock structure hypotheses of Jack mackerel

Conclusions on the most likely population structure

In total, six different population structure hypotheses were considered. In this study, information from the literature, habitat modelling and spatio-temporal modelling has been collected that clearly shows that the population structure of Jack mackerel cannot be considered as a single discrete population (H1), two (H2 & H3) or multiple discrete populations (H4). The lack in genetic difference, substantial degree of exchange of fish between areas and partial synchrony in cohorts and population development show that one or several discrete units are very unlikely to exits. Remaining hypotheses contain a patchy or metapopulation structure. Due to lack in synchrony in population dynamics between Jack mackerel off Peru and Chile, and separation in habitat during the first four months of the year, one has to reject the hypothesis of a patchy population (H5) too which leaves the metapopulation hypothesis as the only remaining one. No strong evidence was presented to reject this hypothesis. Therefore we conclude that the metapopulation structure (H6) is most likely for Jack mackerel in the South Pacific. Simulations in this study suggest that there is an isolated (but small) 'New Zealand' unit, a South-Central Chilean unit extending onto the high seas and a Peruvian unit, which receives significant contribution in biomass from the South-Central unit. There seems to be a small contribution in the opposite way, i.e. from the Peru region to the Southern regions.

Annex A – WP2, D2.1   Annex A – WP3, D3.1, D3.2

Conclusion on the most likely stock structure

To conclude on stock structure, the population structure must be studied together with the fisheries exploiting it. We argue here that all fish being targeted by one fishery can be considered a separate stock, as long as this part of the stock is not targeted by any other fishery in the same year (else, there is a risk that the same part of the population is targeted twice without appropriately accounting for double counting the same fish). In this instance, the fish inside Peruvian waters is bounded by its habitat during the fishing season from January till May with peak catches in April. During this period the habitat restricts exchange of fish to other regions. The same applies for the fish inside the Chilean coastal areas which is targeted around the same time of the year, with a peak around April. The catches inside the Chilean coastal area however cannot be considered in isolation from the catches at the high-seas. The South-Central Chilean fleet targets fish inside jurisdictional waters in the beginning of the year and track these fish when they (or partly) migrate onto the high-seas where they are also susceptible to the international fleet. Therefore, catches inside the Chilean zone affect catch potential on the high-seas, and vice-versa. Given that in the past decade no substantial catches are taken from areas far out at the high-seas, we conclude on a two-stock structure in the eastern side of the Southern Pacific.
Given that over years changes in the dynamics of Jack mackerel in the Southern zone affect Jack mackerel in the Northern zone, management of the two areas cannot be considered in complete isolation from each other.

Annex A – WP4, D4.1 D4.2

In this project, three approaches were taken to investigate the most likely population structure: 1) a literature study to list existing population structure hypotheses and key factors that determine population structure, 2) statistical modelling of the 3D habitat of Jack mackerel that provides insight in potential separation of populations and 3) spatial and temporal simulation of the Jack mackerel environment and population that provides insight in migration of fish and overlap of potentially different population units over time and space. On the basis of these three analyses, Table 1 below has been constructed listing the six population structure hypotheses that were proposed. The table contains a short summary of the information obtained from different sources that would support or contradict the hypotheses. Each of the information sections listed were grouped (colour coded) according to the quality of the information. Where peer-reviewed or SPRFMO reports could be linked to the information, references to these documents are given under the 'source' column. Where new information is presented owing to analyses in this project, the source column states 'this project'.

Methods and results to inform on population structure

Literature review

Table 1 below shows a summary of the supporting and contradicting information collated for each of the population structure hypotheses. Each table cell contains a short summary of the information and the source column lists where the information is obtained from, indicating either peer-reviewed sources, SPRFMO documentation or results obtained within this project. Additional information was collected within the literature study, 3D-habitat modelling and SEAPODYM spatial population dynamics modelling activities in this project. Further analyses of population structure requires tagging studies that provide direct information on fish movement and mixing between population units and the variability in mixing between years and population units.

Table 1. For each of the six hypotheses listed, supporting and contradicting information has been collected and brought together in this table. Colour coding indicates the quality of the information and the source where the information was obtained from is listed behind each statement.

Supported by peer-review	Supported by SPRFMO report or MS in prep. / submitted	Observation supported by analyses	Observation, not supported by analyses

1) Single discrete population. Under this assumption all Jack mackerel in the South Pacific are assumed to be belong to one population that is homogenously in structure throughout the entire distribution area.			
Support	**Source**	**Contradict**	**Source**
No genetic evidence is found to differentiate fish caught in different regions ranging from Peru to Chile and onto the high seas	Cardenas et al. 2011	A certain degree of segregation in otolith biogeochemistry was found for adults to distinguish between fish caught off Peru and Chile	Ashford et al. 2011
No clear segregation in otolith biogeochemistry was found for juveniles to distinguish between fish caught in Peruvian or Chilean waters.	Ashford et al. 2011	Differences in growth and estimated growth parameters are observed between fish caught off Peru and Chile	Goicochea et al. 2013 (book)
There is a high degree of similarity in length distribution from Northern Chile and Southern Peru catches	SPRFMO CHJMWS 12 + SPRFMO CHJMWS 5	A difference in encountered natural mortality between fish off Peru and Chile is observed	SPRFMO SC-01-2013 Annex 5
Strong cohorts appear all over the Pacific	Konchina and Pavlov 1999	Based on an analyses of the metazoa parasite fauna, a small difference between fish off Peru and the Chilean coast is observed	Oliva et al. 1999
Only a continuous and permanent distribution of adult fish is shown off Chile **Annex A – WP3, D3.2**	**(this project)**	A difference in age distribution in the catch taken off Peru and off Chile / high seas is observed	Gerlotto et al. 2012
		A difference in estimated recruitment / productivity, obtained from assessment results, is observed between stock assessments separating the Northern and Southern fisheries	SPRFMO SC-02 Annex 4
		The existence of a 'few-fish zone' between ~19-22° South is observed in acoustic and catch geo-referenced data. In addition, the predicted separation in coastal habitat during part of the year limits extensive mixing. **Annex A – WP3, D3.1**	SPRFMO CHJMWS 5 Habasque & Bertrand **(this project)**

2) Two discrete populations (off Peru and Chile). Under this assumption the Jack mackerel in the South Pacific are assumed to be belong to two populations, one population off Peru and one off South-Central Chile extending onto the high seas up to New Zealand. The populations are assumed to be discrete and therefore do not mix during their life.			
Support	**Source**	**Contradict**	**Source**
A certain degree of segregation in otolith biogeochemistry was found for adults to distinguish between fish caught off Peru and Chile	Ashford et al. 2011	No clear segregation in otolith biogeochemistry was found for juveniles to distinguish between fish caught in Peruvian or Chilean waters.	Ashford et al. 2011
Differences in growth and estimated growth parameters are observed between fish caught off Peru and Chile	Goicochea et al. 2013 (book)	No genetic evidence is found to differentiate fish caught in different regions ranging from Peru to Chile and onto the high seas	Cardenas et al. 2011
A difference in encountered natural mortality between fish off Peru and Chile is observed	SPRFMO SC-01-2013 Annex 5	Analyses show that the 2008 cohort, first captured off Chile, may have migrated under a strong La Nina effect into Peruvian waters in the beginning of 2011 **Annex E –2014 -03**	SPRFMO SC-02-JM-03 **(this project)**
Based on an analyses of the metazoa parasite fauna, a small difference between fish off Peru and the Chilean coast is observed	Oliva et al. 1999	Observations suggest a certain degree of time-lagged correlation in recruitment success in both Peruvian and Chilean waters	SPRFMO SC-02 Annex 4
The existence of a 'few-fish zone' between ~19-22° South is observed in acoustic and catch geo-referenced data. In addition, the predicted separation in coastal habitat during part of the year limits extensive mixing. **Annex A – WP3, D3.1**	SPRFMO CHJMWS 5 Habasque & Bertrand **(this project)**	Substantial connectivity between fish in Chilean, Coastal and Peruvian areas **Annex A – WP3, D3.2**	**(this project)**
A difference in estimated recruitment / productivity, obtained from assessment results, is observed between stock assessments separating the Northern and Southern fisheries	SPRFMO SC-02 Annex 4		
A difference in age distribution in the catch taken off Peru and off Chile / high seas is observed	Gerlotto et al. 2012		
Spawning is observed in multiple patches / areas throughout the South Pacific and is not limited to one spawning area	Ayon and Correa, 2013 + Gretchina, 2009		

3) Two discrete populations (coastal & high seas). Under this assumption the Jack mackerel in the South Pacific are assumed to be belong to two populations, one coastal population and one population at the high seas up to New Zealand. The populations are assumed to be discrete and therefore do not mix during their life.			
Support	**Source**	**Contradict**	**Source**
No clear segregation in otolith biogeochemistry was found for juveniles to distinguish between fish caught in Peruvian or Chilean waters.	Ashford et al. 2011	Differences in growth and estimated growth parameters are observed between fish caught off Peru and Chile	Goicochea et al. 2013
		A difference in encountered natural mortality between fish off Peru and Chile is observed	SPRFMO SC-01-2013 Annex 5
		Based on an analyses of the metazoa parasite fauna, a small difference between fish off Peru and the Chilean coast is observed	Oliva et al. 1999
		The existence of a 'few-fish zone' between ~19-22° South is observed in acoustic and catch geo-referenced data. In addition, the predicted separation in coastal habitat during part of the year limits extensive mixing. **Annex A – WP3, D3.1**	SPRFMO CHJMWS 5 Habasque & Bertrand **(this project)**
		The spatio-temporal SEAPODYM model, parameterized for Jack mackerel, shows that the distribution of adult and juvenile fish is also oriented perpendicular to the coast **Annex A – WP3, D3.2**	**(this project)**
		Analyses show that the 2008 cohort, first captured off Chile, may have migrated under a strong La Nina effect into Peruvian waters in the beginning of 2011 **Annex E – 2014 - 03**	SPRFMO SC-02-JM-03 **(this project)**
		A recent eastward shift in distribution area of the main catches in the south-central area of the South Pacific has been observed with limited availability of Jack mackerel outside Chilean jurisdictional areas.	SPRFMO SC-01-04-rev2 + SPRFMO SC-02 Annex 4
		Analyses of the 3D habitat modelling show a continuous suitable habitat perpendicular to the coast off Chile **Annex A – WP3, D3.1**	**(this project)**
		A certain degree of segregation in otolith biogeochemistry was found for adults to distinguish between fish caught off Peru and Chile	Ashford et al. 2011
		Substantial connectivity from fish at high-seas to coastal areas **Annex A – WP3, D3.2**	**(this project)**

4) Three or more discrete populations (off Peru, Chile & multiple populations in the high seas). Under this assumption the Jack mackerel in the South Pacific are assumed to be belong to three or more populations, one population off Peru, one off South-Central Chile and one or multiple populations at the high seas up to New Zealand. The populations are assumed to be discrete and therefore do not mix during their life.			
Support	**Source**	**Contradict**	**Source**
Differences in growth and estimated growth parameters are observed between fish caught off Peru and Chile	Goicochea et al. 2013 (book)	No clear segregation in otolith biogeochemistry was found for juveniles to distinguish between fish caught in Peruvian or Chilean waters.	Ashford et al. 2011
A difference in encountered natural mortality between fish off Peru and Chile is observed	SPRFMO SC-01-2013 Annex 5	Observations of spawning activity span from the Chilean coast up to 110°W	Gretchina et al. 2008 (Presentation)
Based on an analyses of the metazoa parasite fauna, a small difference between fish off Peru and the Chilean coast is observed	Oliva et al. 1999	The spatio-temporal SEAPODYM model, parameterized for Jack mackerel, shows that the distribution of adult and juvenile fish is also oriented perpendicular to the coast **Annex A – WP3, D3.2**	**(this project)**
The existence of a 'few-fish zone' between ~19-22° South is observed in acoustic and catch geo-referenced data. In addition, the predicted separation in coastal habitat during part of the year limits extensive mixing. **Annex A – WP3, D3.1**	SPRFMO CHJack mackerelWS 5 Habasque & Bertrand **(this project)**	A recent eastward shift in distribution area of the main catches in the south-central area of the South Pacific has been observed with limited availability of Jack mackerel outside Chilean jurisdictional areas.	SPRFMO SC-02 Annex 4
At least two main spawning areas are defined	Ayon and Correa, 2013	No genetic evidence is found to differentiate fish caught in different regions ranging from Peru to Chile and onto the high seas	Cardenas et al. 2011
Observations show local spawning activity inside New Zealand waters. Most catches correspond to large and old Jack mackerel	SPRFMO CHJMWS 19	Analyses show that the 2008 cohort, first captured off Chile, may have migrated under a strong La Nina effect into Peruvian waters in the beginning of 2011 **Annex E – 2014 - 03**	SPRFMO SC-02-JM-03 **(this project)**
A segregation in otolith biogeochemistry was found for adults to distinguish between fish caught off Peru and Chile	Ashford et al. 2011	Substantial connectivity from fish at high-seas to coastal areas **Annex A – WP3, D3.2**	**(this project)**
No flow of juveniles from coastal areas to high seas **Annex A – WP3, D3.2**	**(this project)**		

5) Patchy population. Under this assumption the Jack mackerel in the South Pacific are assumed to be organised in different populations but maintain a high degree of inter-population exchange resulting in correlated population fluctuations.			
Support	**Source**	**Contradict**	**Source**
No genetic evidence is found to differentiate fish caught in different regions ranging from Peru to Chile and onto the high seas	Cardenas et al. 2011	A difference in age distribution in the catch taken off Peru and off Chile / high seas is observed	Gerlotto et al. 2012
Differences in growth and estimated growth parameters are observed between fish caught off Peru and Chile	Goicochea et al. 2013 (book)	The existence of a 'few-fish zone' between 19-22° South is observed in acoustic and catch geo-referenced data. In addition, the predicted separation in coastal habitat during part of the year limits extensive mixing. **Annex A – WP3, D3.1**	SPRFMO CHJMWS 5 Habasque & Bertrand **(this project)**
There is a high degree of similarity in length distribution from Northern Chile and Southern Peru catches	SPRFMO CHJMWS 12 + SPRFMO CHJMWS 5	Analyses of the trend in population units, based on assessment results separating Peruvian and other catches, do not show a close synchrony in development	SPRFMO SC-02 Annex 4
Based on an analyses of the metazoa parasite fauna, a small difference between fish off Peru and the Chilean coast is observed	Oliva et al. 1999	No extensive connectivity between fish in Peruvian and Chilean waters or to the high seas except during strong El Niño when there is a flux from offshore to coast and south to north. **Annex A – WP3, D3.2**	**(this project)**
Jack mackerel is considered a highly migratory species with the ability to migrate between potential habitat patches	Arcos et al. 2001		
The heterogeneous habitat owing to the Humboldt current system results in patchy suitable habitats **Annex A – WP3, D3.1**	Habasque & Bertrand **(this project)**		

6) Metapopulation. Under this assumption the Jack mackerel in the South Pacific are assumed to be organised in different populations and maintain a limited to moderate degree of inter-population exchange. Correlated population fluctuations may, but do not need to occur.			
Support	**Source**	**Contradict**	**Source**
Spawning is observed in multiple patches / areas throughout the South Pacific and is not limited to one spawning area	Ayon and Correa, 2013 + Gretchina, 2009	No connectivity between coastal Chile and high-seas fish, no connectivity between Peru and high-seas fish **Annex A – WP3, D3.2**	**(this project)**
Differences in growth and estimated growth parameters are observed between fish caught off Peru and Chile	Goicochea et al. 2013	Habitat is only partly fragmented throughout the year. There is no fragmentation between habitat off Chile and onto the high seas **Annex A – WP3, D3.1**	**(this project)**
A difference in age distribution in the catch taken off Peru and off Chile / high seas is observed	Goicochea et al. 2013		
The existence of a 'few-fish zone' between ~19-22° South is observed in acoustic and catch geo-referenced data. In addition, the predicted separation in coastal habitat during part of the year limits extensive mixing. **Annex A – WP3, D3.1**	SPRFMO CHJMWS 5 Habasque & Bertrand **(this project)**		
Based on an analyses of the metazoa parasite fauna, a small difference between fish off Peru and the Chilean coast is observed	Oliva et al. 1999		
Analyses show that the 2008 cohort, first captured off Chile, may have migrated under a strong La Nina effect into Peruvian waters in the beginning of 2011 **Annex E – 2014 - 03**	SPRFMO SC-02-JM-03 **(this project)**		
Analyses of the trend in population units, based on assessment results separating Peruvian and other catches, do not show a close synchrony in development	SPRFMO SC-02 Annex 4		
A segregation in otolith biogeochemistry was found for adults to distinguish between fish caught off Peru and Chile	Ashford et al. 2011		

3D habitat modelling of Jack mackerel

Annex A – WP3, D1.3, D3.1

A statistical framework was developed to relate the presence of Jack mackerel at survey and catch locations to biotic and abiotic factors observed at these locations. For this purpose, acoustic and fisheries data were used. Factors considered were temperature, chlorophyll-a concentration, a proxy for prey abundance, and dissolved oxygen. Indeed, fish need sufficient amounts of both food and oxygen, but the latter might be more difficult to obtain than the former (Pauly, 2009).

Dissolved oxygen concentration and oxycline depth, i.e., the limit between the surface oxygenated waters and the Oxygen Minimum Zone – (OMZ) is a fundamental property regulating pelagic ecosystem structure in the coastal Southeastern Tropical Pacific (Bertrand et al., 2011). In accordance with the literature (Bertrand et al., 2004b, 2006) results of the statistical analyses performed here indicate that Jack mackerel thermal habitat is limited between 9ºC and 26ºC. Minimal chlorophyll-a concentration was estimated at 0.07 $mg.m^{-3}$. However, results highlighted the existence of an interaction between these factors. Indeed, the higher the temperature, more food is needed (Kooijman, 2010). We therefore considered the interaction between these parameters. Vertically the habitat was delimited by both the 9ºC isoline (at a minimum of 60 m depth) and the oxycline depth as characterized by the 2 $ml\ l^{-1}$ isoline (at a minimum of 40 m depth). The combination of these parameters allowed to predict the suitable habitat of Jack mackerel and to study whether the habitat would show discontinuities along the area studied. Predictions were made for the years 1998-2007.

