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Stock assessment of Jack mackerel:
A non-homogenous stock and changes in catchability
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Abstract

A stock assessment of jack mackerel (*Trachurus murphyi*) is carried out taking into account a non-homogenous stock and changes in catchability. Some key aspects of fisheries of pelagic fish also include density-dependent effects over the catchability coefficient, which increases when the vulnerable biomass of the stock decreases. This characteristic determines that yields remain high despite the decrease of the stocks' biomass. This feature is also relevant in a stock assessment for *T. murphyi*, when considering catch per unit of effort as an indicator of vulnerable biomass.

This report aims to provide a stock assessment for *T. murphyi* of the South Eastern Pacific Ocean taking into account a minimum heterogeneous spatial structure and density dependent changes in catchability.

The results of the present state (year 2013) of the *T. murphyi* stock are partially similar with that of the SPRFMO stock assessment. Differences are noted in magnitude of total biomass, spawning biomass, recruitments and fishing mortality. The depletion of the *T. murphyi* stock in year the 2013 was close to 14% of its virginal biomass, after reaching its minimum value at 5% in the year 2010.

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1. Introduction

In the South Eastern Pacific Ocean, jack mackerel (*Trachurus murphyi* Nichols, 1920) is widely distributed along the coast of South America, from northern Peru to southern Chile, including Patagonian waters. *T. murphyi* is also found in a band in the high seas which is also referred to as the "jack mackerel belt". This belt ranges from 35°S to 45°S, from the coast of central Chile to the coasts of New Zealand and Australia (Elizarov et al. 1993, Arcos et al. 2001, Cubillos et al. 2008, Gerlotto et al. 2011).

The wide distribution of the stock of *T. murphyi* and its high migratory capability has impeded the structural identification of the stock (Gerlotto et al. 2011). In the literature, attempts to identify such structure have been described by Serra (1991), George-Nascimento et al. (1992) and Ashford et al. (2010). The spatial structure of *T. murphyi* is complex due to the variability shown by high connectivity between zones and the environment. The stock is therefore not demographically uniform (different fisheries availability), thus higher abundance of juveniles are found in the north of Coquimbo (30°S), in both coastal and oceanic waters. In fact, average size of *T. murphyi* individuals are more alike between Arica-Coquimbo and Peru, in the north zone, than those individuals found in the central-south zone off Chile (Serra et al. 2008), thus confirming the spatial segregation of the same biological stock.

In a homogenous stock changes in biomass are dominated by recruitment, mortality and growth (Ricker 1975, Hilborn and Walters 1992), and changes in abundance can be modeled with the survival model. This theory has prevailed in the formulation of assessment stock for *T. murphyi* until now, implying that heterogeneity in its spatial distribution is a consequence of the exploitation pattern of the several fisheries that have access to the stock, generating partial fisheries mortalities.

In a non-homogenous stock abundance is spread amongst areas where groups remain isolated from one another in an annual scale, to subsequently reunite and reproduce (MacCall 1986). Consequently, growth and mortality (natural and by fishing) occur in each geographical stratum of the stock in a year. The general theoretical aspects of a non-homogenous population, which define the conceptual frame for any stock assessment for this type of population, are listed below:

1) a spawning sub-habitat and a coastal feeding sub-habitat are recognized, with residence time in the costal feeding sub-habitat that can vary to several months during the annual cycle (Arcos et al. 2001, Cubillos et al. 2008);

2) Coastal feeding sub-habitats are able to sustain and house various aggregations of the same stock, which do not present considerable interactions with other groups. Thus,

natural and fishing mortality over the vulnerable fraction of the stock are independent from those occurring in other areas; and,

3) The fraction of the stock which survives to natural and fishing mortality (vulnerable fraction) migrates out of the coastal feeding sub-habitat areas to spawn. It is assumed that, at this time, the interaction of the surviving population from other feeding areas takes place.

This configuration is extremely relevant when assessing the *T. murphyi* stock of the South Eastern Pacific Ocean, particularly important amongst the options considered in the stock assessments, which are being currently performed by the South Pacific Regional Fisheries Management Organization (SPRFMO).

Some key aspects of fisheries on pelagic fish also include density-dependent effects over the catchability coefficient, which increases when the vulnerable biomass of the stock decreases. This characteristic determines that yields remain high despite the decrease of the stocks' biomass, consistent with a hyperstability model (Harley et al. 2001). This feature is also relevant in a stock assessment for *T. murphyi*, when considering catch per unit of effort as an indicator of vulnerable biomass.

This report aims to provide a stock assessment for *T. murphyi* of the South Eastern Pacific Ocean taking into account a minimum heterogeneous spatial structure and density dependent changes in catchability.

2. Methodology

For the stock assessment of T. *murphyi* a model with two distribution areas is considered. The first area is located in the north of Coquimbo, Chile (30°S), including the fraction which is shared with Peru and its international waters. The second area is located to the south of Coquimbo, which includes the fishery of *T. murphyi* in the central-south zone of Chile and the fleet which formerly operated in international waters (Fig. 1). For the stock assessment of the T. *murphyi* data was provided by the Subsecretaría de Pesca de Chile and also obtained from SPRFMO reports (Table 1).
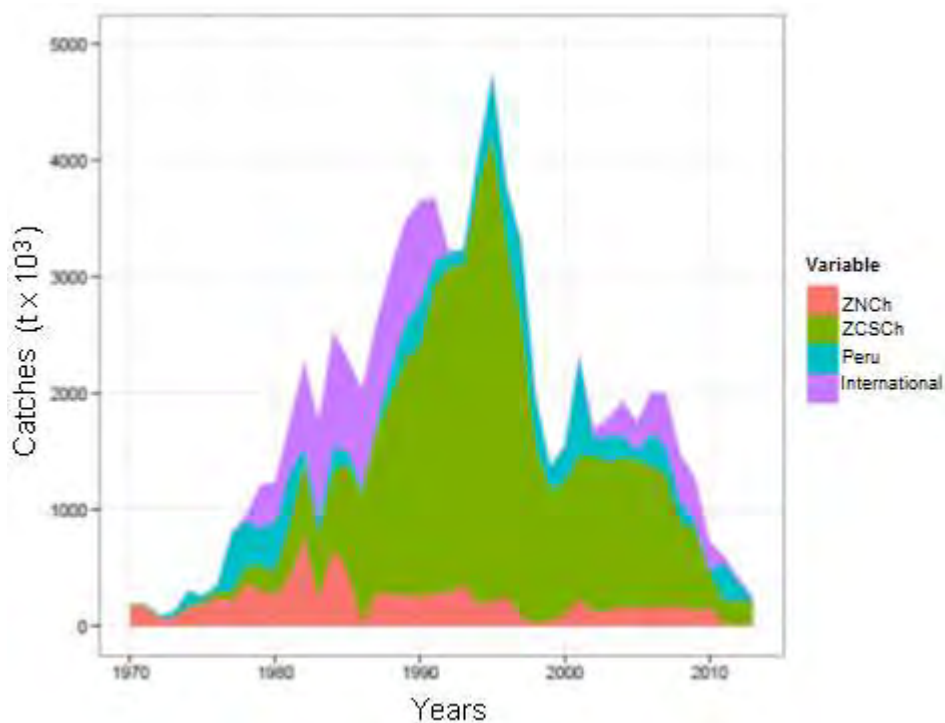

Figure 1. Catch of *T. murphyi* per geographical zones in the South Eastern Pacific Ocean. Nomenclature: ZNCh = off northern Chile; off central-southern Chile. Period: 1970 – 2013.