Both inter-annual and seasonal patterns of habitat suitability variability where explored. A clear seasonal pattern occurs (Figure 6) along the Chilean and Peruvian coasts with a contraction of the favourable habitat towards the cost in austral summer (Jack mackerel is then more concentrated close to the coast increasing its catchability by the Peruvian fleet) and an extension in winter. This leads to a temporal discontinuity (or low connectivity, low potential for fish exchange between areas) at ~19ºS - 22ºS from January to March. A strong inter-annual variability was also observed (Figure 7) with, for instance in January, years with high fish exchange between Chile and Peru (e.g. 2003) and others with a strong gap (e.g. 1998, 1999, 2001 or 2007) at ~19ºS - 22ºS.

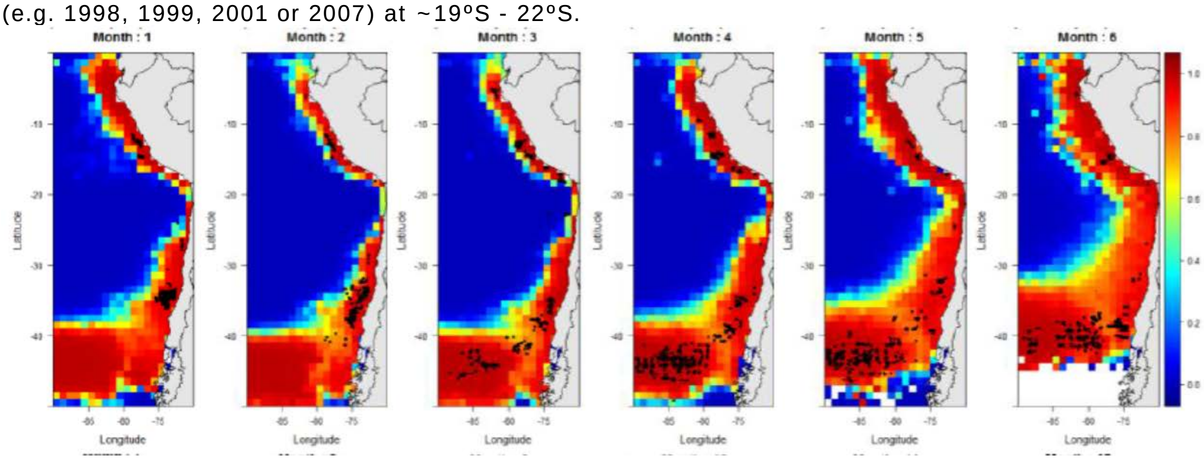

Figure 6. Predicted suitable Jack mackerel habitat during the first months of the year when the majority of the catches in Peru and Chile are taken. Catch observations are superimposed as black dots. Migration of fish from Peru to Chile or vice versa is limited during these months due to unfavourable environmental conditions around 20°S.

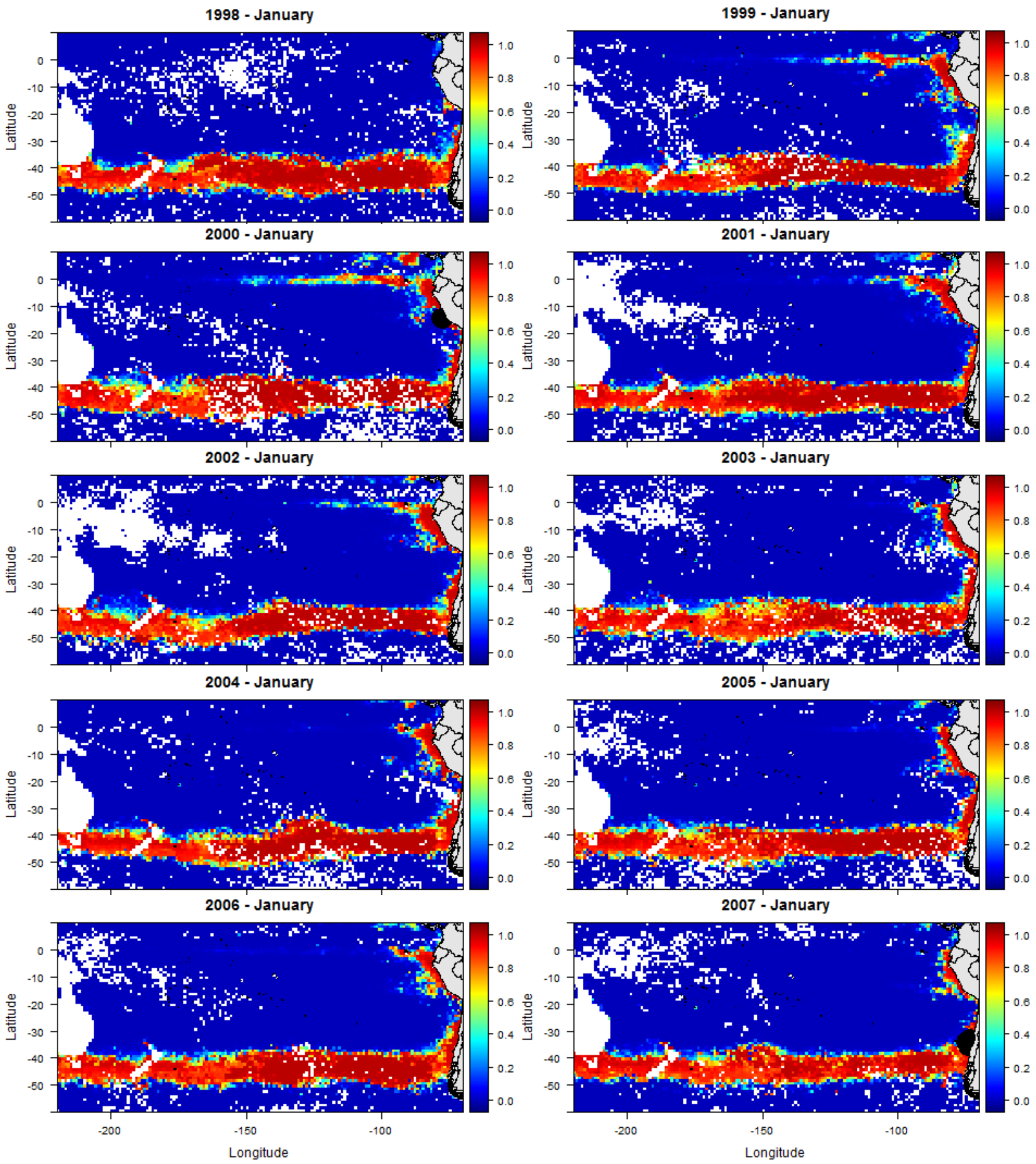

Figure 7. Predicted habitat probability maps for the month of January from 1998 to 2007. Presence data are in black solid circle. White pixels correspond to missing SST or CHL-a data.

Model outputs indicate that both extreme scenarios, i.e. single and multiple discrete population structures, are unlikely. A high continuity in Jack mackerel habitat occurs in austral winter permitting exchanges from the high seas to the Peruvian coast via the Chilean coast. However this exchange potential is reduced in austral summer with a gap at ~19°S - 22°S. The degree of separation varies at an inter-annual scale. The lack of exchanges at some periods/season explains why growth patterns (Goicochea et al., 2013) and parasite composition (Oliva et al., 1999) can differ between Chile and Peru that present different thermal, prey and biodiversity conditions. On the other hand the continuity in the habitat during part of the year helps to understand why strong exchanges in juveniles and in a lesser extend adults occur (Ashford et al., 2011). The favourable habitat can be highly reduced off Peru during certain years (e.g. during El Niño 1997-1998, Figure 7). Therefore even if Jack mackerel can spawn all along the Peruvian coast (Ayón and Correa, 2013; Gretchina, 2009), when the suitable habitat shrinks, the main source for Jack mackerel is located off Chile. The most probable population structure is therefore a metapopulation as described by Gerlotto et al. (2012).

Using the results of the statistical analyses we constructed a 3-dimensional conceptual model of the Jack mackerel habitat and distribution in the South-eastern Pacific (Figure 8). Jack mackerel habitat is horizontally and vertically limited by temperature, productivity and oxygen concentration. Figure 8 corresponds to a case where the oxycline off south-centre Peru (~ 19-22°S) is very shallow limiting fish exchanges between the Chilean and Peruvian sub system. This kind of situation is likely to occur on a seasonal basis, in austral summer, when the oxycline is shallower (Passuni et al., resubmitted) but also at longer temporal scales. Shallow oxycline conditions occurred during the 1960s and the 2000s (Bertrand et al., 2011). Historical timescale paleo-reconstructions (Gutiérrez et al., 2009; Salvatteci, 2013) show that during the 21st century, characterised by low oxygen conditions, Jack mackerel was likely not abundant off Peru, except during the 1970s - 1990s. This period and the years since 2010 where characterized by a deeper oxycline and corresponded to an increase in Jack mackerel abundance and caches off Peru. Furthermore if paleo-reconstructions show that Jack mackerel was likely not abundant off Peru during the last centuries, it was present throughout the last two centuries further south, off Chile (Gutiérrez et al., 2009) where oxygen is less limiting. With productivity, oxygen seems therefore a fundamental factor that allows Jack mackerel to migrate from Southern areas into Peruvian waters.

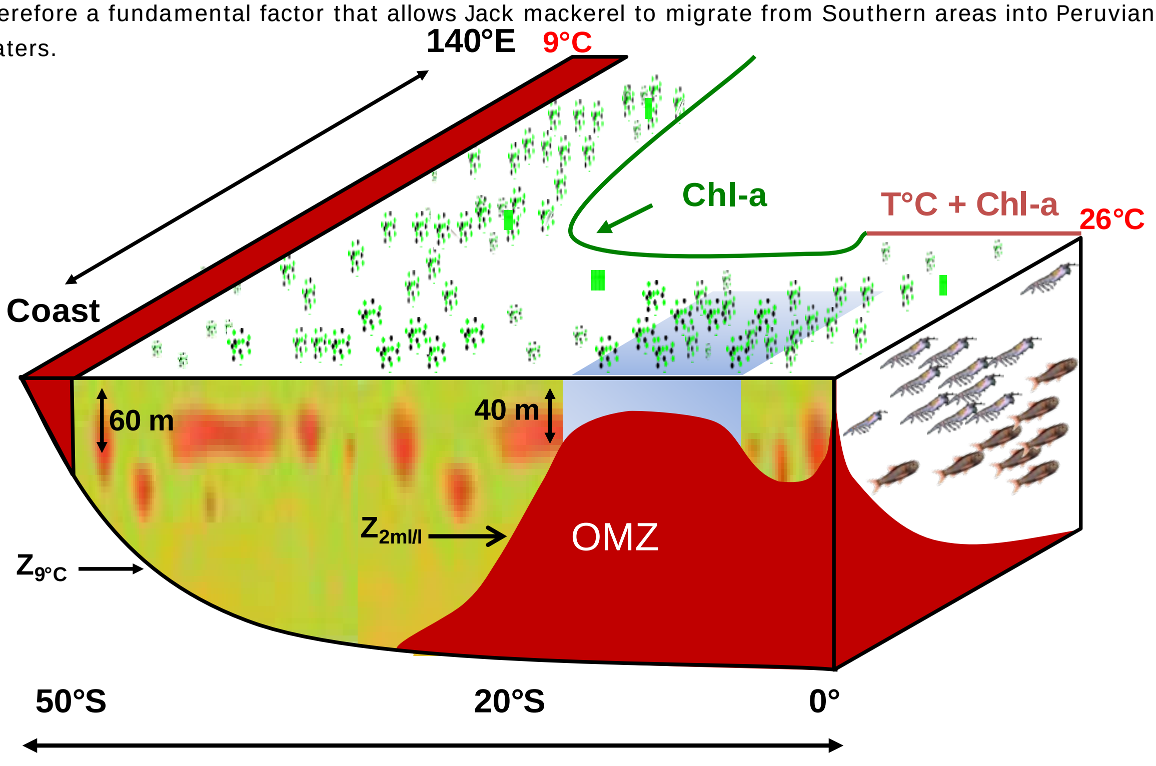

Figure 8. 3D conceptual model of the Jack mackerel habitat in the South Pacific. The habitat is limited by temperature ($Z_{9°C}$), productivity (Chl-a) and oxygen concentration ($Z_{2ml/l}$). Red surfaces correspond to unfavourable habitat delimited in the south by the 9ºC SST isoline and a minimum depth of 60 m for the 9ºC isotherm ($Z_{9°C}$) and in the north by the 26ºC SST isoline. Between these limits, the horizontal range of Jack mackerel is limited by the oligotrophic waters of the subtropical gyre (green solid line) or a combination of temperature and productivity (T°C+Chl-a, light red solid line). Vertically the distribution of Jack mackerel is limited by $Z_{9°C}$ or when the oxygen concentration reaches 2 ml/l ($Z_{2ml/l}$). If $Z_{2ml/l}$ is lower than 40 m then the habitat is unfavourable (light blue-grey area). Jack mackerel are represented by yellow to red small structures (fish abundance and density increasing from yellow to red). The green patches represent the primary productivity. The distribution of euphausiids and mesopelagic fish (important Jack mackerel prey) is schematically represented on the right part of the habitat as a typical cross-shore section with euphausiids more abundant just after the shelf break and the mesopelagic further offshore.

Annex A – WP3, D1.2, D1.1, D3.1, D4.2

The SEAPODYM model was configured for the Jack mackerel population and fisheries. SEAPODYM is developed to investigate spatial dynamics of fish populations, under the influence of both fishing and environmental effects (Lehodey et al. 2008). SEAPODYM simulates fish density distribution of age-structured populations with length and weight relationships obtained from independent studies. Different life stages are considered: larvae, juveniles and (immature and mature) adults. The model includes a representation of fisheries and predicts total catch and size frequency of catch by fleet when fishing data (catch and effort) is available. A statistical approach based on a maximum likelihood estimation framework is used to estimate population dynamic parameters (Senina et al., 2008).

The simulation outputs suggest three spawning grounds (Figure 9) in accordance with the known distribution of larvae and juveniles of Jack mackerel, i.e. in the Chilean coastal waters, off Chile and far to the east, and in Peruvian waters, in particular the Southern coast. There is a strong connection between Coastal Chile and offshore Chile spawning grounds, but a weak connection between coastal Chile and the Northern region (Peru). The spawning is predicted to occur in the 3^{rd} quarter with a peak around September.

The feeding habitat changes with age of cohorts due to changes in the thermal habitat, i.e., larger fish can access lower temperature water masses. Therefore feeding habitats of young fish extend further north than those of older fish (Figure 9). Oldest (largest) fish would feed only in the Southern Pacific below 30°S, but can move north seasonally for spawning.

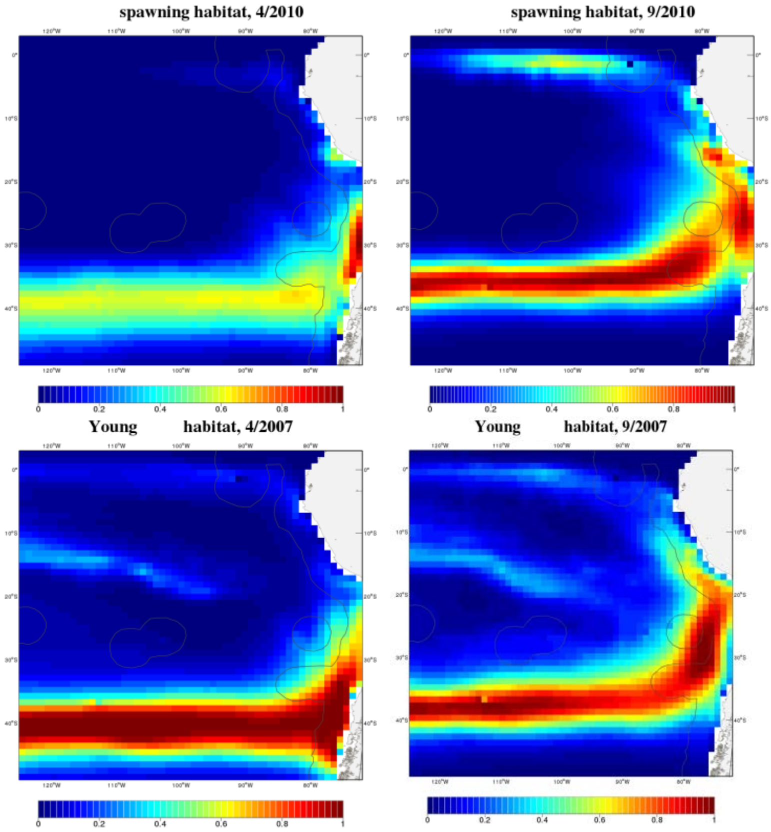

Figure 9. Maps of habitat indices of spawning (top) and feeding habitat of fish at 1st age of maturity predicted with SEAPODYM for Jack mackerel in April and September of 2010.

Based on these spawning and feeding habitat definitions, the model also simulates the complete spatial and temporal dynamics of the fish population, from larvae to oldest cohorts. These outputs were used to analyse the spatial structure of the population. Additional simulations were conducted to estimate the exchange rate of fish between areas and the seasonal migration rates.