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Table 1. Parameters and data considered in the stock assessment of *T. murphyi.*

Area	Fishery	Catch	Age/Length	CPUE	Acoustic survey	Eggs
North	Peru				1983-2011[a]	
	Chile	1970-2013	1975-2013		1984-1988 [b]	
	Oceanic [c]	1978-1991	1978-1991			
South	Chile	1970-2013	1975-2013	1983-2013	1997-2012	1999-2008 [d]
	Oceanic	1979-2013	1979-1991			

a: Segura and Aliaga (2013).

b: Time series gaps: 1984-1988, 1991 and 2007-2012.

c: Catch in international waters adjacent to Chile and Peru belong to the Sub-Division North and Sub-Division South (Grechina 1998). Catch in the South Western Pacific Ocean was not incorporated in the assessment.

d: *T. murphyi* acoustic surveys provide ichtyoplankton information and also spawning biomass estimations, which is assumed proportional to the spawning biomass.

2.1 Dynamic of the abundance

The dynamic of abundance considers that recruitment starts each year with the spawning season in November. Age composition is assumed for 12 age groups, starting at age 2. A Beverton-Holt stock-recruitment relationship is included with an h=0.75 steepness. Abundance of all annual classes at the beginning of the exploitation period is assumed to decrease by natural mortality (M=0.3 y^{-1}), except for recruits.

The dynamic of the abundance starts with the repartition of total recruitment between k zones, i.e.,

$$T_{i,1,k} = \pi_{i,k} N_{i,1}$$

Where $T_{i,1,k}$ is the recruitment at the beginning of the year i in zone k, $\pi_{i,k}$ is the total recruitment fraction ($N_{i,1}$) in year i distributed in zone k, and k; $\pi_{i,k}$ is the fraction of total recruitment ($N_{i,1}$) in year i with is distributed in the zone k:

$$\sum_k \pi_k = 1.$$

Recruitment abundance in each zone decreases by total mortality (Z) in each zone, i.e.,

$$T_{i+1,j+1,k} = T_{i,1,k}\exp(-Z_{i,1,k})$$

$$T_{i+1,m,k} = T_{i,m-1,k}\exp(-Z_{i,m-1,k}) + T_{i,m,k}\exp(-Z_{i,m,k})$$

Therefore, at the end of the year (or the beginning of the next year) in each zone, the sum of surviving abundance represents total abundance, i.e.,

$$N_{i,j} = \sum T_{i,j,k}$$

Total mortality rate ($Z_{i,j,k}$) is composed of natural mortality ($M = 0.3$), which is constant between years, ages and zones; and fishing mortality ($F_{i,j,k}$), which is separable in associated effects of the exploitation pattern ($V_{i,j,k}$) and fishing annual mortality in each zone ($F_{i,k}$). The exploitation pattern was estimated for each age group in the ascending portion ($j < g$). Starting from age g the same value is assumed for the estimated value of g. Inter-annual variability was considered. Also, slow inter-annual changes were considered every two years for the exploitation pattern, using random walk.

In each zone spawning biomass is described by

$$S_{i,k} = \sum_j W_j\, P_j T_{i,j,k}\exp(-0.875 \times Z_{i,j,k})$$

Therefore total spawning biomass is described by

$$S_{i,j} = \sum_k S_{i,j,k}$$

The assessment considers the catch equation of Baranov, i.e.,

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$$C_{i,j,k} = \frac{F_{i,j,k} N_{i,j,k}}{Z_{i,j,k}} \left(1 - \exp(-Z_{i,j,k})\right)$$

$$Y_{i,k} = \sum_j W_j\, C_{i,j,k}$$

$$p_{i,j,k} = \frac{C_{i,j,k}}{\sum_j C_{i,j,k}}$$

In order to counteract catch observations against population dynamics, we assumed a negative log-like log-normal function. Age composition was transformed to size composition by an age-size key. The age-size key was estimated by the assessment model based on growth and length at age variance coefficient. Indexes of abundance were also used to constrain parameter estimations of the population dynamics and are detailed in Table 2. The model was programmed using AD Model Builder (Fournier et al. 2011).

2.2 Catchability

The catchability density dependent coefficient was estimated in two phases. The first incorporated a random walk for the parameter in the stock assessment. Once inter-annual changes for q were estimated, the values were related to the average vulnerable biomass of *T. murphyi*, detailed in the following model:

$$\log(U_{i,k}) = \log(q) + \beta \log(Bv_{i,k})$$

The significance of β was tested.

Table 2. Abundance index used in the *T. murphyi* stock assessment.

Years	Acoustic biomass in Peru (t x 10³)	CPUE CSZ Chile (t/total trips)	CPUE NZ Chile (t/vcp)	Acoustic biomass CSZ Chile (t x 10³)	Acoustic biomass NZ Chile (t x 10³)	Spawning biomass (t x 10³)
1983	8513	0.646	0	0	0	0
1984	5002	0.569	0	0	99	0
1985	180	0.466	146	0	324	0
1986	4330	0.402	83	0	123	0
1987	6472	0.481	90	0	213	0
1988	2812	0.410	105	0	134	0
1989	4365	0.419	104	0	0	0
1990	5972	0.333	99	0	0	0
1991	5597	0.409	93	0	242	0
1992	2958	0.349	92	0	0	0
1993	8471	0.302	93	0	0	0
1994	6413	0.359	80	0	0	0
1995	3251	0.322	85	0	0	0
1996	3376	0.334	67	0	0	0
1997	1892	0.293	49	3530	0	0
1998	107	0.277	48	3200	0	0
1999	662	0.329	40	4100	0	5724
2000	1071	0.309	0	5600	0	4688
2001	1067	0.397	0	5950	0	5627
2002	447	0.331	0	3700	0	0
2003	454	0.289	0	2640	0	1388
2004	239	0.316	0	2640	0	3287
2005	562	0.287	0	4110	0	1043
2006	879	0.316	0	3192	112	3283
2007	236	0.240	0	3140	275	626
2008	110	0.161	0	487	259	1935
2009	70	0.134	0	328	18	0
2010	23	0.099	0	0	440	0
2011	363	0.057	0	0	432	0
2012	45	0.173	0	0	230	0
2013	0	0.148	0	0	0	0

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2.3 Model configuration

The model configuration was based on the degree of emphasis which is given to the structural parameters, such as the influence of the data being used. The base model being considered for the assessment is detailed in Table 3. Model fits made for each piece of information can be found in Annex 1. Higher model fits are found in parameters such as size composition in each zone, catch per unit of effort and to abundance index.