With the parameterization achieved, and without considering any fishing effect, the model simulates a biomass distribution with a core area of fish extending along the eastern and Southern part of the South Pacific gyre and the cold currents moving north along the South American coasts (Humboldt current system). A diffusion pattern is observed from these core areas (Figure 10). Though there is continuity along this “Jack mackerel Belt” from Peru to Chile, New Zealand and Australia, several patches with highest concentrations of larvae are predicted in central Coastal Chile, offshore Chile, the South Pacific central and the eastern New Zealand regions. A lower but separate concentration of juvenile Jack mackerel appears along the Southern Peruvian Coast (Figure 10). When getting older, the fish distribution is predicted with two connected core areas between offshore Chile and far east of New Zealand (Figure 10).

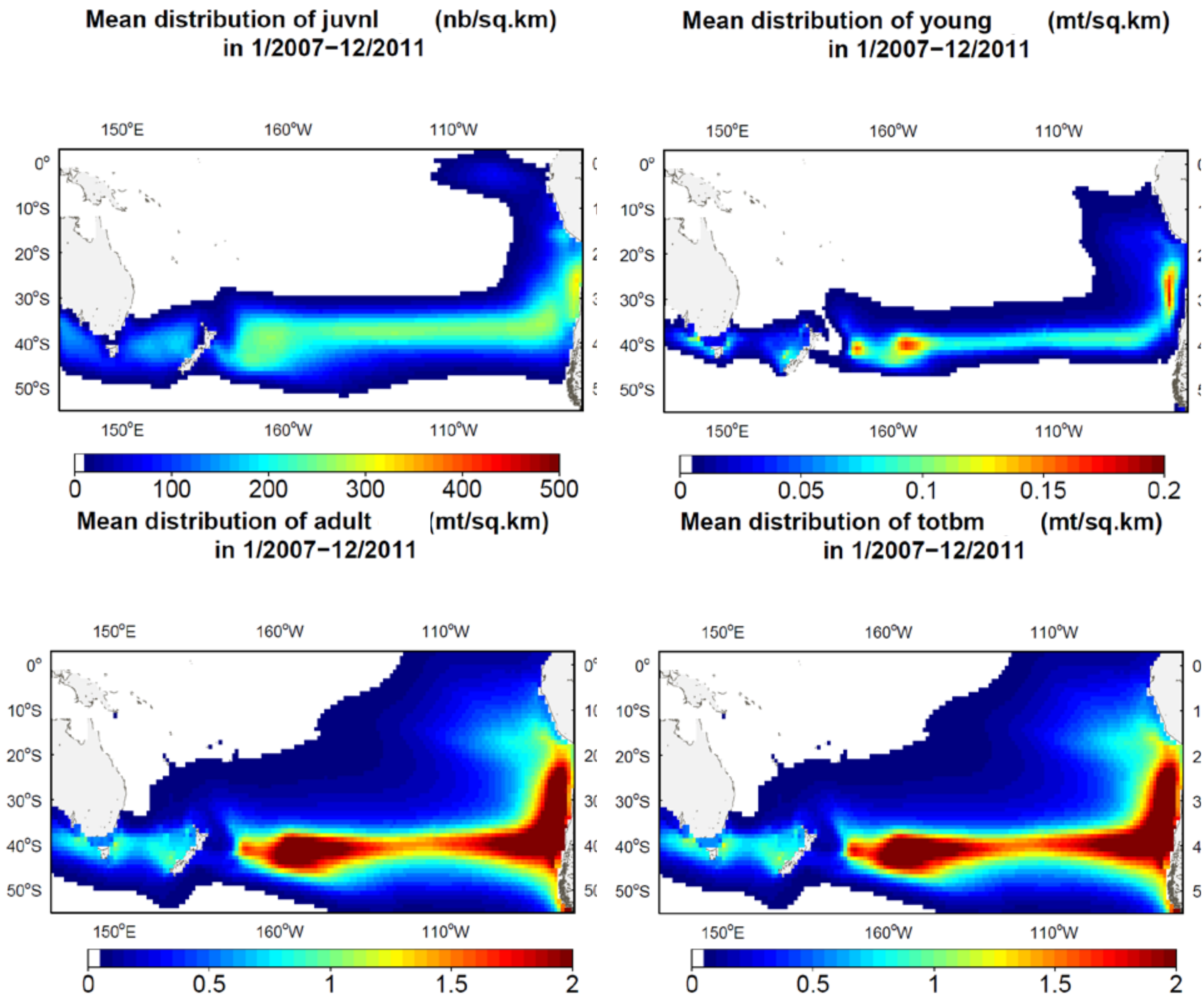

Figure 10. Predicted average distribution (2007-2011), without fishing impact, of juvenile, young immature, adult mature and total biomass of South Pacific Jack mackerel.

Exchange rates of fish and seasonal migration between large oceanic regions were studied (Figure 11, Table 2). To estimate the exchange rate of Jack mackerel between distant or adjacent geographical regions, the distribution area of Jack mackerel has been divided into seven large areas (Figure 11): the coast of south Chile (region 1), the coast of north Chile (region 2), the transition offshore zone (region 3), the coast of Peru (region 4), the New Zealand and Tasman Sea (region 5), the western (region 6a) and eastern (region 6b) South Pacific. The exchange rate of fish between these large areas was estimated through a set of SEAPODYM simulations by setting the spawning output in one area (the donor area) to zero and computing the difference with the reference simulation without fishing to observe the resulting change in biomass in the other (recipient) areas. This provides a measure of the contribution of spawning in one area on the biomass in all areas.

The results suggest that the most western region (region 5 and 6a) are isolated from the others both in term of recruitment of young fish and fluxes of adult fish. Region 6b receives young and adult fish from its western adjacent region (6a) but has a weak exchange of fish with eastern and Northern regions. The Peruvian region (4) provides extremely limited recruits and adults to other regions but receive significant contribution in young recruits from adjacent regions 2 and 3 and relatively good contribution also of region 6b for adult fish. Finally regions 1, 2, 3 appear inter-connected and receive also strong contributions of region 6b.

The results are confirmed by the analysis of seasonal migration between the eastern Pacific regions (1 to 4 and 6b) for three selected annual cohorts of age 1, 5 and 10 years (Table 3). There is an important migration of fish from region 6b to region 1 and at a lower level to region 3; the migration towards region 4 are coming from adjacent region 2 and 3 but there is very limited migration from region 4 to the others. Basically, the computation of migration suggest the same results as with the exchange rate of fish study based on recruitment but highlight paths of movements that are high only between adjacent regions, i.e., from region 6b to 1, then region 1 to region 2, region 2 to region 3 and region 3 to regions 2, 3 and 4.

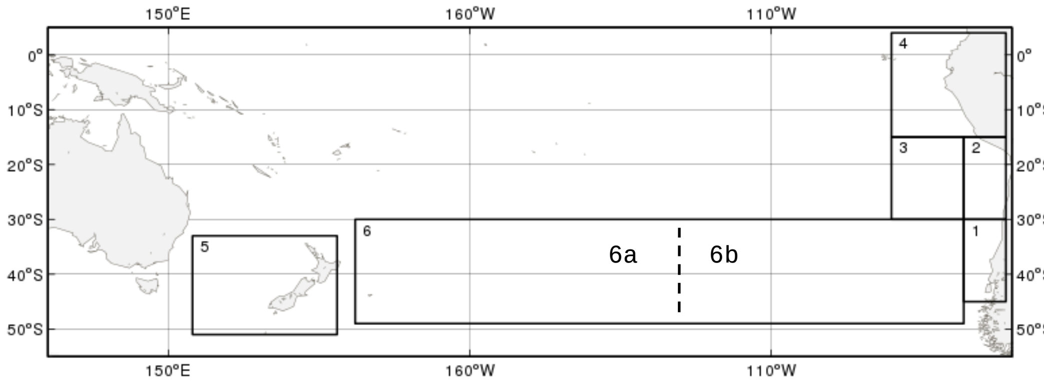

Figure 11. Representation of the initial 6 geographical boxes used to compare Jack mackerel biomass trends, and additional division (dotted line at 125°W) of region 6 in two west (6a) and east (6b) sub-regions used for the connectivity study.

Table 2. Exchange rate (connectivity) table for young (top) and adult (bottom) Jack mackerel fish between geographical boxes as defined in Figure 11 and giving the percentage of decrease in Jack mackerel biomass in each recipient region when the donor region is set to zero.

Donor recipient	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6a	Region 6b
Region 1	15.0	1.9	1.4	0	0	0	71.1
Region 2	24.1	30.7	6.9	0.2	0	0	35.4
Region 3	14.4	24.2	22.7	3.2	0	0	32.6
Region 4	3.9	29.4	17	29.7	0	0	3.4
Region 5	0	0	0	0	72.6	0.1	0
Region 6a	0	0	0	0	4.4	77.1	0.2
Region 6b	0.7	0.1	0.6	0	0	19.1	64.7

Donor recipient	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6a	Region 6b
Region 1	3.5	2.9	1.8	0.2	0	4.3	23.5
Region 2	7.8	7.6	3.3	0.5	0	1.6	30.5
Region 3	6.2	7.4	4	1	0	1.8	24.2
Region 4	5	8.6	4.7	2.7	0	0.4	13.1
Region 5	0	0	0	0	16.4	0.5	0
Region 6a	0	0	0	0	3.7	21.3	0.1
Region 6b	0.6	0.7	0.7	0.1	0.2	12.5	10.6

Table 3. Mean yearly migration rates (averaged over 2007-2011) of (from top to bottom) 1yr old, 5 yr old and 10 yr old cohorts of Jack mackerel.

Donor / Recipient	Region 1	Region 2	Region 3	Region 4	Region 6b
Region 1	0.68	0.03	0.01	0	0.29
Region 2	0.09	0.82	0.07	0	0.02
Region 3	0.01	0.14	0.73	0.03	0.09
Region 4	0	0.03	0.11	0.86	0
Region 6b	0.01	0	0.01	0	0.98

Donor / Recipient	Region 1	Region 2	Region 3	Region 4	Region 6b
Region 1	0.51	0.12	0.04	0	0.34
Region 2	0.09	0.69	0.16	0.02	0.03
Region 3	0.02	0.16	0.66	0.08	0.08
Region 4	0	0.05	0.19	0.76	0
Region 6b	0.03	0.01	0.03	0	0.93

Donor / Recipient	Region 1	Region 2	Region 3	Region 4	Region 6b
Region 1	0.58	0.06	0.03	0	0.33
Region 2	0.09	0.63	0.21	0.03	0.04
Region 3	0.03	0.15	0.61	0.09	0.11
Region 4	0	0.03	0.12	0.85	0
Region 6b	0.06	0	0.02	0	0.92

Methods and results to inform on stock structure

<u>Seasonal catch patterns and habitat separation</u>

Analyses of fisheries catches by month suggest that the majority of the catch is taken in the first months of the year by the Peruvian and Chilean fisheries. The high-sea fisheries is active later in the year tracking migrating fish from the coast of Chile onto the high-seas. The monthly catch distribution for the three different areas is given in Figure 12 below. During the first months of the year, the suitable habitat for Jack mackerel along the coast is discontinuous with a clear break around ~19-22°S. During this period, there is hardly any exchange of fish from Peru to Chile or Chile to Peru possible which is graphically shown in Figure 6. During the second half of the year, the suitable habitat forms a continuous stretch from coastal Peru all the way to the South of Chile and the high seas allowing for potential migration or exchange of fish between these areas. Due to the limited possibility of exchange of fish during the fishing season, we consider the fish in either of the two areas as two separate stocks. Fishing in one area does not affect population dynamics in the other area within the year, which would be a necessary requirement to consider all Jack mackerel as one stock.

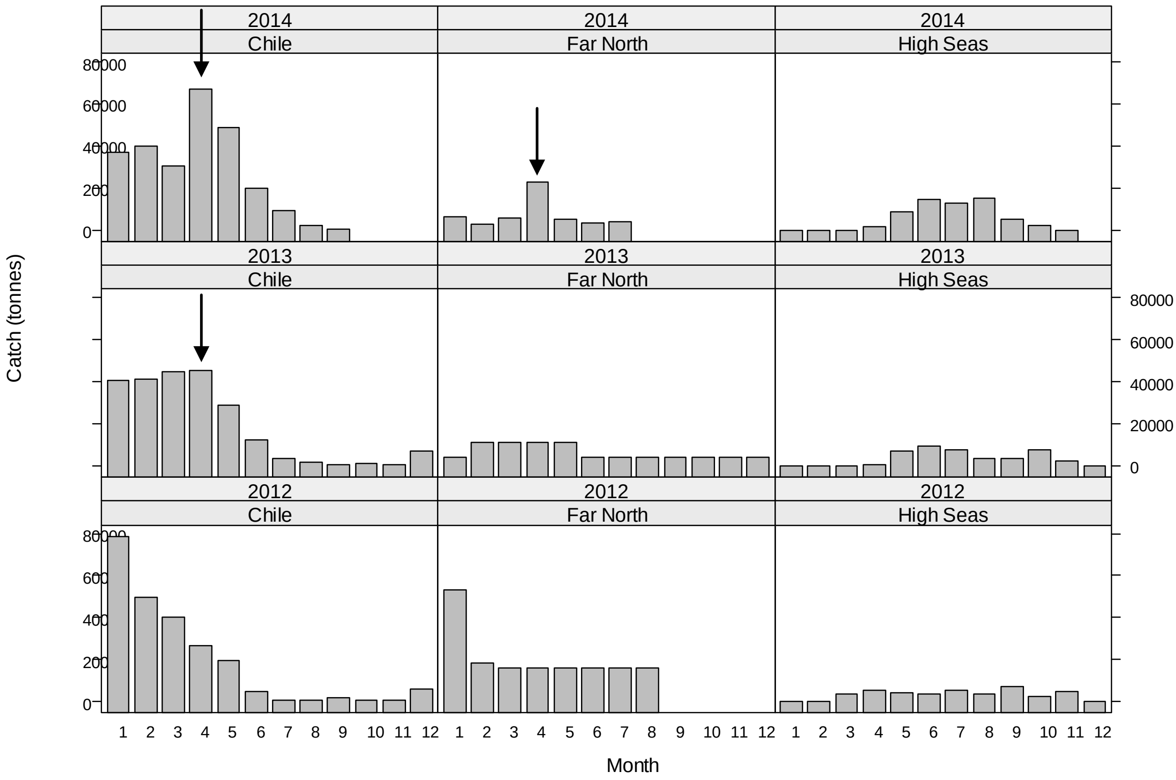

Figure 12. Monthly catches by fleet for the years 2012 – 2014. The arrows indicate the peak of the fishing season in April.

2) Considering the most likely stock structure, identify management objectives (reference points and management plans) for Jack mackerel

Conclusions on reference points:

Reference points for Jack mackerel were estimated taking the single stock assumption currently used as default hypothesis in the SPRFMO science committee. Reference points for the alternative assumption of two stocks (Northern off Peru and Southern off Chile) were estimated as well. The single stock assumption was investigated as it corresponds to the current approach by the SPRFMO and the two stock assumption was investigated as it corresponds to the findings in this project.

The estimation of reference points is affected by the length of the time-series on recruitment that is taken into account. Because recruitment has been low since 2003, sustainable exploitation in the short term is associated with an F_{MSY} around 0.14 $year^{-1}$. Under expectations that productivity will return to the situation prior to 2003, sustainable exploitation can be associated with an F_{MSY} around 0.21 under the single stock hypothesis and between 0.15 – 0.2 $year^{-1}$ for the two stock hypothesis. In 2013, the SPRFMO Science Committee proposed preliminary values for F_{MSY} and B_{MSY} at 0.25 and 5.5 million tonnes respectively. B_{MSY} estimates presented in this study vary greatly due to the uncertainty regarding future recruitment. Under the low recruitment regime, it is however unlikely that the population will rebuild to 5.5 million tonnes.

Annex A – WP4, D4.1.3

Conclusions on Harvest Control Rules:

Sustainable management objectives for Jack mackerel need to be considered in the light of current stock productivity. Since 2003 observed recruitment is in a low state compared to the period prior to 2003. Under these conditions, the stock has the potential to rebuild to a biomass around 4.5 – 5 million tonnes. This is below preliminary estimated B_{MSY} values of 5.5 million tonnes in 2013. Only a near-closure of the fishery would result in a high chance to rebuild the stock from its current state at 2.7 million tonnes to B_{MSY} or above. Fishing at or below the 2014 estimate of fishing mortality (at 0.13 $year^{-1}$) can be considered sustainable and any Harvest Control Rule that ensures setting TACs on that basis can be considered sustainable. From six selected HCR designs, out of the 26 evaluated in this project using Management Strategy Evaluation (MSE) techniques, the HCRs setting an F_{target} of 0.13 $year^{-1}$, a B_{target} of 5.5 million tonnes, a rebuilding plan that was designed by the SPRFMO commission in 2013 and an alternative to this rebuilding plan, all fall within this limit. These HCRs however are associated with lower catches than would be possible under the remaining two HCRS that set an F_{target} at 0.2 $year^{-1}$ and a sloping HCR.

In the context of this study, evaluations were carried out to identify potential positive effects of an increase in mesh size or minimum landing size. There appears to be little gain in implementing an increase in either mesh size or minimum landing size, as potential increases in biomass results in SSB, being defined by predominantly younger age classes. This can result in considerable fluctuations in SSB from year to year which make management more difficult. Also, the gain in yield is limited under all scenarios tested.