Table 3. Structural assumptions involve in the log-likelihood functions of the base case in the stock assessment of *T. murphyi*.

Zona	Catches	Catch-at-Length	Selectivity	Abundance Index
North	λ=100	Multinomial n=80	λ=10 λ=10	acoustic Peru: CV=0.1; q=1 Acoustic ZNCh: CV=0.2 CPUE: CV=0.2
South	λ=1000	Multinomial n=100	λ=100	Acoustic ZCSCh: CV=0.1 Spawning biomass: CV=0.1

3. **Results**

3.1 Total Biomass and Spawning Biomass *T. murphyi*

Total biomass and spawning biomass of *T. murphyi* are shown in Fig. 2. Total biomass increases exponentially from 8 million tonnes in 1975 to 27 million tonnes in 1988, slowly decreasing until 1999. Following the year 2000 until 2002 a slight increase in total biomass is noted. The downward trend continues until 2013, where total biomass reaches near 2 million tonnes. Spawning biomass follows the same trend as total biomass, reaching its lowest level at the beginning of 2010.

T. murphyi biomass in south Coquimbo (30°S) contributes significantly to the changes in total biomass. Nevertheless, to the north of Coquimbo total biomass of *T. murphyi* decreases until 1985, and shown signs of recovery from 1986 to 1996, to slowly decreases with minor fluctuations until 2013.
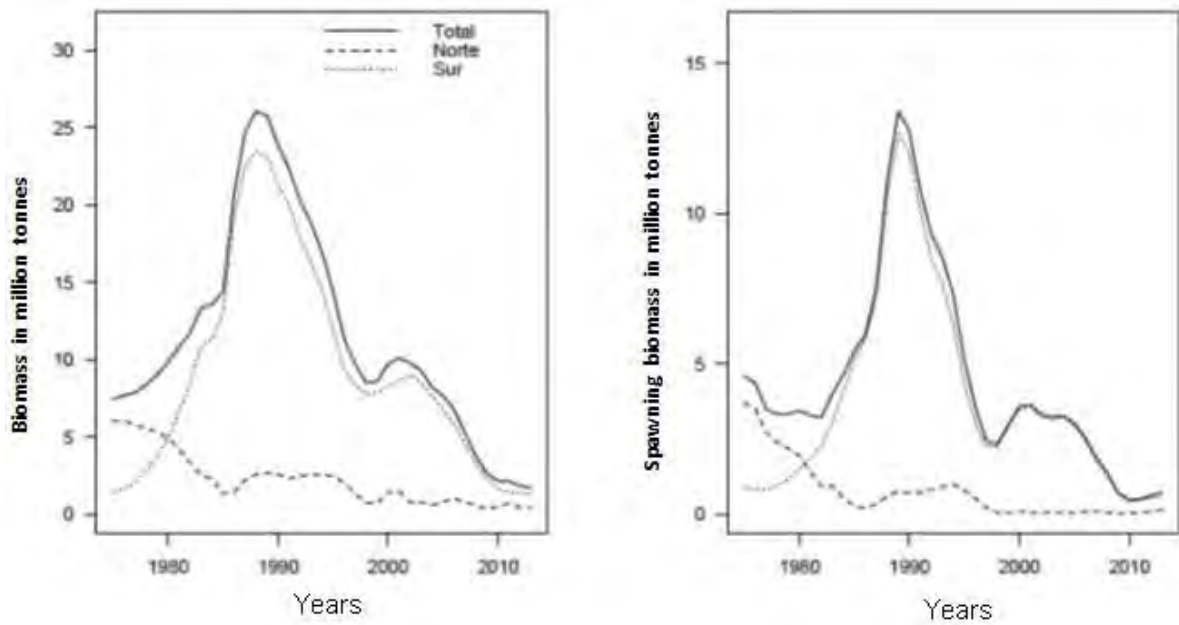
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Figure 2. Total biomass (left) and spawning biomass (right) of *T. murphyi* stock by geographic zone (North: to the north of 30°S; South: to the South of 30°S). Period: 1975 to 2013.

3.2 Fishing mortality

Fishing mortality (F) is constantly high for the assessed period (1975 to 2013). Highest fishing mortality is observed since 1997 in the northern fraction of the stock of *T. murphyi* (Fig. 3). Average fishing mortality (average weight by abundance in each zone) is better explained by the influence of the southern fraction of the stock.
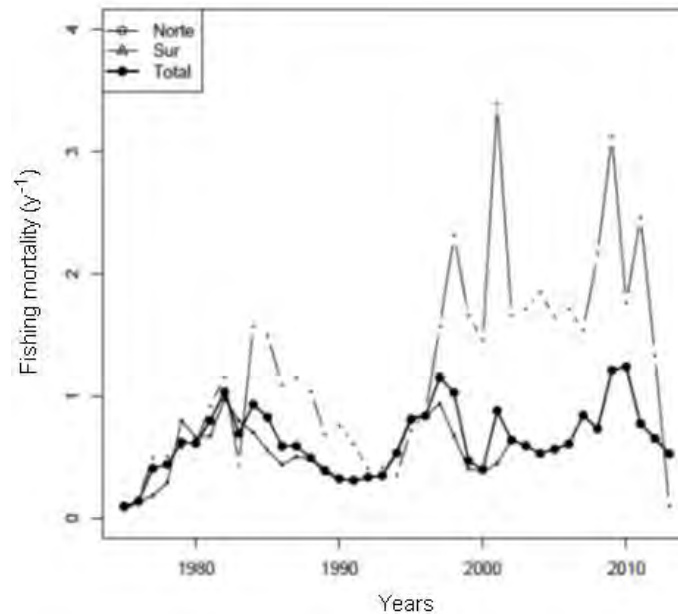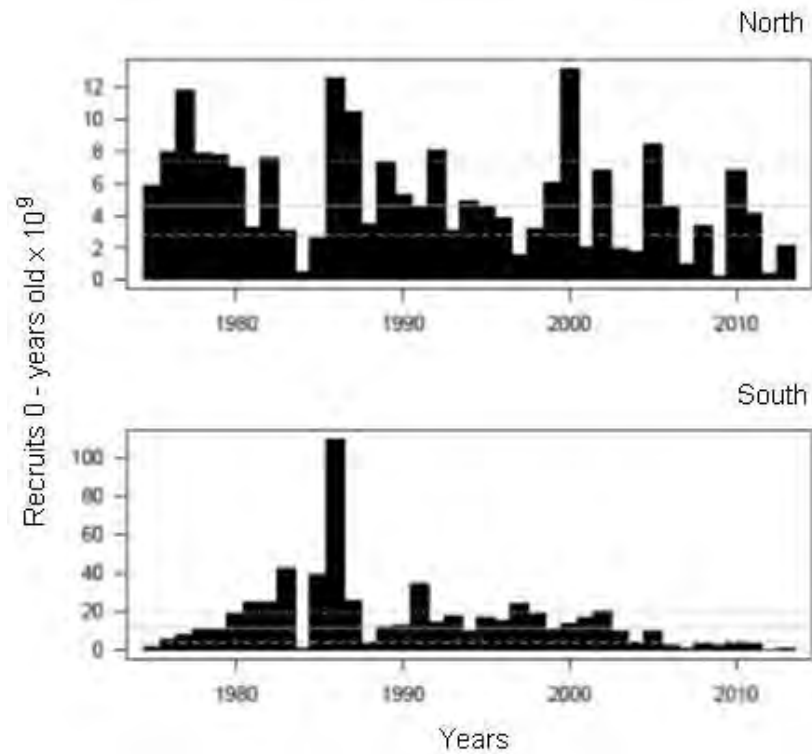
Figure 3. Fishing mortality for *T. murphyi* by geographic zone. North: to the north of 30°S;
South: to the South of 30°S. Period: 1975 to 2013.