Annex A – WP4, D4.1.1, D4.1.4

Methods and results:

<u>Evaluating reference points and Harvest Control Rules using Management Strategy Evaluation</u>
Two activities were undertaken to identify management objectives. 1) Defining reference points under which Jack mackerel could be sustainably exploited and 2) identifying Harvest Control Rules that result in sustainable management and are potentially associated with high catches, low inter-annual TAC variation and rapid rebuilding of the stock. In the development of the HCRs, a single-stock structure hypothesis was assumed, in accordance with the SPRFMO Science Committee roadmap. The HCRs were tested under different population and stock structure hypotheses too and these results are described under chapter 3. To estimate reference points for Jack mackerel, a Management Strategy Evaluation (MSE) framework was designed. This framework allows users to simulate the process from stock assessment to TAC setting and catching fish by the fishing fleet as close as possible to the activities in the real world. Figure 13 shows the schematic building blocks of the framework. The fish population (biological operating model) simulates the dynamics of the fish including recruitment, growth and mortality, the stock assessment procedure (perceived stock) simulates a stock assessment using catch and survey data, the TAC setting procedure (management measures to evaluate) defines on the basis of the stock assessment what TACs should be implemented the year after and the fishery (fleet operating model) simulates catches by four different fishing fleets in the South Pacific. These four blocks are linked together and simultaneously evaluated over time.

SPRFMO assessment results were used to create a starting condition of the biological model, using data from 1970 – 2013. From here onwards, the changes in biomass, TAC and catches were simulated over time and mainly depend on recruitment, the selectivity of the fishery and the TAC set according to the harvest control rule.

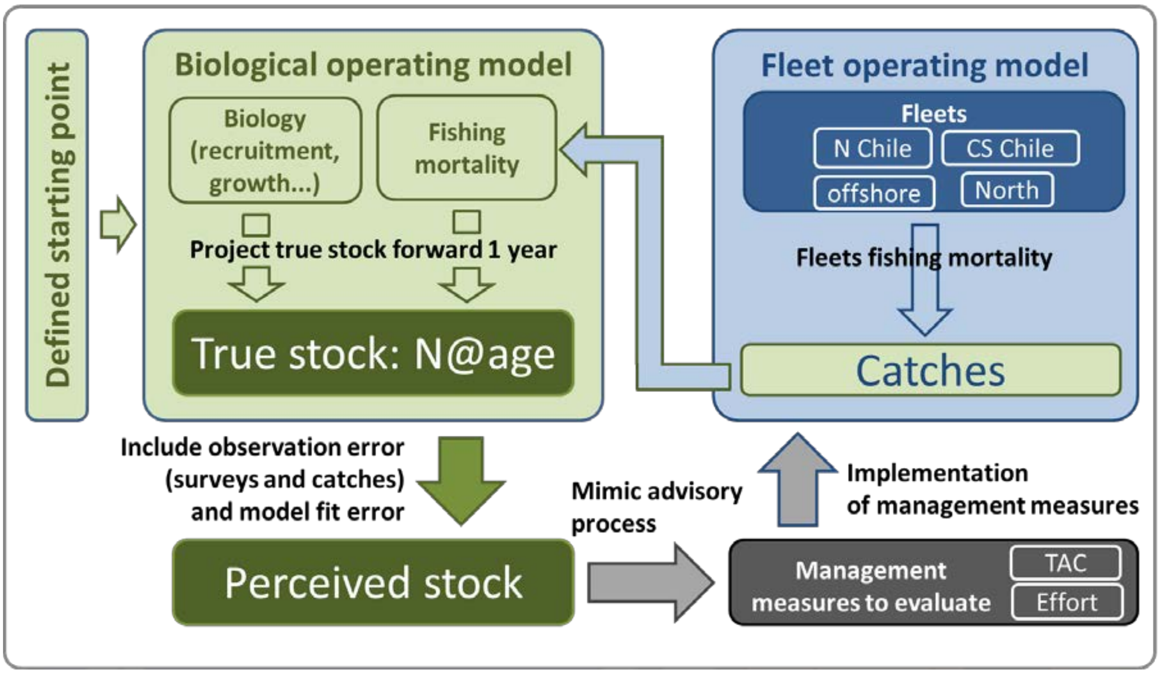

Figure 13: Conceptual representation of the management strategy evaluation where four main elements exist. A biological operating model simulating the dynamics of the fish species, the stock assessment process via the 'perceived stock' element, the incorporation of the advisory process under 'management measures to evaluate' and the implementation of these measures via the fishing fleet catching the fish species under element 'fleet operating model'.

To estimate reference points using the MSE framework, simulations were run to investigate the link between fishing mortality, SSB, and at equilibrium. These simulations were run by imposing a constant fishing mortality (F) value over the simulation period (2013 to 2040) directly in the biological operating model (i.e. not based on the perceived stock, and not implementing any management rule). The aim of these simulations at constant F is to reach a “dynamic” equilibrium, where the stock would be on average at an equilibrium situation corresponding to the level of fishing mortality imposed, but will still fluctuate around this equilibrium due to the stochastic variability in the model. The equilibrium state is defined by computing the mean of SSB and Yield over the period 2030 to 2040. The MSY estimates from these simulations are given in Table 4 below, as well as values proposed for other reference points.

Table 4. Reference points estimated using the MSE framework for the single-stock structure hypothesis.

	Value	**Description**
Biomass reference points (single stock)		
B_{MSY}	10.6 million tonnes	Biomass at MSY
B_{LIM}	2.8 million tonnes	Biomass under which recruitment may be impaired
B_{PA}	3.9million tonnes	Biomass below which there is a risk to fall below Blim, given the uncertainty in the assessment
Fishing mortality reference point (single stock)		
F_{MSY}	0.14	Fishing mortality at MSY

In addition, the SPRFMO Joint Jack mackerel assessment model was used to run assessments for the single stock and Northern and Southern stock assumptions. Within the stock assessment model, reference points were estimated. The estimation of reference points inside the assessment model is similar to the approach described above. However, in the assessment model, information on fleet selectivity and weight-at-age for the entire time-series (since 1970) need to be taken into account, while in the MSE approach, there was freedom to only select relevant information from the most recent years. For this exercise, not only the single-stock assumption, but also the two-stock assumption (North + South) could be used. Results are presented in Table 5 below.

Table 5. Reference points estimated using the Joint Jack mackerel assessment model for the single as well as two stock structure assumptions.

	Single stock	**Northern stock**	**Southern Stock**
Biomass reference point			
B_{MSY}	5.4 million tonnes	1.0 million tonnes	5.6 million tonnes
B_{LIM}	3.1 million tonnes	0.1 million tonnes	3.2 million tonnes
B_{PA}	4.0 million tonnes	0.2 million tonnes	4.4 million tonnes
Fishing mortality reference point			
F_{MSY}	0.2	0.23	0.18

Based on the reference point findings and after consultations with two stakeholder groups, a number of Harvest Control Rules were prepared. Five groups of Harvest Control Rule designs were tested: i) simulated fishing at a constant fishing mortality for the next 30 years, ii) achieving B_{MSY} and maintaining the stock at that level, iii) evaluating the SPRFMO Fisheries Commission rebuilding plan, iv) sloping rules under which fishing mortality increases with increases in SSB up till a maximum break point and (v) productivity rules, where TACs are set based on changes in productivity of the stock. In total 26 different configurations were tested, assuming either low recruitment inflow, similar to the current situation, or more optimistic recruitment inflow comparable to the productivity observed over the entire time-series. The MSE framework was used to simulate the Jack mackerel stock for 30 years and test each of the

HCRs. The results from the simulations show expected trends in F, SSB, and catches, as well as interannual catch variability, recovery time to B_{MSY}, and risk of decline in SSB compared to the starting year. A selection of results is presented below, based on consultations with the SPRFMO Science Committee. The selected six results below are considered relevant for Jack mackerel. This because they result in sustainable exploitation with high probability of rebuilding the stock (F_{target} of 0.13, B_{target} of 5.5 million tonnes, Annex K (Commission proposed rebuilding plan) and Adjusted annex K (including a TAC stabilisation mechanisms once the stock increases above 80% of B_{MSY})). And, because they result in high and stable catches (F_{target} of 0.2 and Sloping rule (associated with an increase in F from 0 to F_{MSY}=0.25 following an increase in SSB from 0 to B_{MSY}=5.5million tonnes)).

Table 6. Key indicators of HCR performance for six selected HCRs. Indicators calculated for the medium term are provided.

	F target of 0.13	F target of 0.2	B target of 5.5Mt	Annex K	Adjusted annex K	Sloping rule
Prob < B_{MSY} (%)	96	100	73	98	95	100
Catch (1000 tonnes)	654	761	46	554	586	793
TAC variability (%)	13	17	791	114	15	12
Prob decline SSB (%)	26	66	4	12	10	49
Recovery time to B_{MSY} (yr)	12	29	3	12	6	24

Under none of the selected management plans, rebuilding to B_{MSY} is possible in the medium term. This is due to the current low recruitment and abundance. Therefore, all selected plans have a high probability not to reach B_{MSY} in the medium term, except for the B_{target} plan. The implementation of a management plan where each year the stock would be exploited at a fishing mortality equal to 0.13 $year^{-1}$, similar to the exploitation observed in 2014, catches would amount to approximately 650kt per year and catch variation among years would be limited. Under this scenario there is a substantial probability of a decline in SSB. Imposing a yearly fishing mortality of 0.2 $year^{-1}$, in the proximity of F_{MSY}, would reduce the probability of rebuilding the stock even further. Managing the stock on the basis of a biomass target of 5.5 million tonnes will likely result in rebuilding of the stock in the proximity of B_{MSY}. This plan however is associated with extreme fluctuations in TAC from year to year and catches around 10% of the TAC in 2014. The evaluation of Annex K management plan is associated with large fluctuation in TAC from year to year, potentially leading to a closure in the fisheries under occasional low recruitments. Catches are expected to stabilize at around ~550kt. Under the alternative commission proposed management plan, the TAC fluctuations are significantly lower, resulting in a catch around 600kt. This plan can be considered to be more precautionary than the original commission proposed plan as the risk in SSB decline and recovery time to B_{MSY} are both lower under this plan. The sloping rule plan is associated with the highest catches compared to the other plans, as well as a long recovery period and high risk of a decline in SSB.

Spatial distribution of the fishing impact on spawning biomass

Because there is a strong discrepancy between total nominal catch known to SPRFMO and available geo-referenced data for this study, no accurate predictions for fishing mortality could be generated in the SEAPODYM modelling exercise. Though, as a first indication, the impact of spatial fishing activity on the spatial abundance of Jack mackerel is analysed by running the SEAPODYM model under a scenario with and without fishing activity. The fishing impact on the spawning adult biomass computed at the end of the simulated time series (average 2007-11) is predicted to occur essentially in the Chilean coastal area and offshore regions with a large decrease (50-70%) in adult biomass compared to the simulation with no fishing (Figure 14). This is not too surprising since the catch has been concentrated in this region over the historical exploitation period.

Management would aim to maintaining spawning biomass above at least 40% of unexploited adult biomass (e.g., Walters and Kitchell 2001, Sibert et al 2006). Based on this 40% biomass limit of unexploited adult biomass, the SEAPODYM results show that the fishing mortality on adult Jack mackerel would be too high in the Coastal Chilean area (region 1).

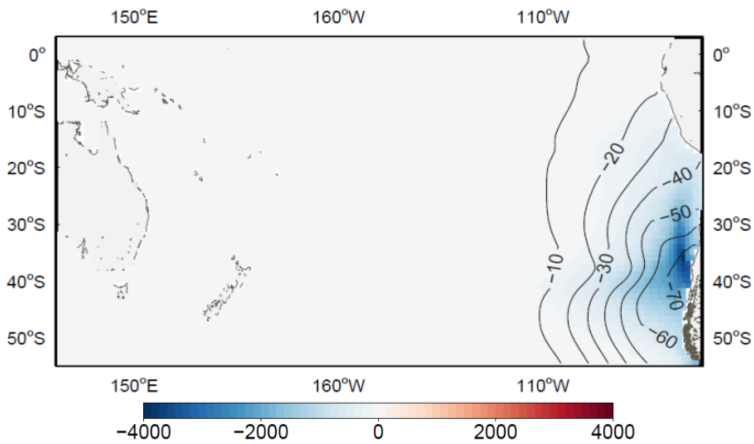

Figure 14. Impact of fishing from SEAPODYM simulation. Change in biomass of adult JM over 2007-2011 (kg km^{-2}; isopleths show the change in % of the virgin biomass).

The projection using SEAPODYM with the forcing from the IPSL-CM4 climate model for the coming decades until 2050 and the average fishing effort of the 2003-2012 period suggests a recovery in spawning biomass after 2020 and then a regular decrease in biomass driven by the environmental conditions.

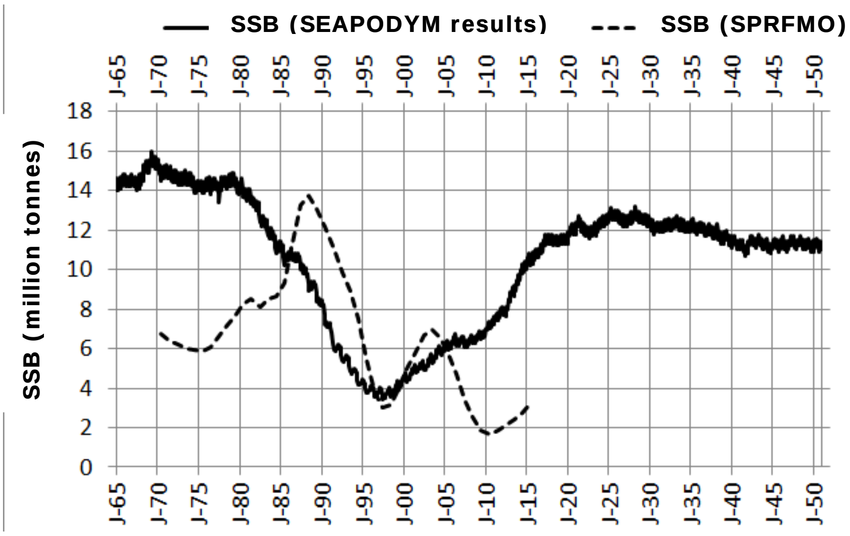

Figure 15. Comparison of spawning biomass estimated with the stock assessment model (SSB) and the IPSL-CM4 SEAPODYM configuration used for the projection until 2050 and fishing effort being the average of 2003-2012, for aggregated regions 1 to 4 (see Fig. 10).

3) Evaluate sustainable management strategies to achieve these objectives

Conclusions on Harvest control rules in light of population and stock structure:

The six harvest control rules as designed under paragraph 2 were also evaluated under different population structure designs. One of these designs represents a metapopulation, as identified as being the most likely population structure in this study. The other ones represent a single population unit and a two population unit structure, similar to the assumptions in the SPRFMO Science Committee. Each of these population designs are simulated over time, catches are being generated by fisheries and thereby providing key information for one or two stock assessments, resulting in total to six scenarios. The names of the six scenarios (S1-S6) are given in the table below.

		Management structure	
		1 stock assessment	2 stock assessments
Population structure	1 single population unit	**(S1)** Base scenario	**(S2)** Two stock scenario
	2 fully separated population units	**(S3)** Two unit scenario	**(S4)** Two unit match scenario
	2 separate population units with connectivity	**(S5)** Meta scenario	**(S6)** Meta match scenario

The assumption on management structure currently taken in the Science Committee of the SPRFMO is most similar to S1 and S3. In case the latter scenario is closest to the unobserved structure in reality, the Jack mackerel unit in the Northern area is at risk of being overexploited. The risk for overexploitation of the unit in the Southern area is low. The alternative hypothesis explored by the Science Committee, close to S2 and S4 poses less risk to overexploitation compared to S2. Also, when two population units are connected through mixing of fish, managing according to two separate stocks (S6) is still more risk adverse. Concluding that under all population structure hypotheses investigated, assuming two stocks for management is less likely to result in over exploitation, even when in reality there is only one population unit. This recommendation also applies to the results obtained in this study, indicating that the population is organized as a metapopulation but is being managed as one stock by the SPRFMO.

Setting TACs on an F=0.13 basis seems most sustainable while still being associated with relatively high catches. The Biomass target HCR (set to stabilize the spawning stock biomass at 5.5 million tonnes) is also sustainable under most scenarios, but is associated with very low catches. Under this HCR however, the Northern unit is overexploited under some scenarios. The population unit is overexploited in years with large incoming year classes when there would be a potential to rapidly increase above B_{MSY}, and substantially high catches are needed to keep the population at B_{MSY}..

Methods and results:

Evaluating harvest control rules using Management Strategy Evaluation under different population and stock structure hypotheses.

The six selected HCRs from paragraph 2 were evaluated using the MSE framework described above, but now assuming different population and stock structures. The biological operating model building block from the MSE is now used to simulate one single, two fully separated, or two population units that exchange fish (connectivity) during part of the year. These three hypothetical population structures match with the findings on likely population structure described in section 1. The building block of the MSE simulating the perception of the stock now performs an assessment assuming that either all catches belong to one population, i.e. one stock assessment, or belong to two populations: the two stock assessment scenarios. Each of these simulations has been given a specific scenario name presented in Table 7 below.

Table 7. Scenario descriptions and fishing mortality targets under different assumptions of population and management structure

		Management structure	
		1 stock assessment	2 stock assessments
Population structure	1 single population unit	**(S1)** Base scenario	**(S2)** Two stock scenario
	2 fully separated population units	**(S3)** Two unit scenario	**(S4)** Two unit match scenario
	2 separate population units with connectivity	**(S5)** Meta scenario	**(S6)** Meta match scenario

- 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 according to the HCR evaluated.

- 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 according to the HCR evaluated.

- 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 according to the HCR evaluated for the combined stock. The TAC is shared among the fisheries, whereby the fishing mortality-at-age ratios among the fisheries are maintained.

- 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 according to the HCR evaluated.

- 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 according to the HCR evaluated for the combined stock. The TAC is shared among the fisheries, whereby the fishing mortality-at-age ratios among the fisheries are maintained. Fishing targets are set according to the HCR evaluated.

- 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 according to the HCR evaluated.

Predicted trends in SSB, Catch and Fishing mortality of the HCR using an F_{target} of 0.13 are shown in figure 16 below. Results indicate that overall SSB is lower than B_{MSY}, catches are lower than MSY and under some scenarios stocks are being overfished, above F_{MSY}. In this case, the Northern components of the Two unit and Meta scenario is being overexploited.

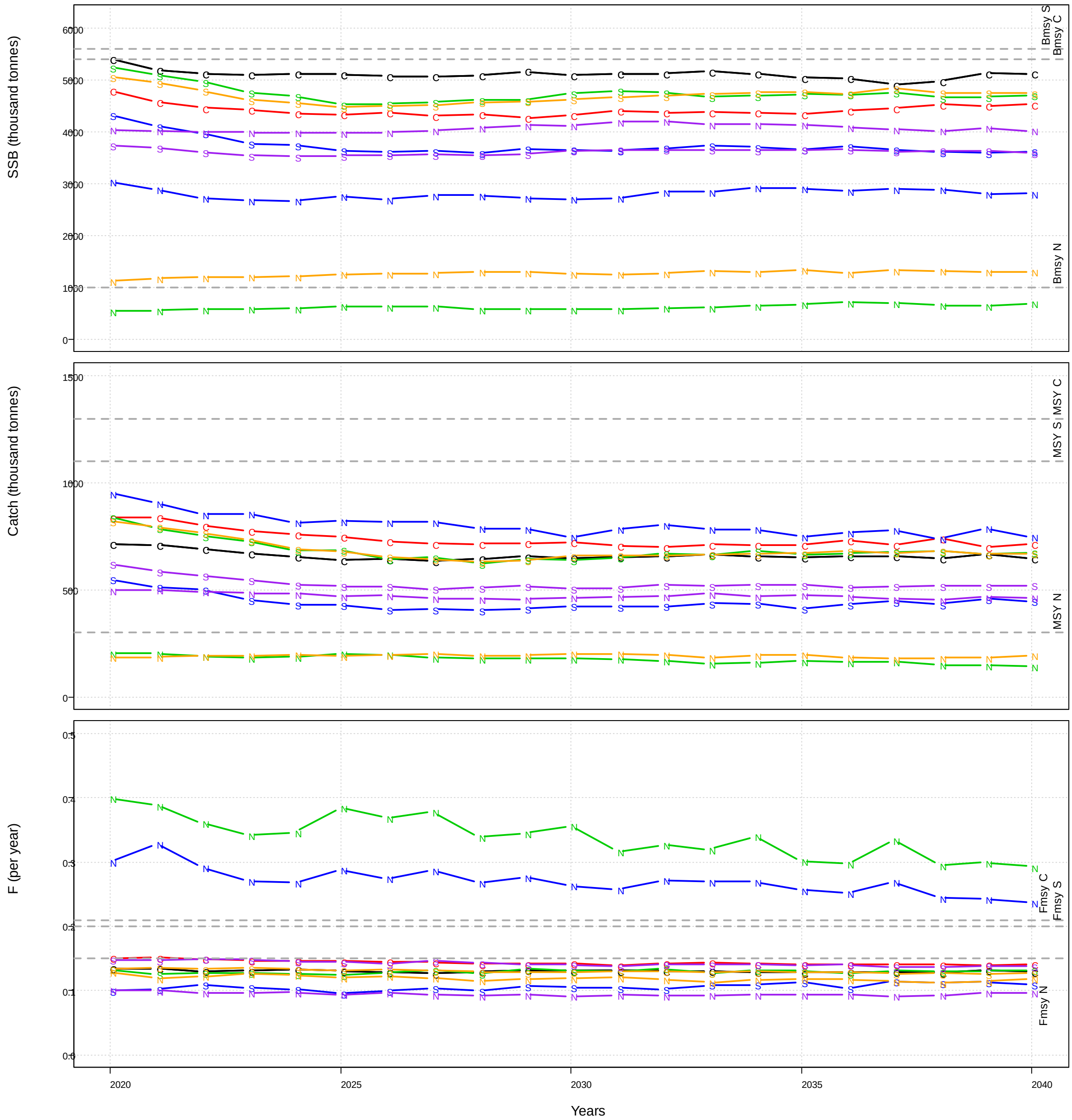

Figure 16. Panels of SSB (top), catch (middle) and Fishing mortality (bottom) under each of the six scenarios evaluated. Black lines correspond to S1, red lines to S2, green lines to S3, orange lines to S4, the blue lines to S5 and the purple lines correspond to S6. In case the scenario simulated two 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.

One of the main criteria to define whether a selected Harvest Control Rule leads to sustainable exploitation, is to investigate the probability to overexploitation. Figure 17 shows the probability to overexploitation, defined as fishing mortality larger than F_{MSY}. When fishing at F_{MSY}, population units are expected to experience fishing mortality larger than F_{MSY} with a probability of 0.5 and experience fishing mortality smaller than F_{MSY} with a probability of 0.5. For this reason, the probability to overexploitation is given as the percentage above or below 50%. The results indicate that under S3 and S5 the Northern unit is overexploited when setting Fs at 0.13 year^{-1}. Exploitation is here compared to the F_{MSY} reference point, at 0.18-0.2, which is well above the fishing target from the HCR at 0.13. Therefore, under all other scenarios, all units are underexploited as the realised fishing mortality is closer to the target of 0.13. The fishing mortality of the Northern unit is however well above F_{MSY} of 0.23. The blue lines (S5) indicate that overexploitation is less when fish predominantly migrate from the Chilean area into the Peruvian area, hereby creating a net increase of fish in the Peruvian area.

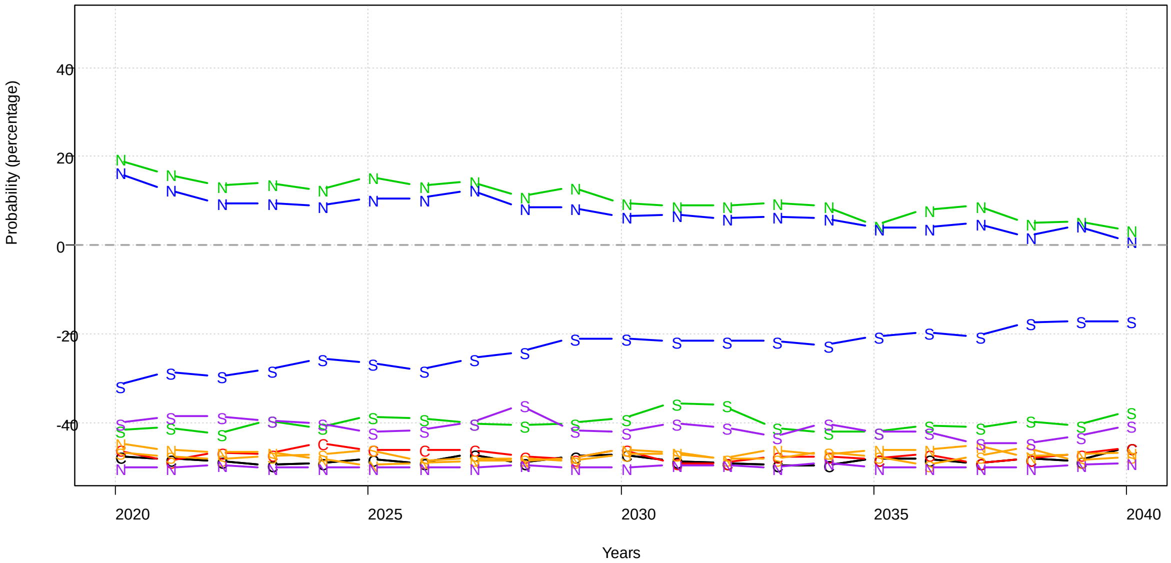

Figure 17. Probability to overexploitation under each of the six scenarios. Black lines correspond to S1, red lines to S2, green lines to S3, the orange lines to S4, blue lines to S5, and the purple lines correspond to S6. In case the scenario simulated two population units, lines contain the letters 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).

Table 8 shows the risk to overexploitation for each stock structure assumption combined with each harvest control rule tested. In case none of the biological components is overexploited, a green tick is presented. When either the Northern or Southern unit is lightly overexploited, a yellow round is presented and under high overexploitation a red cross is given. The results show that the F_{target} =0.13 is sustainable under almost all scenarios, except when the true population structure consists of two components but is assessed as one (Two unit scenario, S3). The B_{target}= 5.5 million tonnes (B_{MSY}) is sustainable as well, but results in very low catches during the entire time-series and is associated with high fluctuations in TAC from year to year.

Table 8. Risk to overexploitation under each of the population and stock structure assumptions. ✓ *indicates no overexploitation for any of the population units considered,* o *indicates moderate levels of overexploitation and* ✗ *indicates high levels of overexploitation.*

Management option	Base scenario	Two stock scenario	Two unit scenario	Two unit match scenario	Meta scenario	Meta match scenario
F_{target}=0.13	✓	✓	✗	✓	o	✓
F_{target}=0.20	✓	✓	✗	✓	✗	✓
B_{target}=B_{MSY}	✓	✓	✓	✓	o	o
Annex K	✓	✓	o	o	o	✓
Adjusted annex	✓	✓	o	o	o	✓
Sloping rule	✓	✓	✗	✓	✗	✓

<u>Projections with SEAPODYM</u>

Simulations have been conducted within this project to explore how the Jack mackerel population and catch production could change in the coming few decades (Figure 18) under the combined effect of fishing, using the average fishing effort of the last 10 years (i.e. 2003-12) and the environmental changes associated to the climate change. The forcing was provided by the Earth Climate model IPSL-CM4 with the A2 greenhouse gas release scenario developed by IPCC, known as the "business as usual" scenario, and which is until now close to the actual observed trend. This forcing has been used and corrected for a temperature bias in other applications with SEAPODYM to different tuna species (Lehodey et al 2010; 2013*; in press*). This new configuration of SEAPODYM for Jack mackerel was again optimized and provided parameter estimates close to those achieved with the historical PISCES-INTERIM forcing for the habitats definitions.

The configuration using the IPSL climate forcing for projection shows an overall decreasing trend in abundance of recruits leading to a reduction of 10% between 2010 and 2050, without considering the fishing impact. The future of the population under exploitation is also investigated using a fishing scenario for the coming decades equivalent to the average fishing effort of the last 10 years (2003-2012), that is a low fishing effort relatively to the one deployed in the 1980s and 1990s. In that case the spawning biomass is predicted to increase and to reach an equilibrium level of exploitation after 2020 and a level of spawning biomass ~20% below the biomass predicted at the end of the 1970s.

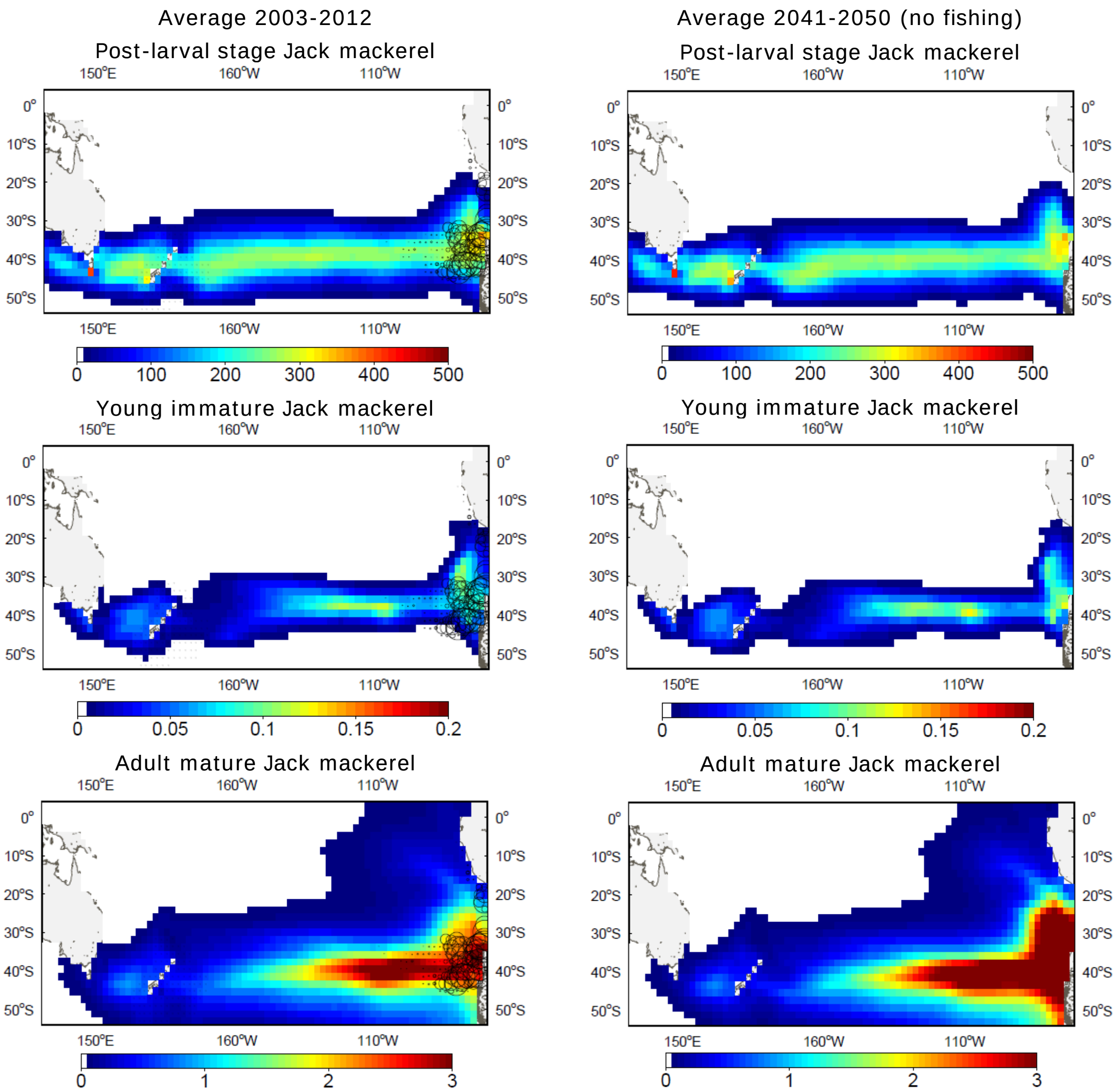

Figure 18. Average distribution of JM (2003-2012) predicted with the IPSL-CM4 climate change configuration used with SEAPODYM to forecast projection of population until 2050. Circles are proportional to observed total catch used in the model for the corresponding period. Darker red indicates higher abundances.

Summary on project conclusions

- The population structure of Jack mackerel is best described by the concept of a metapopulation. A population unit exists off Peru and off Chile and onto the high seas, with substantial exchange of fish between these population units
- The stock structure of Jack mackerel is best described by two stocks, one off Peru and one off Chile. These can be assessed separately, but management targets should be set jointly.
- The fishing mortality associated with maximum sustainable yield, F_{MSY}, is estimated around 0.14 for the short term and 0.2 for the long term.
- Harvest control rules that set TACs associated to fishing mortalities around 0.14 are therefore considered to be precautionary.
- Different harvest control rule designs can be used to manage Jack mackerel sustainable, where there is a trade-off among the rules in maximum catch, stability in catch and rebuilding of Jack mackerel.
- Managing on the basis of two stocks (one off Peru and one off Chile extending onto the high seas) is considered more precautionary, even when the assumptions made in this study regarding population structure are invalid.

Discussion on project objectives

Concluding on population structure relies on interpretation of the information presented to either support or reject the six population structure hypotheses. The information presented is not fully conclusive, hampering our ability to draw strong conclusions. Here we discuss the rationale of rejecting five out of the six hypotheses.

The single discrete population hypothesis is possibly one of the most difficult one to reject given that there is no clear evidence of genetic differentiation along the entire Jack mackerel population and that under large recruitment events strong spatial synchrony of year-class strength is shown. The hypothesis can however not explain why there is substantial differentiation in age structure and life-cycle dynamics of local patches off Peru, in the Chilean coastal area and at the high seas, shown also in the otolith biogeochemistry. This is the main reason to reject the single discrete population hypothesis. Given that the Humboldt Current System dynamics result in a very heterogeneous habitat for Jack mackerel, with spatial segregation (~20°S) between Jack mackerel in Peruvian waters and off Chile during part of the year also contribute to the information base to reject this hypothesis.

The two discrete populations (one population off Peru and one off Chile extending onto the high seas) hypothesis can be rejected based on the information that there is no genetic difference between Jack mackerel found in the South Pacific. Given that the habitats are substantially different in the Northern distribution area from the Southern area, if two discrete populations would exist, genetic difference would be found. Project results also show substantial exchange of fish between Southern Peru and Northern Chile. These arguments together reject the hypothesis of two discrete populations.

The two discrete populations (one coastal and one high seas population) hypothesis can be rejected for similar reasons as the one above. Thereby, the spatial segregation (~20°S) of Jack mackerel during part of the year limits the likelihood of having one coastal population. Results from this project also suggest a continuous favourable habitat and distribution of Jack mackerel from the Chilean coast onto the high seas. These arguments together reject the hypothesis of a coastal and high seas population.
The arguments to reject the existence of three or more populations (one population off Peru, one off Chile and one or multiple on the high seas) are similar to rejecting the two discrete population hypotheses. In addition, results in this study show substantial exchange of fish between the high seas and coastal areas which would contradict the hypothesis. It is likely however that a separate population exists in New Zealand. There is however no evidence that suggests an exchange of fish of any age range

between the local New Zealand patch and the Eastern South Pacific. For this reason, this local patch was excluded from further analyses.