3.3 Recruitment and recruitment pattern

At the beginning of each year, recruitment changes inter-annually (Fig. 4), with intense recruitments in the north for the years 1976-1979, 1982, 1986-87, 1992, 2000 and 2005; since the year 2001 and onwards, recruitments in the north are low. In the southern zone, high and moderate recruitments since 1981 to 1987 are recognized, with an extremely high recruitment in 1986.

Since the year 1991 most recruitment are low, with the exception of moderate recruitments in 1987 and 1988. In the southern zone weak recruitments are recognized from 2004 to 2013. Consequently, the highest total recruitments are in the years 1982-1983 and 1985-1987, with the highest recruitment in 1986. The two previously mentioned high recruitments events caused a subsequent increase in the biomass of *T. murphyi* in the South Eastern Pacific Ocean. Average recruitments results in a decrease of *T. murphyi* biomass, which is modulated by high fishing pressure. Following the year 1991 only moderate recruitments in 1997, 2000 and 2002 allows the slow recovery of the stock in the period following the year 2000 (Fig. 5).

Figure 4. Recruitment of *T. murphyi* by geographic zone. North: to the north of 30°S; South:
to the South of 30°S. Period: 1975 to 2013. Horizontal lines represent quintiles at
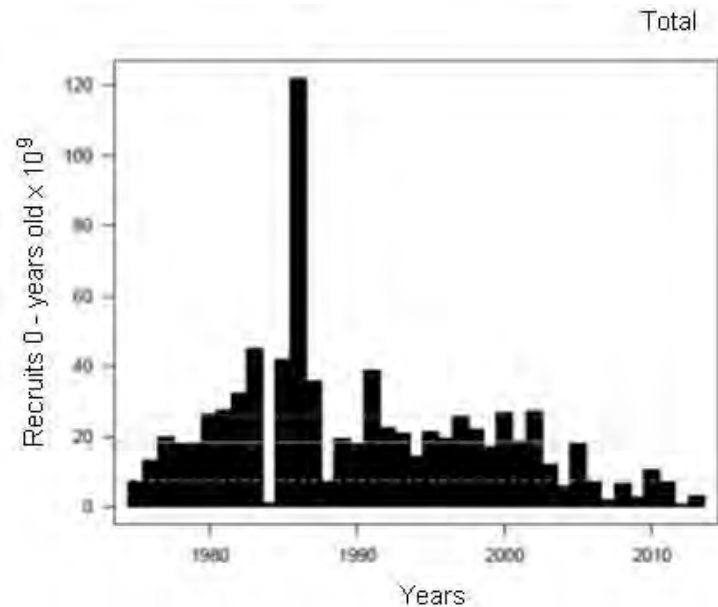75%, 50% and 25% respectively.

Figure 5. Total recruitment of *T. murphyi* where both geographic zones are included. Period: 1975 to 2013. Horizontal lines represent quintiles at 75%, 50% and 25% respectively.

The stock-recruitment relationship shows that highest recruitments normally range between $40x10^9$, but under $50x10^9$ fish. The relationship also shows that the recruitment of 1996 is extraordinary and reaches $120x10^9$ fish, and it contributes largely to the stock biomass. Recruitments between 20 and 25 x 10^9 fish are likely the result of favorable environmental conditions and, as a result, *T. murphyi* recruitments have been very weak since the year 2003 (Fig. 6).
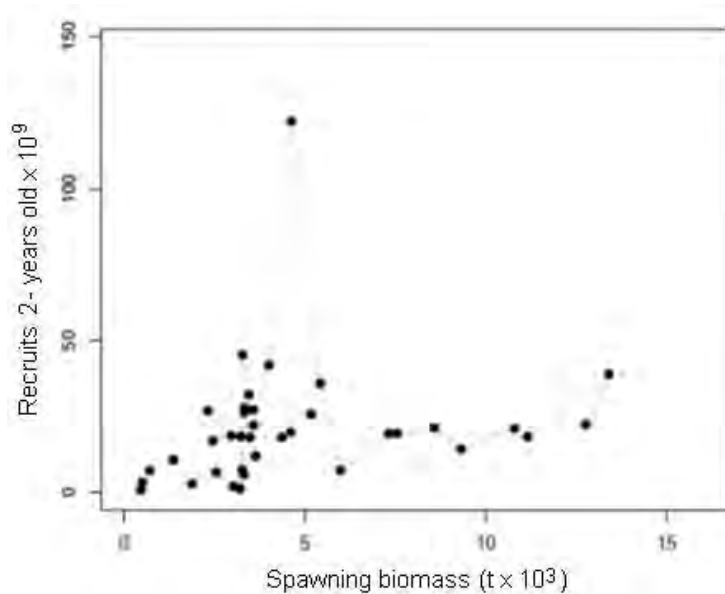
Figure 6. Stock-recruitment relationship of *T. murphyi*. Period: 1975 to 2013.

The exploitation pattern of *T. murphyi* shows that, at the beginning of the series until the year 1990, in the north and in the south of 30°S, fish older than 6 years were able to escape fishing activities. Following the year 1990, fish older than 6 years also became vulnerable to fishing activity (Fig. 7).
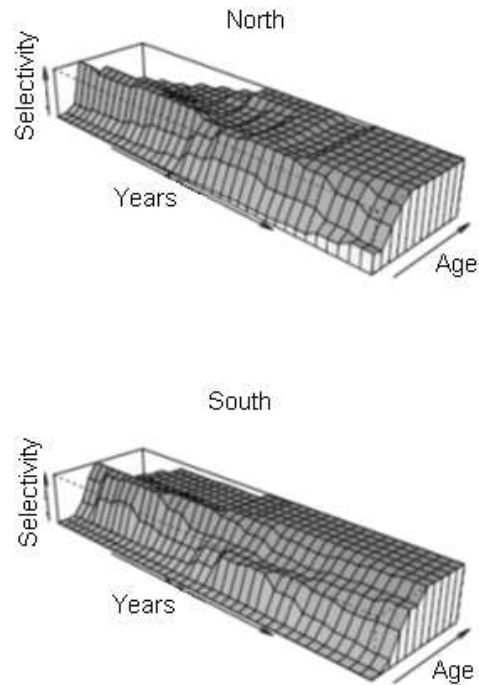
Figure 7. Exploitation pattern of *T. murphyi* by age and geographic zone to the north and
south of 30°S. Period: 1975 to 2013.

3.4 Catchability

The relationship between catch per unit of effort and vulnerable biomass in each zone is a
non-linear equation. This result follows the hyperstability model (Fig. 8). The coefficients are
significant for each zone ($p<0.05$), implying that catchability coefficient increases when
exploited biomass decreases.   In other words, *T. murphyi* stock keeps aggregating or
structuring in huge fish schools, despite a decrease in biomass.
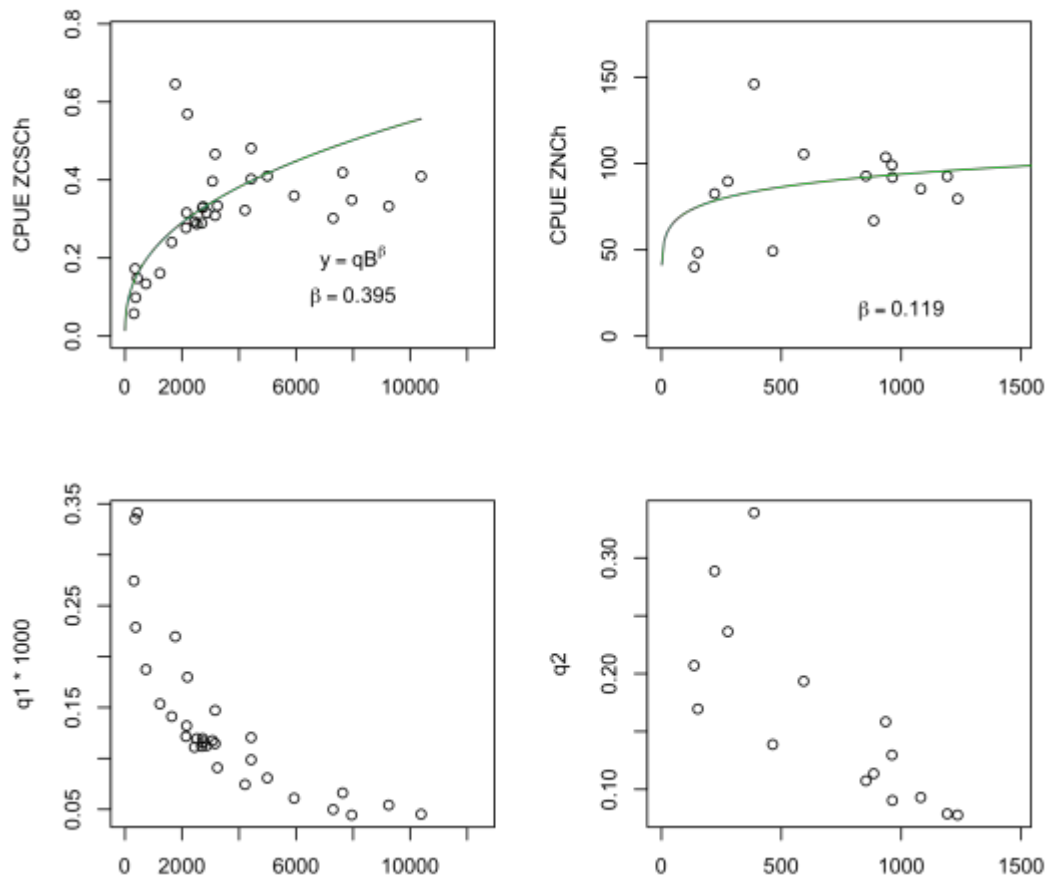
Figure 8. Catch per unit of effort by vulnerable biomass of *T. murphyi* stock in the central southern zone of Chile (upper left), northern zone of Chile (upper right), and between catchability coefficient and vulnerable biomass in central southern zone of Chile (lower left) and northern Chile (lower right).

3.5 State of the stock

In order to construct a phase diagram, fishing mortality of $F_{40\%}$ = 0.328 y^{-1} was considered as a proxy value associated to maximum sustainable yield (F_{MSY}). The diagram shows that fishing mortality is located over the reference line, implying that *T. murphyi* is overfished (Fig. 8). Spawning biomass lays over management objectives and only decreases under reference levels until the year 2007, reaching 40% of the spawning biomass related to the maximum sustainable yield.

In year 2013, changes in the potential reproductive ratio show the state of the *T. murphyi* stock is depleted, reaching close to 14% of its virginal biomass (Fig. 9), higher than the 5% shown in the year 2010.
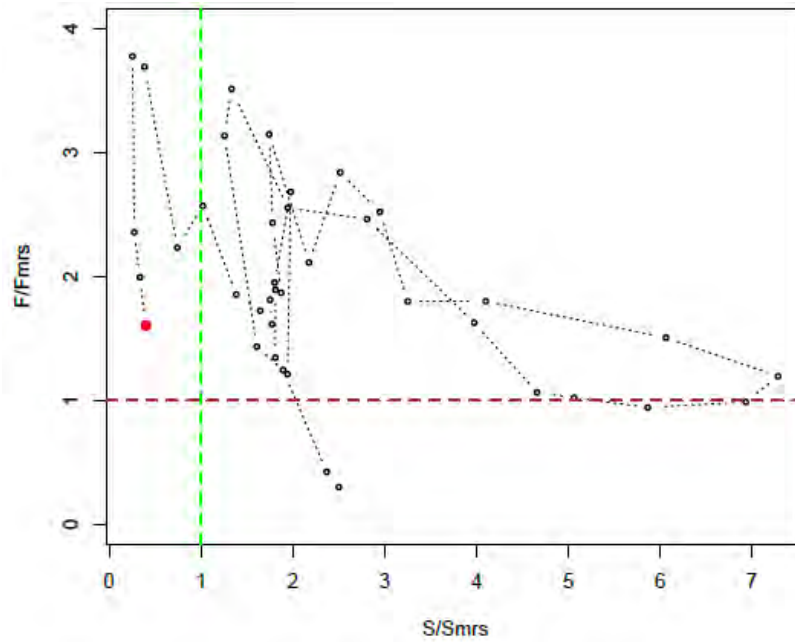