The patchy population hypothesis suggests spatially structured population units, allowing for a discontinuous distribution in space, but with high exchange rates of fish and migration between each of the patches, such that dynamics at each of the patches is similar. Given that there is substantial differentiation in age structure and life-cycle dynamics of local patches off Peru, in the Chilean coastal area and at the high seas, shown also in the otolith biogeochemistry, indicates that mixing or exchange rates are not high enough to support this hypothesis. Preliminary assessments of a potential Southern and Northern population indicate different trends in productivity as well. These arguments together reject the hypothesis of the patchy population.

The last remaining hypothesis is that of a metapopulation. This hypothesis receives support from both genetic evidence, allowing for differences in growth, maturity and otolith biogeochemistry between adults caught off Peru and Chile and the difference in population dynamics on these patches. Results from this study indicate that it is, in addition, likely that the Chilean unit may function as a predominant source of fish to Peru and New Zealand during high times. Information is available however that spawning takes place in each of the respective areas. The lack of connectivity from Peru and Chile to the high seas, as well as the existence of a rather continuous favourable habitat connecting Peru to Chile and the high seas limits us in conclusively defining the population structure of Jack mackerel.

In this study we conclude that the most likely stock structure of Jack mackerel is one consisting of two stocks, one off Peru and one off Chile extending onto the high seas. The main argument for this conclusion is the impossibility of Jack mackerel exchange during the predominant fishing season. This separation calls for separate management tailored to the productivity in each of the areas. It is not said however that these stock should be managed in complete independence from each other. It is highly likely that the Jack mackerel population unit in Chile contributes (a net movement of fish), with a one-year lag, to the Peruvian population unit. Therefore, mismanagement of the Southern stock will likely affect the Northern catch potential and population unit sustainability.

The conclusion drawn regarding the most likely stock structure has ample consequences for management of the Jack mackerel population in the South Pacific. Under our conclusions, it is recommended that the SPRFMO exercises additional evaluations of reference points assuming two different stocks, improves assessment and TAC advice for two stocks. This may imply that additional management plan scenarios have to be evaluated considering two separate stocks and therefore two separate Harvest Control Rules. Owing to the request by DG-MARE (Annex B, meeting report kick-off meeting), management scenarios evaluated in this study have especially been evaluated in the light of a single stock hypothesis. Evaluated management targets actually do show a difference in productivity between the Northern and Southern stocks. This difference may however be caused by movement of fish from the Southern to the Northern stock. Sustainable single-stock or Southern stock targets, which are estimated with higher precision due to data availability and scientific monitoring programmes, would likely result in sustainable management targets for the Northern stock as well, as productivity is expected to be higher in the latter area. The variability in net movement of fish from the Southern to the Northern stock would require further analyses to estimate how this variability affects F_{MSY}.

Preliminary results suggest however that the Northern stock may be fished at slightly higher F_{target} values than the Southern stock, but that rebuilding in the Northern area depends on rebuilding in the Southern area too. This in turn implies that management plans for the two areas have to be co-developed. Clear guidelines on management goals should be communicated to make this exercise practically possible, given that there are two HCRs to be designed with trade-offs among them. In the interim-period, simulations show that fishing mortalities around 0.13 or lower are sustainable in the medium term even if the conclusions drawn here on population and stock structure are not correct and would be better defined by alternative population and stock structures.

In the interpretation of the population structure, stock structure and management results, one has to be aware that the data collection may not be complete as the majority of the information used in this study relies on catch information and stock assessment results. As the South Pacific spans a very large area, it is not without question if in other areas local patches of Jack mackerel may exist which are currently unexploited, such as shown by the spatial modelling exercises in this study.

1) Inter-comparison of results

3D habitat

The selected range of parameters i.e. temperature, chlorophyll-a and dissolved oxygen were in accordance with the literature (Quiñones et al., 1997; Grechina, 1998; Bertrand et al., 2004b, 2006). Overall, in spite of the low number of environmental parameters we used, predicted maps of potential habitat match the observed Jack mackerel data and knowledge from the literature (Serra, 1991; Grechina, 1998; Cardenas et al., 2005; Gerlotto et al., 2012; Gutiérrez et al., 2012). These results stress that Chlorophyll-a was a rather robust proxy for Jack mackerel prey abundance (see Quiñones et al., 1997; Bertrand et al., 2004a, 2006). However adding the interaction between chlorophyll-a and temperature was a critical step to obtain a realistic model because food requirements increase with temperature (Kooijman, 2010).

The habitat model provided further evidence on the discontinuity in Jack mackerel distribution at ~19-22°S that was empirically observed from catch data (SPRFMO CHJMWS 5) but was not fully described yet. This discontinuity and the 3D conceptual model we were able to construct (Figure 8) is an essential piece of information to understand the metapopulation framework (Gerlotto et al., 2012). This discontinuity observed in the data and the statistical model corresponded to the Northern limit of the bulk of Jack mackerel distribution predicted by SEAPODYM (Figure 9). This indicates that SEAPODYM could well model the processes restricting Jack mackerel at ~19-22°S but not well reproduce the Jack mackerel distribution further north (Figures 9 and 10). This is probably due to an over-fit to the thermal conditions observed off Chile (see below). Indeed, Jack mackerel exploits a wide range of oceanographic conditions and prey distribution is probably the main driver of the Jack mackerel distribution within its thermal habitat ranging from ~9ºC to 26ºC (Bertrand et al., 2004b, 2006).

The Jack mackerel belt simulated by SEAPODYM presented low seasonal changes in latitude but was shifted about 5º north in SEAPODYM when compared with the 3D statistical habitat model and the literature (Serra, 1991; Grechina, 1998; Cardenas et al., 2005; Gerlotto et al., 2012). The difference between models was smaller in austral winter since the statistical model predicted a northern displacement of the Jack mackerel belt in winter.

The results from SEAPODYM indicate a thermal habitat ranging for the entire Jack mackerel population mainly between 8 and 18°C. However, these results cannot be directly compared to the estimate from the 3D statistical habitat model which indicate preferable temperatures between 8.7 and 25.9 because here the temperature is estimated for the entire vertical habitat instead of Sea Surface Temperature (SST) in the first one. Nevertheless, though the estimated lower temperature limit is very similar in both approaches, the upper limit estimated with SEAPODYM gives a colder value (~18 vs 26°C) even considering the difference between using SST and vertical temperature.

The distribution of Jack mackerel eggs covers a variety of environmental conditions in terms of water masses, temperature and other environmental factors (Grechina et al. 1994; Dioses 1995; Barbieri et al. 2004; Sepulveda et al. 2009; Cubillos et al. 2008). The water preferendum for spawning activity in Peru is at sea surface temperatures higher than 18ºC and surface dissolved oxygen concentration higher than 5 $ml.l^{-1}$, (Dioses, 1995). This suggests that spawning in Peruvian waters mainly occurs at higher temperatures than the predicted spawning thermal habitat. In the south, routine surveys were performed during the exploitation of Jack mackerel by the USSR fleet. Their findings on eggs and larvae distribution showed a good match between the Southern limit of the spawning area with the surface isotherm 16°C (Gretchina 2009). The SEAPODYM average estimates of optimal spawning temperature + 1 standard error is identical to this temperature. Using a large dataset of egg distributions, Cubillos et al. (2008) found a dome shaped relationship between eggs density and temperature for all the Chilean surveys, with egg densities peaking in waters ranging between 18 and 19°C in 1998 while "*in 2001 higher abundance of eggs was found in waters ranging between 14 and 16°C, peaking at 15°C*". The good agreement between the model estimate and the available information in the literature for Chile provides confidence in the results and is remarkable since the estimate is based on catch and length frequency distributions and did not include any eggs or larvae data.

The SEAPODYM feeding habitat changes with age of cohorts because larger fish can access lower temperature water masses. Therefore feeding habitats of young fish extend much further north than the oldest fish. Oldest (largest) fish would feed only in the Southern Pacific below 30°S, but can move north seasonally for spawning. The SEAPODYM feeding habitat also combines temperature and oxygen to describe how the local environment is favourable and accessible to Jack mackerel for feeding. The value of the oxygen threshold parameter was estimated with SEAPODYM to 3.36 mL/L, above the value of 2 ml l^{-1} selected to define the oxycline depth and the lower vertical boundary of the 3D Jack mackerel habitat, confirming high sensitivity to low oxygen concentration. Both the SEAPODYM and 3D habitat model suggest that Jack mackerel habitat is linked to the Humboldt Current with coastal upwelling in Peru and Chile and the South Pacific subtropical convergence zone extending off the Southern Coast of Chile until the eastern coast of New Zealand. Both modelling reasonably predict the Jack mackerel habitat as demonstrated by the good fit to the catch data and acoustic data distributions.

<u>Population abundance and dynamics</u>

Other population dynamics parameters are those defining the natural mortality and the stock-recruitment relationship (Beverton-Holt type function). The recruitment in SEAPODYM occurs at the level of the larvae. Therefore, SEAPODYM recruitment results cannot be compared to standard stock assessment recruitment results. Natural mortality coefficients are estimated to be between 0.01 and 0.05 mo^{-1} (0.12-0.60 yr^{-1}) for cohorts older than 1 year. It was fixed to a constant value of 0.23 yr^{-1} in the SPRFMO stock assessment. This leads to similar natural mortality rates for adult fish but higher rates for young immature fish in SEAPODYM than in the stock assessment model. As a result the estimated population structure differs between the two models, with a higher proportion of young fish in the stock assessment model. Spatially, the western offshore biomass seems overestimated with SEAPODYM, given the current knowledge of fishing condition in this region. Without considering the region 6a, the comparison of adult spawning biomass gives a total range between 16 and 2 million tonnes for the stock assessment model and roughly twice that for SEAPODYM, without considering the far western South Pacific sub-population. However, there is still a large gap between the total nominal catch of Jack mackerel (79.761 million tonnes) declared to the SPRFMO during the period 1979-2011 used to optimize the model SEAPODYM and the geo-referenced catch used in the simulation, representing a total of 45.797 million tonnes after extrapolation for several fisheries. This means that over this period there is still 42.6% of the total catch (~34 million tonnes) not accounted for fishing mortality in the simulations. An updated geo-referenced catch dataset accounting for all the nominal catch, would bring the SEAPODYM model prediction of adult biomass for the main regions of exploitation closer to the estimate of the stock assessment. Biomass may be also overestimated with SEAPODYM due to too coarse resolution leading to high diffusion versus advection and increasing biomass to improve the fit between predicted and observed catch, while in reality fish are distributed in patchy but highly concentrated aggregations.

Reference points

Three approaches were undertaken to estimate reference points for Jack mackerel. 1) Stochastic simulations using the framework developed by Simmonds et al. 2011, 2) long-term evaluations with set target fishing mortalities using the MSE framework and 3) estimating reference points in the assessment model. There is a substantial difference in the estimated values of the assessment model with the two other approaches. The SPRFMO has proposed a preliminary F_{MSY} at 0.25 while the estimations under this project indicate values around 0.13 – 0.21. The difference is mainly related to the choice of the SPRFMO Science Committee in 2013 to pick the 2013 estimated F_{MSY} , which is highly uncertain. A second element that is important in estimating reference points, relates to productivity of the population. Under more optimistic recruitment expectations, F_{MSY} increases. The main difference between the approach taken in this project and the assessment model is that a more optimistic recruitment assumption is used in the latter model. This therefore results in a higher F_{MSY} prediction.

There is good agreement in the short term between catch expectation and biomass increases between the stock assessment based projections and the MSE evaluations shown here. Only a few % difference (the assessment predictions being more optimistic) was observed. The likelihood that SSB will increase to B_{MSY} is lower under the MSE analyses in the medium term than the 10-year assessment based predictions.

There is also a difference in estimated B_{MSY} values for the single stock hypothesis and two-stock hypotheses combined (see Table 5). If B_{MSY} of the Northern and Southern stocks are added up, they amount to substantially higher B_{MSY} values. As we rely on three different stock assessments (a single stock, and two separate stocks) the results between the 1-stock and 2-stock cannot simply be added together as productivity of each stock is estimated depending on many other parameters such as selection of the fleets and natural mortality. Under the 2-stock assessments approach, the productivity of the Northern stock is estimated to be much higher while there is no substantial difference in productivity of the Southern stock compared to the 1-stock assessment approach. Therefore, adding the Northern and Southern stock together, this results in a higher combined productivity.

Managing complex population structures

The analyses performed in this study show that there is an increased risk to overexploitation when the true, unobserved, population structure consists of two units but is being managed as one stock ('Two unit scenario', S3). This is in agreement with the findings of Kell et al. (2009) 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 0.7, well above sustainable targets at 0.18 – 0.21. The results also indicate that not accounting for migration may cause additional risks for sustainable fisheries even though the right population structure is accounted for, in this case for the Southern stock coping with a net movement of fish to the Northern stock. Considering the population as discrete units, as is common in stock assessments (Stephenson, 1999), is then inappropriate (Hart and Cadrin, 2004). Therefore, Jack mackerel should be managed according to a two-stock structure and management of the stocks should be linked. Under the assumption of management structure currently taken in the Science Committee, the Jack mackerel population unit in the Northern area is at risk of being overexploited.

The potential spatial distribution of Jack mackerel is very large and only a limited area is surveyed or fished yearly. This may result in underestimation of population size, but also an incorrect understanding of population productivity. The incorrect understanding of productivity may easily result in overexploitation, similar to the findings by Hintzen et al. 2014. Additional independent surveys covering a wider distribution would be necessary to obtain a more reliable distribution estimate. Potentially, fishing vessel acoustic information can be used. Fishing vessels have the potential to monitor the water column frequently throughout the year. It would require automatized analyses of these datasets to efficiently extract the essential information for Jack mackerel.

The limited information on migration and exchange rates of fish between areas may also affect the results related to suitable management options. The meta-scenarios (meta scenario and meta match scenario (S5 & S6)) assumed flow of fish from the Northern to the Southern units and vice versa. These rates were higher for juveniles than adults, similar to catch compositions of fleets in the coastal zones of Peru and Chile. The exact rates and their variability however determine to what extend the Northern unit can be self-sustaining, as the Southern unit acts as a source. Tagging information would be required to better estimate connectivity, entrainment and migration rates.

2) Input to and feedback of SPRFMO on project results

The 'Hydrography and Jack mackerel stock in the South Pacific' project was designed to provide a contribution to the work of the SPRFMO Scientific Committee. Therefore the project focussed on two main questions that were at the centre of the debates in this committee: (1) should the Jack mackerel in the south-eastern Pacific be considered as a single management unit or as a number of independent management units, and (2) what management strategy would be the most appropriate one to ensure an optimal use of the resource.

Results of the project were reported at meetings of the SPRFMO Scientific Committee in 2013 (La Jolla, USA) and in 2014 (Honolulu, USA). In the following paragraphs, a short review is given of the presentations by project members during these meetings and the feedback from the Scientific Committee.

I. Presentation of the bibliography on Jack mackerel

The key question on the population structure of Jack mackerel was subject of many scientific discussions. During the 90s a large number of sub-populations and at least two major units were identified using morphometric studies. Results obtained in 2004 using genetic markers led to part of the scientific community to conclude that there was a single population in the South Pacific Ocean, while another group considered at least two and possibly three sub-populations. The SPRFMO listed the possible hypotheses and recommended work to be performed to evaluate these hypotheses. A literature review was a first step to list all available knowledge on population structure.

A limited number of peer reviewed papers were produced on Jack mackerel: of the 550 references available, 20% were peer-reviewed papers, being published during the 1980s (26 papers), 1990s (38) and 2000s (42), when Jack mackerel became of economic importance. This means that most of the knowledge about Jack mackerel was produced in internal reports (since 2006, almost all of the work on Jack mackerel was presented as working papers to SPRFMO) and local papers, and although some syntheses were presented to the international community, no synthesis was published. Therefore, a bibliographical list was produced at the beginning of this EU Project (January, 2013), from which a review was produced and presented at the SPRFMO meeting in October, 2013.

The literature review concluded that a single general population was unlikely, but the lack of information on Jack mackerel habitat made drawing final conclusions difficult. Therefore a recommendation was given to SPRFMO to develop the use of acoustic data from fishing vessels that are likely to fill the gap between the scientific and catch data. This recommendation was well received and a specific task group on "fishing vessels as scientific platforms" was implemented in 2014.

II. Presentation of project findings on the migration of juvenile Jack mackerel from Chile to Peru

Within the context of the project, a study was conducted on the cause of the sudden appearance of large number of recruits in the Peruvian zone in 2011. This observation was preceded by large catches of young Jack mackerel in offshore waters in 2010, a potential indicator of a strong incoming year class. However, the catches in 2011 in the area off Chile were very small, and the expectations about a strong cohort did not come true. Considering the decrease of abundance of this year-class in Chilean waters in 2011, and the simultaneous appearance of an abundant year-class in Peru, the hypothesis was formulated that the fish in Peru in 2011 belonged to the same cohort that had been observed in 2010 off central Chile, and that the latter had migrated from central Chile to Peru in the second half of 2010.

A working document with the results of the study on the recruitment in the Peruvian zone was presented at the meeting of the Scientific Committee in Honolulu in October 2014. In this document, it was suggested that juvenile fish moving accidentally from Chile to Peru because of strong water currents would develop an attachment to the Peruvian zone after they had spawned there for the first time. Results of the habitat modelling study show that the two main potential habitats off Chile and Peru are separated by a narrow corridor which is opened only on certain occasions. The exchange of juveniles between Chile and Peru probably only occurs in years when this corridor is open at the time when juvenile fish occur in the north of Chile.

The presentation was positively received by colleagues both from Chile and from Peru. For Chilean scientists, the migration theory provided support for their claim that there is a connection between the Chilean stock and the Peruvian one. At the same time, Peruvian scientists could use the theory in support of their claim that the stock in Peruvian waters should be treated as a separate management unit. There was a general agreement that the results of this study could contribute towards solving the long standing dispute about the population structure of Jack mackerel in the south-eastern Pacific. It was proposed that the study on the exchange of juvenile Jack mackerel between Chile and Peru should be continued in cooperation with scientists from both countries, and that the results should be used for an article in a peer-reviewed journal.