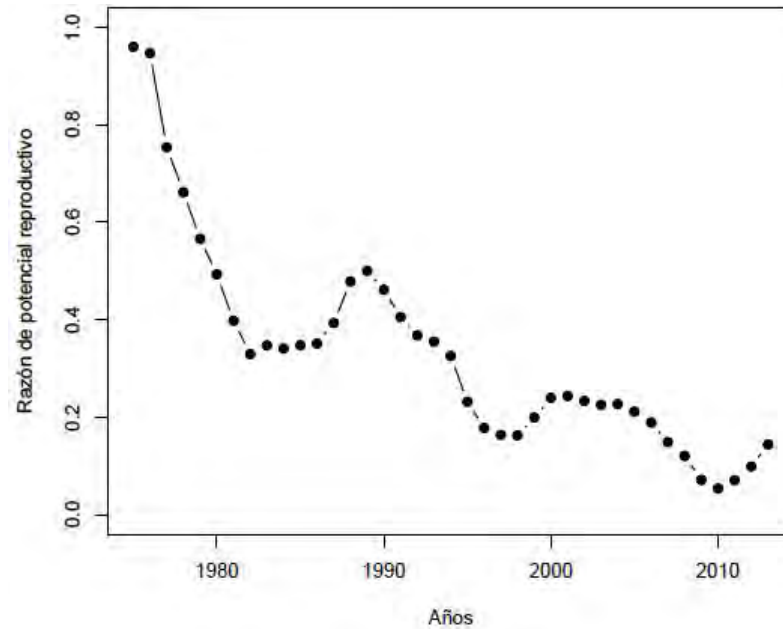Figure 9. Exploitation diagram of *T. murphyi*. Period 1975 to 2013.

Figure 10. Potential reproductive ratio of T. *murphyi*. Period: 1975 to 2013

4. Discussion

The present T. *murphyi* stock assessment differs partially from the results of the stock assessment presented by the SPRFMO (Canales et al. 2013), which is attributed to the assumptions implied in the structure of the model. A minimum structure of the stock in two large zones (to the north and south of Coquimbo 30°S) is shown in this report, including four zones which represent "coastal fisheries" (inside the respective EEZ) and for the two international water fisheries (outside de EEZ). Index of abundance data, which allow further disaggregation of the spatial distribution of T. *murphyi* in the South Eastern Pacific Ocean is limited, and thus constraining the viability of such approach.

In the present study, the acoustic biomass in Peruvian waters reported by Segura and Aliaga (2013) is used (see Table 2, second column, in the present report). The SPRFMO stock assessment uses a different time series of acoustic survey in Peru, with higher biomass in some years, which is notably higher for the years 2001 to 2002 (Fig. 11). It could lead to a change in the recruitment estimations, which is extremely high in the year 2000, and generates increased biomass estimations for the year 2000 and 2001 by the SPRFMO.
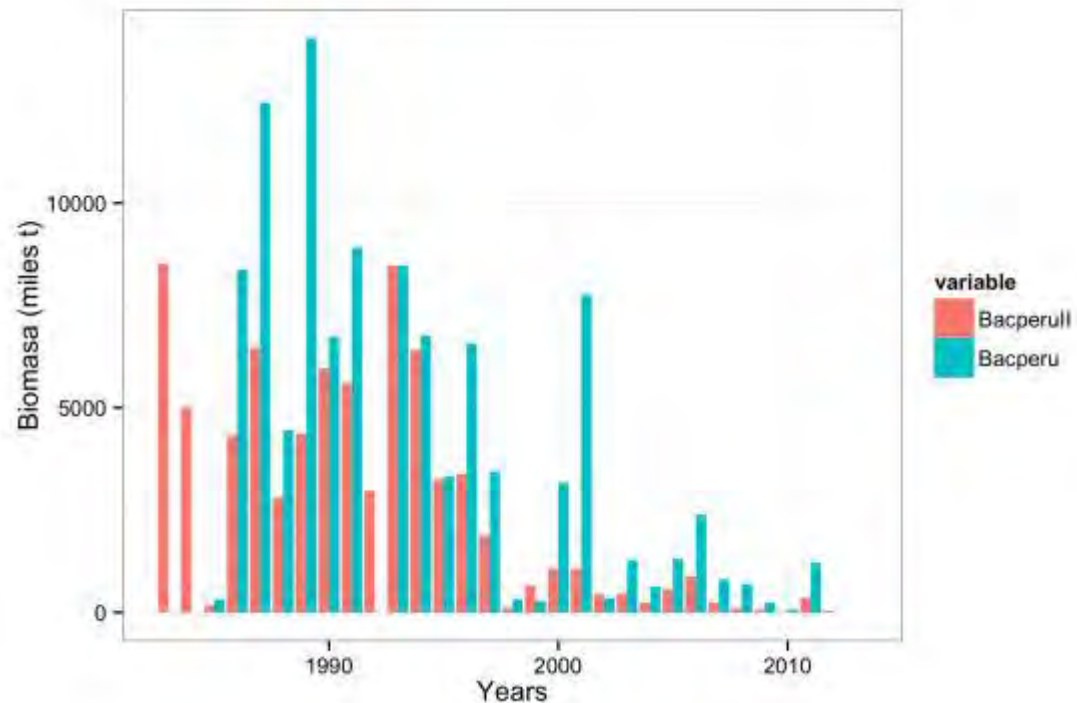
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Figure 11. Comparison between acoustic biomass estimations of *T. murphyi* in Peru (Segura and Aliaga 2013; in red) with biomass estimations used by the SPRFMO (Canales et al. 2013; in blue).

A fundamental aspect of pelagic fisheries is that the catchability coefficient varies inversely with the exploitable biomass. Even though this compensatory measure is well known, its impact is not always taken into account when assessing fisheries on pelagics which use catch per unit of effort series. In this case biomass decreases at a faster rate than abundance indexes, and consequently the stock biomass is over-estimated.

Age composition and acoustic survey associated with age composition are not considered in the present study. This piece of information could allow us to know if the catchability and selectivity associated with inter-annual changes could be better reflected on the population dynamic.

In this study, length at catch was used rather that age at catch to avoid likely errors in the assignation of ages. Biological parameters used for *T. murphyi* were obtained from literature (Gili et al. 1995), where $L\infty$ = 70.8 cm de fork length, K = 0.094 y^{-1} and t_0= -0.896 years, although it is not ideal since a sensibility analysis must have been performed between known biological parameters for *T. murphyi*.

The results of the present state of the *T. murphyi* stock are partially similar in both assessments (this report and that of the SPRFMO). Differences are noted in magnitude of

total biomass, spawning biomass, recruitments and fishing mortality. The last one is higher in the present study than what has been reported by the SPRFMO (Canales et al., 2013).

The depletion of the *T. murphyi* stock in year the 2013 was close to 14%, after reaching its minimum value at 5% in year 2010. High fishing mortalities indicate that the stock has been constantly overexploited and has been able to remain under this state due to moderate recruitments in year 2002, but strongly declining since 2003 until 2013. The stock of T. *murphyi* probably remains, in the near future, in the same phase of low productivity and low abundance. Thus, the recovery of the stock in the short and medium term is uncertain.