III. Presentation of management strategies developed by the project

At the 1st and 2nd SPRMFO Science Committee (SC) meeting, the development of a Management Strategy Evaluation framework for Jack mackerel was presented. This framework was tailored to the output of the joint-jack-mackerel (jjm) stock assessment results. During the 1st meeting, the framework was discussed and preliminary results compared to projections obtained from stochastic forecast scenarios using the jjm model. Some feedback was given related to the MSE structure and the model was improved in preparation to the 2nd Science Committee meeting. At the 2nd meeting, an elaborate presentation was prepared and results were thoroughly discussed in plenary. As a follow-up, a subgroup was erected during the meeting that was tasked to summarize the results of this study and prepare advice for the SPRFMO committee meeting. The advice is annexed to the 2nd SPRFMO Science Committee report and was adopted by all SC members.

Another presentation was prepared for the 2nd SC meeting, showing the results of the entire Hydrography and Jack mackerel study. The conclusions related to management: manage on a 2-stock rather than a single-stock basis, were received by the group without any further discussion. It is likely that during the 3rd SC meeting, more attention is given to the 2-stock approach, thereby taking the conclusions from this study more actively into account. This would require a change in the SC meetings where the focus has predominantly been on the single rather than 2-stock approach.

3) Dissemination of project results

Future research needs

The availability of data, such as catch data, biological sampling, survey data (acoustic, egg, trawl), all in high spatial and temporal detail, should be made available for research in SPRFMO. Due to strict SPRFMO regulations, this information was only available for a subset of the fleets and predominantly covered the last 5 to 10 years. Studies similar to this project will likely improve if these data sources becomes more easily available.

Tagging

One of the main recommendations is for the development of an international tagging program including conventional and pop-up tags. Pop-up tagging indeed provided critical information to re-evaluate migration and spawning patterns of other high migrating species such as the bluefin tuna (*Thunnus thynnus*). Several hundred thousand tropical tuna (skipjack, yellowfin, bigeye) have also been marked with conventional tags to provide key information on growth, movements, natural mortality and exploitation rates. Tagging is the only way to finely describe the spatial dynamics of the species and to obtain a definitive answer on the genuine Jack mackerel population structure.

Additional data for SEAPODYM parameter estimation approach

Unlike standard assessment models, SEAPODYM has an explicit spatial structure and requires geo-referenced data for both estimating the model parameters and to compute fishing mortality. The access to such data for this project required considerable efforts. Still, additional efforts are needed to build the most possible comprehensive spatially-disaggregated fishing dataset for the whole industrial fishing period. The SPFRMO should convince member states to exchange at the highest detail possible the catch and survey information, including distributions of biomass acoustic, eggs and larvae density that could be used in the parameter optimization approach for better estimates.

Climate change and decadal forecast simulations with SEAPODYM

Preliminary work has been conducted within this project to include the potential impact of climate change on the projection of population of Jack mackerel with the model SEAPODYMfor the coming decade. The results were encouraging and should improve with the new generations of Earth Climate models. They have increased resolutions and, thanks to data assimilation techniques, also provide more realistic past history of the ocean over the last century and better decadal forecast (e.g. the pacific Decadal Oscillation), which is typically the time scale of interest for Jack mackerel fisheries investment and management. Therefore, these new climate and decadal forcings should be used with SEAPODYM to provide Jack mackerel population projections complementary to the equilibrium hypothesis for testing management options and Harvest Control Rules over the next decades.

Climate change and Jack mackerel habitat

With the warming of ocean leading to stronger stratification in the surface layer, climate change is expected to lead to decreasing ocean productivity. Though it can be a decadal effect, the monitoring of chlorophyll *a* since 1998 with satellite ocean colour sensors shows effectively a decrease in ocean productivity associated to the increase of ocean oligotrophic gyres, expanding at average rates between 0.8%/yr and 4.3%/yr (Polovina et al., 2008). Mean monthly SST over the subtropical gyres is increasing concurrently with the expansion of the oligotrophic gyres which is consistent with the hypothesis that as the subtropical gyres become warmer they become more stratified and the oligotrophic gyres expand. Biogeochemical models coupled to Earth Climate models project also an expansion of the Oxygen Minimum Zone (OMZ), while some observations seem to confirm this trend (Stramma et al., 2008). As already observed for sardine (Bertrand et al., 2011), Jack mackerel could be therefore expulsed from these new low oxygen areas. Since temperature, dissolved oxygen and chlorophyll *a* are the three variables used to define the Jack mackerel habitat, these projected changes would certainly have strong consequences on the habitat distribution. They could be quantified on the basis of the habitat estimated in this study from historical data.

Higher modelling and sampling effort of dissolved oxygen (DO) for the habitat vertical dimension
Bertrand et al. (2011) showed that when the oxycline is shallow, fish such as sardine are expulsed from the system. The upwelling of highly re-mineralized, suboxic water is the strongest close to the coast. This study confirmed that oxygen plays a fundamental role in structuring the ecosystem in the south eastern Pacific. We aimed to study the impact of different ocean-scape on Jack mackerel distribution and population structure from different scenarios of contrasted habitat conditions. In particular we tested if the habitat conditions (e.g. oxycline depth) constrain the population structure (range of distribution, spawning area, development of meta-populations) when the OMZ weaken in the Northern Humboldt Current off Peru. Unfortunately, no sufficient DO profiles were available over the past decades. Decadal time series are needed to make comparison between low abundance period and high abundance period. Thus, the hypothesis of a distribution contraction southward in Peru due to the fundamental role played by oxygen could be tested. To include the vertical dimension in the representation of Jack mackerel habitat, a monthly climatology of dissolved oxygen would be highly relevant. However such feature cannot be resolved with climatology at 1º; for that purpose at least 1/3° climatology is required. Efforts on high resolution biogeochemical are thus recommended.

In addition the sampling should be secured in time to collect long time series of dissolved oxygen concentration. We recommend to systematically including oxygen concentration in hydrological profiles. This means a need to fund oxygen sensors. These further efforts on oxygen are particularly critical since the range of Jack mackerel would probably shrink with the predicted oxygen minimum zone expansion (Stramma et al., 2008).

Improving biological components in the MSE

The results of suitable HCRs in the management strategy evaluations relies on the simulated dynamics of the population units. Improvements made with regard to mixing of population units and migration, and therefore availability to different fisheries, will considerably improve the robustness of the HCR results. Improving the biological model, by e.g. incorporating the SEAPODYM framework, may more appropriately address the question of TAC allocation between member states, as spatial simulations can be evaluated, driven by climatic events. In that case, the model would provide useful detailed outputs with changes associated to the spatial structure of the population and the changes in spatial distribution of fishing effort. In addition projections based on IPCC Earth climate model forcings would include impact due to climate variability and anthropogenic CO2 release, ideally with an ensemble of simulations using several climate models to provide an envelope of uncertainty. Hence, incorporating SEAPODYM as the biological operating model in the MSE framework will provide robust predictions and quota share possibilities under changing climatic conditions.

Analyses and integration of acoustic data collected by fishing vessels

Acoustics is generally developed using research vessels for surveys over limited areas. Extrapolating the results from such “sampled windows” to the whole distribution area is complicated and risky. Moreover this extrapolation is not only related to space but also to time: the usual scientific budget allows for one survey per year, which must be short enough in time to allow considering it as a snapshot view of the fish distribution.

Therefore using data from fishing vessels is a potential solution, as these vessels are much more numerous than research vessels; they use the same acoustic devices; they are present during all the fishing season; they focus on the high density areas; they sample the detections by fishing, etc.

Using fishing vessels as observation platforms is considered all over the world. Two actions developed during this project show: (1) the success of a proposal to publish a special issue on the theme of “fishing vessels as scientific platforms” in Fisheries Research: more than 30 contributions from all over the world

were received. (2) Answering our suggestion, SPRFMO created a dedicated task group on this theme in 2014.
Nevertheless these data present a series of limitations, mostly methodological, linked to the way they are collected. Hence, there is need for a research project on this topic. There is a need to develop adapted statistical and analytical tools to analyse the acoustic data collected under the “fisher’s sampling strategy”. A general research project should be prepared with the help of mathematicians, statisticians, ecologists and fishery biologists. Results of such a project would be applicable worldwide (and especially in the EU fisheries).

Evaluating the effects on management of the rebuilding of Jack mackerel
The spatial distribution of Jack mackerel has gone through different spatial distribution phases, from very local along the Chilean coast to a wide distribution far onto the high seas. It is likely that this spatial distribution is directly linked to population abundance, with wider dispersion at higher spawning stock biomasses. When the Jack mackerel population in the South Pacific will rebuild, it is likely that its spatial distribution changes too. Under this change, sustainable exploitation may change substantially since different fleets have access to the fish resource. Under such a distribution change, reference points and harvest control rules may need to be adapted. Investigating how a change in spatial distribution (potentially also caused by changes in climatic conditions) affect sustainable management is therefore needed to propose sustainable exploitation regimes for the medium to long term.

Concise description of deliverable and task products

Task 1.1. Collection of fisheries information.

Annex A – WP1, T1.1

Disaggregated data on the fisheries were obtained from a number of institutes and organisations. These data included catches per tow, fishing effort and length distribution of Jack mackerel catches.

The most detailed set of catch data was obtained from vessels working for the Pelagic Freezer trawler Association (PFA) in the Netherlands. These vessels had provided catch data per haul since the beginning of their activities in the Pacific in 2005. In addition, scientific observers working on these vessels had provided detailed biological information such as length composition, age and maturity for the years 2007 – 2013.

The second source of information was the SPRFMO data base. According to SPRFMO regulations, all contracting parties were obliged to provide catches by 1x1° rectangles starting from the year 2007 and catches by 5 x 5 degree rectangles for earlier years. The restriction that SPRFMO could not release data for time/space units in which less than three vessels had operated, limited the amount of data that could be released to approximately 90% of the total amount of data held in the SPRFMO data base, except for 2007 when this percentage was approximately 50%. For the years prior to 2007, the amount of data that had been provided by contracting parties was limited to annual 5x5° data from China and daily 5x5° data from Korea.

The Chilean institute IFOP provided data on Chilean catches inside and outside the Chilean EEZ. The data consisted of day-by-day information on catches of the purse seine fleet in 2007 – 2012, aggregated by 1x1 degree rectangles. In addition, biological information was provided for trips during which an observer was on board. Aggregated catch data were received from New Zealand as well.

Task 1.2. Collection of environmental data.

Annex A – WP1, T1.2 Annex A – WP3, D3.1, D3.2

Three environmental datasets (NetCDFfiles) were produced and stored to be used in activities of WP3-4-5 (Deliverable D1.2) in:

- one long term (1960-2008) hindcast simulation at coarse resolution (2°x month) from a coupled physical-biogeochemical model NEMO-PISCES forced by atmospheric reanalysis NCEP providing 3D temperature, currents, and dissolved oxygen, euphotic depth and vertically integrated primary production.
- a second shorter time series (1998-2012) at higher resolution (1/4° x week) based on the GLORYS2 reanalysis and PSY operational model of Mercator-Ocean providing 3D fields of temperature and currents. To these physical fields were associated over the same domain at the same resolution the fields of primary production and euphotic depth derived from ocean colour satellite data and based on the VGPM model (Behrenfeld and Falkowski 1997). A dataset at degraded resolution of 1°x month was also prepared to facilitate the optimization approach.
- a third long-term (1979-2010) hindcast simulation at medium resolution (1°x month) from a coupled physical-biogeochemical model NEMO-PISCES forced by atmospheric reanalysis DFS5.2 which is based on the ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis ERA-INTERIM. This simulation product included 3D temperature, currents, and dissolved oxygen, euphotic depth and vertically integrated primary production.

Primary production and euphotic depth derived from ocean colour satellite data over the same domain and at same resolution were produced based on the VGPM model (Behrenfeld and Falkowski 1997). A dataset at degraded resolution of 1°x month was also prepared to facilitate the optimization approach.

A climate change forcing from the IPSL-CM4 Earth Climate model with the IPCC A2 scenario was used for preliminary investigation of climate change impacts on Jack mackerel. It provided 3D temperature, currents, and dissolved oxygen, euphotic depth and vertically integrated primary production. The resolution is 2° x month for the period 1900-2100, and the temperature fields were corrected as described in Lehodey et al. (2013).

Task 1.3. Preparation of acoustic data sets.

Annex A – WP1, T1.3, D1.3 **Annex A – WP3, D3.1, D3.2**

The Peruvian National Society of Fisheries (SNP) provided an extensive set of acoustic data for the Peruvian purse seine fleet. This information represents around 200 000 sampling units of 0.5 nm covered by the fishing fleet between January 2011 and May 2013.

The Peruvian Sea Institute (IMARPE) collected acoustic data during surveys performed since 1983 on several vessels, the R/V Olaya (41 m), the R/V SNP2 (21 m) and the RV Humboldt (76 m). Specifically, the original dataset contains information on:

- Acoustic nautical area scattering coefficient integrated in 1 nautical mile ESDU,
- Acoustic energy until 500m at 38kHz and 150 m at 120 kHz,
- Acoustic energy by schools
- Biological sampling, CTD stations, eggs and larvae densities, plankton

However, only a limited fraction corresponding to published data was available.

The Chilean research institute IFOP collected acoustic data during three cruises of acoustic evaluation of Jack mackerel biomass performed on board the RV ‘‘Abate Molina’’ in austral autumn/winter: 5 May to 17 June 1997, 3 June to 20 July 1998, and 15 May to 30 June 1999 (Cordova et al., 1998, 1999, 2000). Specifically, the dataset contains information on:

- Acoustic nautical area scattering coefficient, sA (MacLennan et al.,2002) integrated in 0.5 nautical miles elementary sampling distance units (ESDU) at a -65 dB threshold.
- In each ESDU, acoustic energy was available in four layers in 1997 (3-25 m; 25-100m; 100-200 m; 200-500 m), and in seven layers (3-25 m; 25-50 m; 50-100 m; 100-200 m; 200-300 m; 300-400 m; 400-500m) in 1998 and 1999.

Deliverable 1.1. Fisheries data base .

Annex A – WP1, D1.1

The fisheries data described under task 1.1. were transferred to a standardised database format and made available to all participants. These data included tow-by-tow information (catch per tow, fishing effort per tow, length distribution per tow) for the EU fleet in the Pacific for the period 2005 – 2013 and monthly 1x1° catch data for all fleets in international waters since 2007. Before 2007 data were also available for China (annual 5x5° back to 2000) and for Korea (daily 5x5° back to 2003). The Chilean daily catch and effort data by haul both inside and outside the Chilean EEZ for the period 2007 – 2012 were made available as an additional Access data base.

Deliverable 1.2. Environmental data base.

Annex A – WP1, D1.2 **Annex A – WP3, D3.1, D3.2**

Three physical-biochemical data sets (NetCDFfiles) were made available to all users consisting of:

- one long term (1960-2008) hindcast simulation at coarse resolution (2°x month) from a coupled physical-biogeochemical model NEMO-PISCES forced by atmospheric reanalysis NCEP.
- a second shorter time series (1998-2012) at higher resolution (1/4° x week) based on the GLORYS2 reanalysis and PSY operational model of Mercator-Ocean.

- a third long-term (1979-2010) hindcast simulation at medium resolution (1°x month) from a coupled physical-biogeochemical model NEMO-PISCES forced by atmospheric reanalysis DFS5.2 which is based on the ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis ERA-INTERIM.

A data set containing data on primary production and euphotic depth derived from ocean colour satellite data over the same domain and at same resolution, based on the VGPM model (Behrenfeld and Falkowski 1997).

A dataset at degraded resolution of 1°x month to facilitate the optimization approach.

Deliverable 1.3. Report on biological data used for studying population structure.

Annex A – WP1, D1.3

A report has been written that describes the biological data used in this study.
The following data were used for modelling population structure and connectivity:

A set of acoustic data for the Peruvian commercial fleet. This information represented around 200 000 sampling units of 0.5 nm covered by the fishing fleet between January 2011 and May 2013.

A set of acoustic data collected during surveys performed since 1983 by IMARPE research vessels. This dataset contains information on:

- acoustic nautical area scattering coefficient integrated in 1 nautical mile ESDU;
- acoustic energy until 500m at 38kHz and 150 m at 120 kHz;
- acoustic energy by schools

A set of acoustic data collected by the Chilean research institute IFOP during three cruises of the RV ''Abate Molina'' in austral autumn/winter: 5 May to 17 June 1997, 3 June to 20 July 1998, and 15 May to 30 June 1999 (Cordova et al., 1998, 1999, 2000). This dataset contained information on:

- acoustic nautical area scattering coefficient, sA (MacLennan et al.,2002) integrated in 0.5 nautical miles elementary sampling distance units (ESDU) at a -65 dB threshold.
- In each ESDU, acoustic energy was available in four layers in 1997 (3-25 m; 25-100m; 100-200 m; 200-500 m), and in seven layers (3-25 m; 25-50 m; 50-100 m; 100-200 m; 200-300 m; 300-400 m; 400-500m) in 1998 and 1999.

Task 2.1. Literature review.

Annex A – WP2, T2.1, D2.1

This work consists of a literature study to describe and summarize the current knowledge on the Jack mackerel stock structure.

This was done in two steps.