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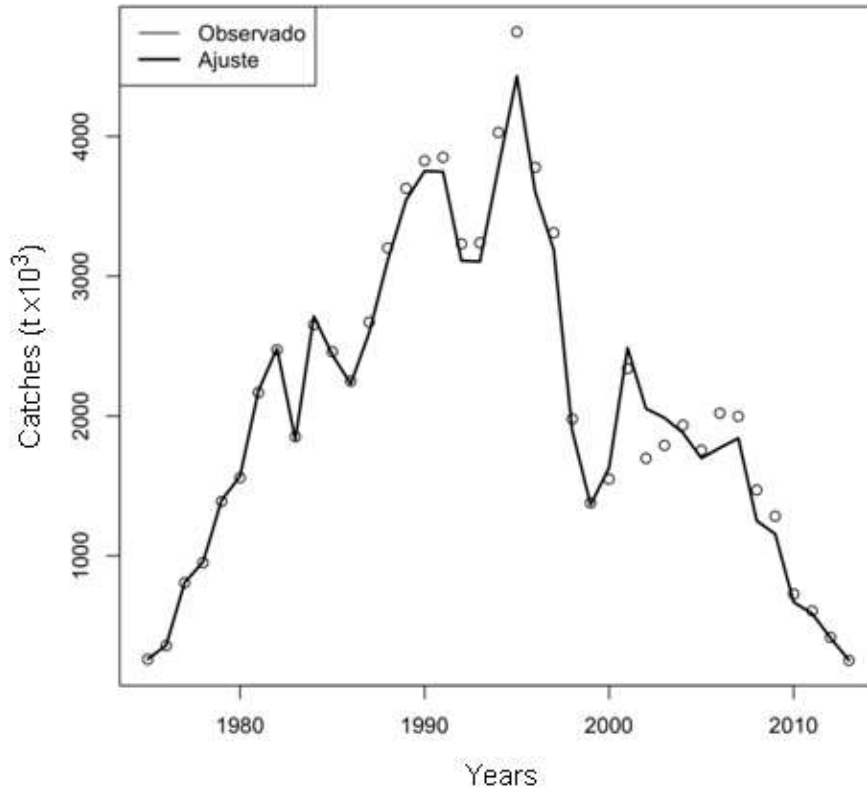
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ANNEX 1

Figure A1. Total observed catches vs. assessment model fit. Period: 1975-2013.
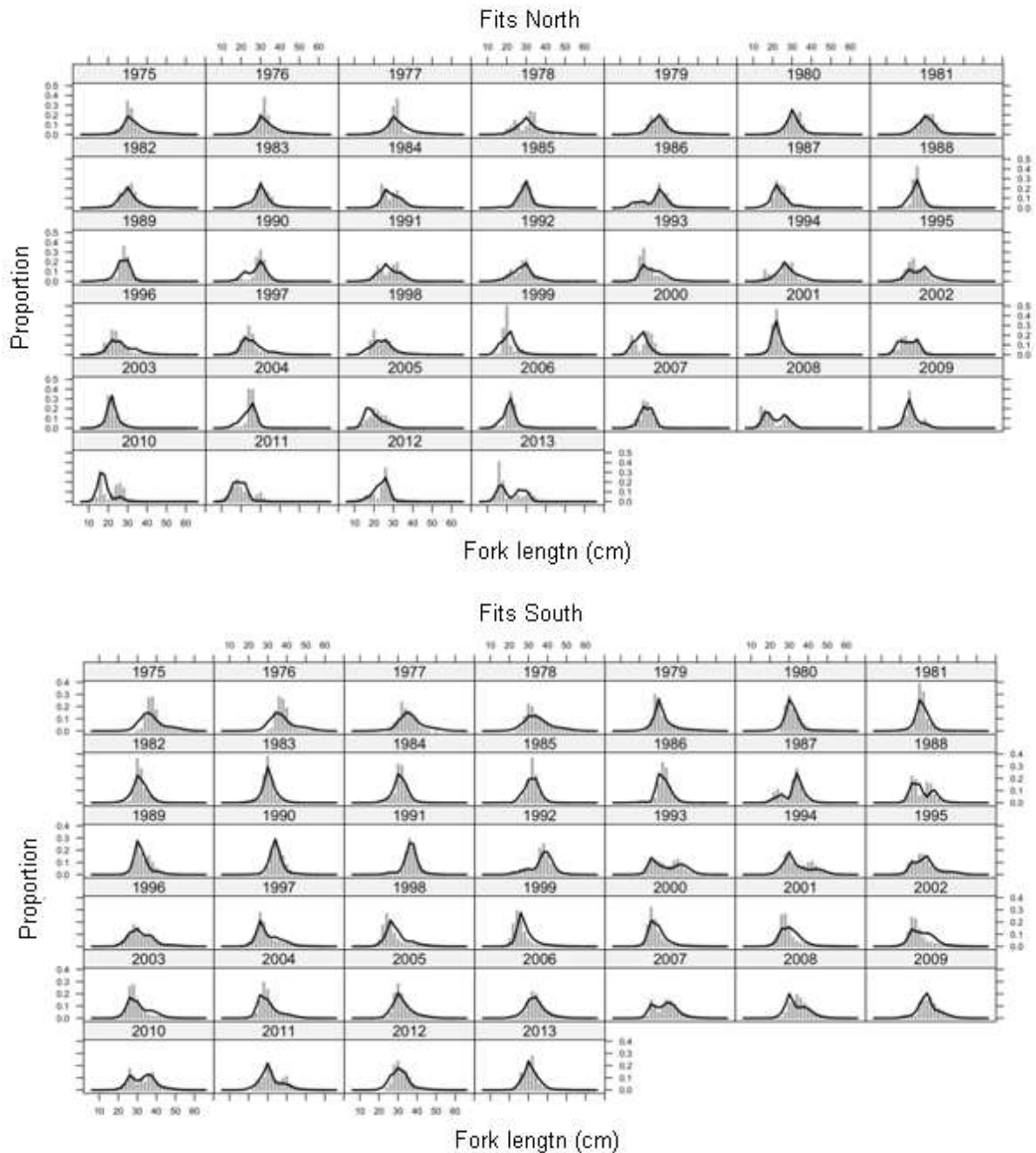
Figure A2. *T. murphyi* assessment model fit to age composition data in the northern zone (north Chile and Subdivision North) and southern zone (central-south Chile and Subdivision South). Period: 1975-2013.
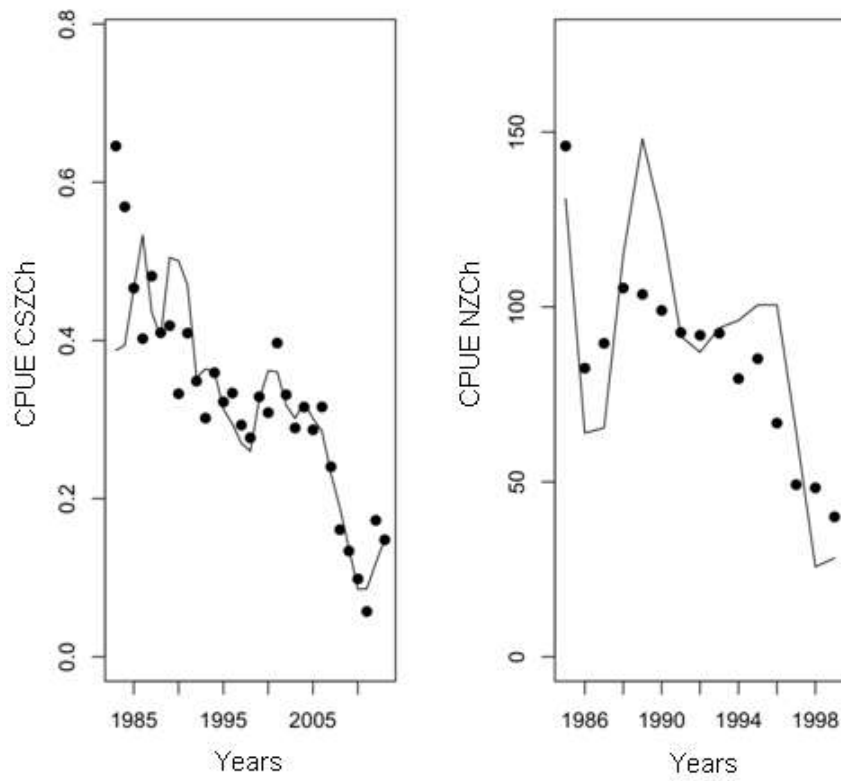
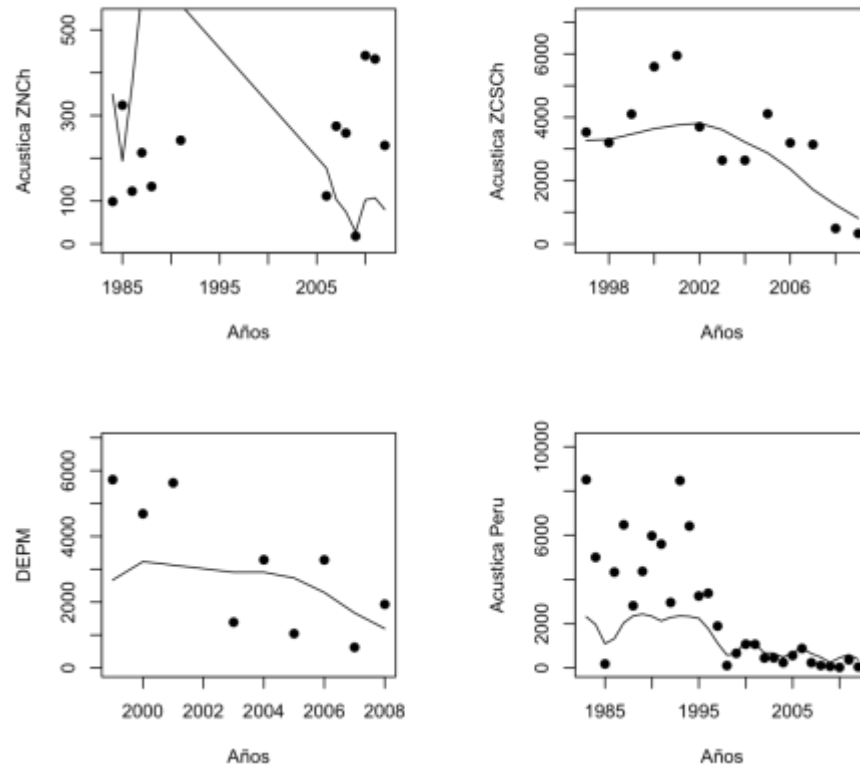Figure A3. Assessment model fit to CPUE data of the central southern zone (CZSCh) and northern Chile (NZCh).