- Gathering most of the existing literature (peer-reviewed articles as well as grey literature) on the South Pacific Jack mackerel. A bibliographic list was established and presented in at the SPRFMO Science Committee meeting in 2013. A total of 559 references have been listed and delivered in January 2013 to the other WPs in this project. The list was updated until October 2013.
- Production of a report synthesizing the information presented in the literature. Most of the documents were not easily accessible and many of them that contain important information even only exist in PowerPoint presentation or e.g. internal reports to SPRFMO. Efforts were spend to make this huge amount of information available in one synthesis submitted to SPRFMO in 2013. The synthesis was presented at the SPRFMO meeting in October, 2013. The final document (217 pages) is organised into an introduction, 6 chapters, a conclusion and a bibliographical list. Chapters refer to: (1) Zoology (taxonomy, morphometry); (2) Biology (Reproduction, migrations, behaviour, trophic, growth); (3) Ecology (hydrology, interactions, habitat); (4) Fisheries (history, fishing

methods, fisheries regulation, monitoring); (5) Populations (distribution, biological markers, demographic structure, population structure).

Task 2.2. Writing of a peer reviewed synthesis on Jack mackerel.

Annex A – WP2, T2.2, D2.1

A manuscript has been prepared and is to be submitted in a months' time to a peer reviewed international journal. The document is based on the general synthesis but focuses on the main question asked by the Project: what is the stock structure of the South Pacific Jack mackerel? Relevant elements of the biology and ecology of Jack mackerel were extracted from the global synthesis and allowed to analyse the different hypotheses on population structure.

Deliverable 2.1. Manuscript on Jack mackerel population structure.

Annex A – WP2, D2.1

A manuscript to be submitted to a peer review journal by the end of December, 2014 has been prepared. Authors and title: F. Gerlotto, F., Hintzen, N., Habasque, J., Gutierrez, M. and Bertrand, A. Unraveling the population structure of the world's largest fish stock: the Chilean Jack mackerel *Trachurus murphyi* in the South Pacific Ocean (to be submitted to Fish & Fisheries).

In addition, the following documents were prepared to support writing of the manuscript.

- Bibliographic list of papers and reports on the South Pacific Jack mackerel. Reported to DG-MARE in this project in January, 2013. Presented at the 1st meeting of the Scientific Committee of SPRFMO in La Jolla, October, 2013
- Bibliographical synthesis on the Chilean Jack mackerel, Reported to DG-MARE in this project in October, 2013. Presented at the 1st meeting of the Scientific Committee of SPRFMO in La Jolla, October, 2013.

Both deliverables were included in the same document:
Gerlotto, F. and Dioses, T., 2013. E.U. Project "Hydrography and Jack mackerel stock in the South Pacific". Bibliographical synopsis on the main traits of life of *Trachurus murphyi* in the South Pacific Ocean. ref. SC-01-INF-16, SPRFMO, La Jolla, October 2013.

Task 3.1 Identify the key hydrological and biogeochemical factors determining Jack mackerel distribution.

Annex A – WP3, T3.1, D3.1

Available data bases (e.g. world ocean data and satellite databases) of relevant environmental factors to characterise the Jack mackerel habitat in the horizontal and vertical plans have been selected and extracted. From the literature (e.g. Quiñones et al., 1997; Bertrand et al., 2004b, 2006) and the comparison of extracted environmental data with catch and fish distribution positions we identified the key environmental factors driving Jack mackerel distribution. For each selected parameter we determined the minimal and maximal threshold values according to the range of tolerance of Jack mackerel. These threshold limits and the interactions between factors have been included to develop a statistical model of Jack mackerel habitat. This model allowed exploring the spatial extension of the Jack mackerel habitat and its variability at seasonal and inter-annual scales. The model also allowed determining the presence of permanent or temporal discontinuity in the habitat.

Task 3.2 Develop a conceptual model of the habitat of the Jack mackerel in 3D.

Annex A – WP3, T3.2, D3.1

From the literature and the results of the statistical model we constructed a conceptual model of habitat of the Chilean Jack Mackerel in 3D. This model proposes a comprehensive vision of Jack mackerel distribution according to the hydrological factors, including temperature and dissolved oxygen, and prey distribution. This model was used as a straightforward basis to better understand how the habitat structure, in particular the presence of discontinuities likely impact the population and stock structure.

Task 3.3 Create an optimal parameterization of feeding and spawning habitat of Jack mackerel.

Annex A – WP3, T3.3, D3.2

The optimal parameterization of feeding and spawning habitat of Jack mackerel for SEAPODYM application was achieved based on a priori information from WP2 and the maximum likelihood estimation approach implemented in the model and using the best possible available geo-referenced information, including catch, length frequency and acoustic data. An analysis of population structure was conducted based on hindcast simulations of feeding and spawning habitat and compared with the results from Task 3.2.

Deliverable 3.1. A description of the statistical 3D habitat model of Jack mackerel identifying likely population structure hypothesis given the key hydrographical and biochemical parameters.

Annex A – WP3, D3.1

A report has been written that describes the statistical 3D habitat model of Jack mackerel. To describe this 3D habitat and to assess stock structure, two main analyses were performed: (ii) defining the relevant environmental and hydrographical parameters that contribute to the favourable habitat of Jack mackerel, and (ii) simulating the species distribution based on the habitat characteristics.
Using a variety of data sources such as acoustic information and biological sampling, we tested the significance of different environmental and hydrographical conditions to explain the distribution of Jack mackerel. Identified key parameters were temperature, oxygen concentration and oxycline depth, and chlorophyll-a concentration (used as a proxy for prey abundance).

Species distribution was modelled using a statistical framework. Due to the high variability of environmental conditions in the study area, we focused both on inter-annual and intra-annual patterns of variability. Using the best fish distribution model, probability maps of Jack mackerel distribution over time and space were produced. The spatial distribution of the potential habitat and its temporal variations provided relevant information on the likelihood of different hypotheses on population structure. Inspection of these maps shows that Jack mackerel is most of the time united in one large area from the 'Jack mackerel belt' to North Peru. However at certain periods the continuity within the overall range of habitat can disrupt. This can lead to temporally reduced exchanges between the different parts of the overall population. Finally we synthesized these by constructing a comprehensive conceptual model of Jack mackerel habitat in 3D.

Deliverable 3.2 A report describing the SEAPODYM model of Jack Mackerel identifying likely population structures.

Annex A – WP3, D3.2

A report has been written that describes the SEAPODYM model of Jack mackerel. The SEAPODYM (Spatial Ecosystem and Population Dynamics Model) configuration includes a definition of habitat indices, spawning, local movements as the responses to the habitat quality and basin-scale seasonal migrations, accessibility of forage for fish within different vertical layers, predation and senescence mortality and its change due to environmental conditions. Developing an application for Jack mackerel required first to optimize the parameters used in the definition of the spawning and feeding habitats of the species. The spawning habitat combines the mechanisms of interaction with key environmental variables, i.e., the definition of a spawning temperature window for an optimal growth, the coincidence of spawning with presence or absence of food for larvae, the coincidence of spawning with presence or absence of predators of larvae, the redistribution of larvae by the oceanic circulation with natural mortality related to new habitat. Key parameters obtained from the literature study or habitat modelling together with fisheries data of high resolution and quality were used to optimize the habitat parameters, population dynamics (movement, natural mortality and stock recruitment) and evaluate the model outputs.
The simulations outputs shows a continuous spawning grounds from Peru to Chile and New Zealand, but with natural separations of less favourable index between Peru and Chile and between Coastal Chile and

offshore Chile. Habitat of juvenile fish is quite similar to the spawning habitat. The feeding habitats of older cohorts contract south in relation with the change in the thermal habitat, i.e., larger fish can access lower temperature water with oldest (largest) fish feeding only in the southern Pacific below 30°S, and moving north only for spawning season, predicted to occur in the 3rd quarter with a peak around September. It seems that there is a link between inter-annual variability of oceanic conditions due to ENSO and low or high peaks of recruits with most favourable conditions during La Niña phase following an El Niño event. Therefore, the spatial dynamics of feeding and spawning habitats suggest four subpopulations more or less connected. One far in the south west Pacific, a second in the South east (offshore Chile) connected through young and adult habitats to the third one along the coast of Chile. The 4th subpopulation is offshore and along the coast of Peru, with a relatively well marked natural separation from the southern sub-population, excepted maybe during El Nino events when adults move from south to escape too warm Peruvian waters, or conversely strong La Niña with an opposite displacement.

Task 4.1. Define reference points for Jack mackerel.

Annex A – WP4, T4.1, D4.1.3

Reference points on fishing mortality and biomass were defined for Jack mackerel under a one-stock and two-stock assumption. Three exercises were undertaken to estimate reference points. 1) taking the methods as described by Simmonds et al. 2010 into account, estimating F_{MSY} under a single stock assumptions. 2) taking the MSE framework to estimate fishing mortality and biomass reference points, for both the single and two stock assumption. 3) taking the Joint-Jack mackerel stock assessment model and estimating reference points, both fishing mortality, biomass and MSY itself, inside this model, for both the single and two stock assumption. The findings are reported in this report, in the WP reports and in SPRFMO Science Committee reports. Overall, F_{MSY} ranges between 0.13 in the short term to 0.21 in the long term. B_{MSY} ranges between 4.5million tonnes in the short term to 5.5million tonnes in the long term.

Task 4.2. Evaluate changes in mesh size and minimum landing size.

Annex A – WP4, T4.2, D4.1.1

Evaluations were performed using the MSE framework developed under WP4 to estimate SSB and F trends under a change in minimum landing size or mesh size. The simulations considered these changes for all of the fleets, but allowing for a different response to changes in these regulation, as some fisheries catch Jack mackerel as bycatch rather than as main target species. The results show that increasing either mesh size or minimum landing size do not have positive population effects.

Task 4.3. Evaluate effort or TAC based management.

Annex A – WP4, T4.3, D4.1.2

As discussed and agreed upon by DG-MARE in the interim report meeting, no analyses were performed regarding effort or TAC management as effort data was not available at the appropriate scale to do so. In addition, DG-MARE agreed that for a single species fishery, as is the case with Jack mackerel, the analyses of effort versus TAC was less relevant. A document has been written to provide more detail on this consideration.

Task 4.4. Design of Harvest Control Rules.

Annex A – WP4, T4.4, D4.1.4

In preparation to designing different Harvest Control Rules (HCRs), two stakeholder workshops were held. One in Lima, Peru and one in Brussels, Belgium. The stakeholders were asked to define major problems with Jack mackerel management and how these could be resolved. The results of these workshops were analysed and resulted in defining 26 different HCRs. Each of these HCRs were evaluated inside a Management Strategy Evaluation, thereby appropriately accounting for uncertainty in stock assessments, fishery and biological dynamics. The results were presented and discussed at the SPRFMO Science Committee meeting in 2013 and 2014. In total, 6 HCRs were selected. These results were taken directly as input into the advice to the SPRFMO on sustainable management plan options for their meeting in 2015. The results of the HCRs were compared to the medium term forecast of the Joint-Jack mackerel stock assessment model and were found to be similar.

Task 4.5. Compare SEAPODYM configuration with Joint-Jack mackerel stock assessment.

Annex A – WP4, T4.5, D4.2

A configuration of the model SEAPODYM for Jack Mackerel has been used with a forcing form a Earth Climate model (IPSL-CM4) to perform medium term projections taking both the hydrographical and fishing conditions into account. The model was calibrated over the historical fishing period and gave very close parameter estimation to the configuration using more realistic atmospheric forcing and higher resolution. However the natural mortality was estimated higher for juvenile and young fish in the south west region. The total and adult biomasses were estimated higher with this configuration than with the previous one or the stock assessment estimate (a factor 2 between the two models). Again this is due to very high biomass predicted in the region south offshore Chile. When considering only regions 1 to 4 where the catch concentrated in the last ten years, the spawning biomass is in the same range as the stock assessment model.

Deliverable 4.1. A report on the evaluated management goals.

Annex A – WP4, D4.1

A report has been written that describes the Management Strategy Evaluation framework that has been designed to evaluate different management goals, including the process to parameterize the models based on stock assessment results. The report consists out of 3 sections. The first section describes the design of the MSE and parameterisation of the model, including estimation of reference points and the design of 26 different Harvest Control Rules and the results from evaluating these under poor and more optimistic recruitment regimes. The second section describes the scenarios evaluated to investigate the effects of a mesh size increase or increase in minimum landing size. A third section specifies how effort and TAC regimes are similar in a management context.
The results show that six harvest control rules are considered by the SPRFMO Science Committee, and the value of the associated performance indicators for each of the six HCRs. From these six, two HCR are proposed as most appropriate for Jack mackerel. These HCR are associated with fishing mortality close to estimated F_{MSY} values between 0.13 and 0.21. Results also show that increasing mesh size or minimum landing size does not result in positive population dynamics.

Deliverable 4.2. A report on the comparison of the SEAPODYM model medium term projections with the Joint-Jack mackerel stock assessment.

Annex A – WP4, D4.2

A report has been written that describes the comparison between SEAPDOYM and the Jack mackerel stock assessment results. The configuration of SEAPDOYM using the IPSL climate forcing for projection shows an overall decreasing trend in abundance of recruits leading to a reduction of 10% between 2010 and 2050, without considering the fishing impact. The future of the population under exploitation is also investigated using a fishing scenario for the coming decades equivalent to the average fishing effort of the last 10 years (2003-2012), that is a low fishing effort relatively to the one deployed in the 1980s and 1990s. In that case the spawning biomass is predicted to increase and to reach an equilibrium level of exploitation after 2020 and a level of spawning biomass ~20 % below of the biomass predicted at the end of the 1970s. These trends were compared to the Jack mackerel assessment results and show a different perception in total biomass but a similar trend in reaching an equilibrium around 2020 in SSB.

Task 5.1. An MSE model to evaluate complex population dynamics.

Annex A – WP5, T5.1 D5.1

To analyse sustainable exploitation options on a variety of population structures and management / stock structures, a modelling toolbox was developed. This toolbox is available as an add-on to the popular FLR library in R, and allows users to simulate different population structures over time, including those investigated in this study. The MSE model developed here, using this toolbox, was used to simulate a single population, two separated populations and a metapopulation where connectivity between units varies over time and age. On top of that operates the fishery module, where each fishery has a proportionate availability to the fish resource. The combination of biological parameters and catches allowed us to simulate stock assessments within the MSE and provide TAC advice based on Harvest Control Rules. The design of the MSE model was identical for all population and stock structure hypotheses tested which enabled us to compare the results across hypotheses and calculate relevant performance indicators for each of them. The package is known as FLMeta and is available on google code under: https://code.google.com/p/flmetapop.

Task 5.2. Impact of fishing and environmental variability on the population structure of Jack mackerel.

Annex A – WP5, T5.2, D5.2

Impacts of fishing and environmental variability on the (meta) population structure of Chilean Jack Mackerel emerging from past and present oceanographic conditions and biological criteria estimated for the species in WP3 and WP4 were investigated with SEAPODYM. The analysis provided an evaluation of model outputs based on existing data (catch, effort, CPUE, size frequency, acoustic data) and allowed to study the connectivity of JM population between different regions in the South Pacific Ocean.

Task 5.3. Evaluation of management options under changes in population and stock structure.

Annex A – WP5, T5.3, D5.1

In total, six different HCRs were evaluated for each of the six population & stock structure hypotheses. The six HCRs were taken from WP4 where these rules were selected through collaboration with the SPRFMO Science Committee. Under each of these HCRs a set of results regarding SSB, F and Catch was obtained and indicators of risk to overexploitation were calculated. Results show that, assuming the likely population structure of a metapopulation, the Northern unit is at risk to overexploitation when a one-stock assumption is taken for management purposes. Under almost all structure scenarios, fishing associated with an F of 0.13 seems sustainable.

Deliverable 5.1. A report indicating sustainable management options for Jack mackerel.

Annex A – WP5, D5.1

A report has been written that describes the evaluation of six different Harvest Control Rules for a range of population and stock structure assumptions. The population structure assumptions that are considered are a single population unit, two population units and a metapopulation consisting of two units with a considerable degree of connectivity among them. The stock structure assumptions that have been evaluated against these population structures are the one-stock and two-stock approaches, similar to the SPRFMO Science Committee approach and conclusions from this study on likely stock structure. From the six control rules evaluated, none performed without any risk under any of the six structure hypotheses. Hence, one of the major conclusions from this exercise is that sustainable management of Jack mackerel is foremost associated with considering two population structures (or a metapopulation) rather than advising on a specific fishing mortality or TAC. When two stocks are assumed in management, the HCR associated with an F of 0.13, 0.2 and sloping rule are considered sustainable in the medium term. Management following the most likely population and stock structure hypothesis, derived in this study, results in sustainable exploitation except for managing under a biomass target at B_{MSY}.

Deliverable 5.2. report describing the change in spatial structure of Chilean Jack Mackerel population.

SEAPODYM Jack mackerel configuration allowed to simulate the complete spatial and temporal dynamics of the population, from larvae to oldest cohorts, in its marine environment as simulated by present state-of-the-art 3D models of the ocean physics and biogeochemistry. Habitat and population dynamics parameters were estimated through a series of simulation optimization experiments. Spatial structure of the population was analyzed through a connectivity study and computation of fish fluxes between large oceanic regions. The model predicts an isolated western sub-population, a self-sustained sub-population in the eastern subtropical convergence zone off the southern coast of Chile, a sub-population in Chile coastal and offshore areas relying also on the previous adjacent subtropical convergence area, and a last Peruvian sub-population receiving some significant contribution in adult biomass from the subtropical convergence stock likely crossing the offshore and coastal regions, but with very small contribution in the opposite way, i.e. from Peru region to the southern regions. This first application of SEAPODYM to the south Pacific jack Mackerel has been optimized using a fishing data set covering roughly half of the nominal catch of the historical fishing period. A revision of this work with an updated catch data set is recommended to confirm and identify more clearly the impact of intense fishing activity on this proposed spatial structure, and to test various management decisions. These results are described in a comprehensive report.

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Justification

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The scientific quality of this report has been peer reviewed by the a colleague scientist and the head of the department of IMARES.

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