Figure A4. Assessment model fit to indexes of abundance available for *T. murphyi*: northern zone acoustic survey (upper, left), acoustic survey for the central southern zone of Chile (upper, right), spawning biomass by DEPM method (down, left) and acoustic survey for Peru (down, right).
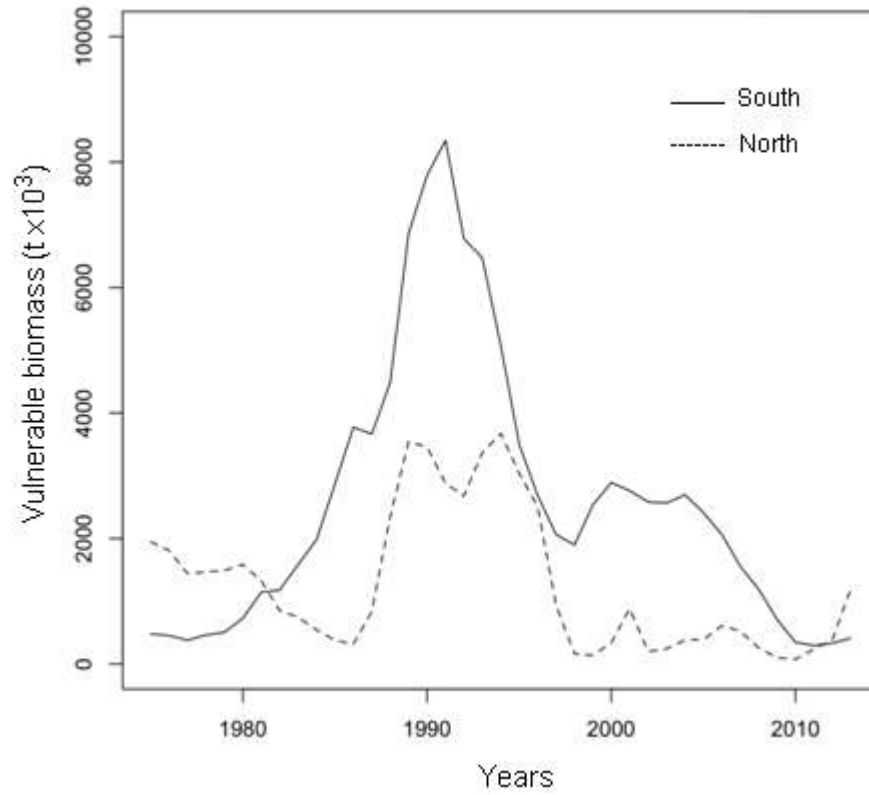
Figure A5. Changes in vulnerable biomass estimations for *T. murphyi* by geographic zone: North and South (see text for explanations). Period: 1975-2013.