Short Communication

Does life history connectivity explain distributions of Chilean jack mackerel *Trachurus murphyi* caught in international waters prior to decline of the southeastern Pacific fishery?

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**A B S T R A C T**

In severely depleted stocks, biological data taken prior to fishery decline are invaluable as a reference for recovery; and to understand the spatial population structure, especially when connectivity crosses management boundaries over the life history. Prior to a precipitous decline from 2010, Chilean jack mackerel (*Trachurus murphyi*) showed strong cyclic migrations hypothesized to encompass coastal areas regulated by national authorities along western South America and unregulated international waters offshore. In a preliminary analysis, we present data taken in international waters between 2000 and 2009 by a program sampling commercial catches from Chinese trawlers. Overall, catch length distributions occupied fork length classes from 240 mm to 600 mm, with a modal length class of 320 mm for females and 340 mm for males and the weight-length relationship was $BW = 0.00000652FL^{1.0708}$. Males showed increasing predominance with length. Nearly 80% of fish had prey items in their stomachs; only 1% had full stomachs, suggesting that few fish were feeding intensively. However, mean fork length declined from 327 mm to 259 mm between 2000 and 2003, and population juvenescence as a result of exploitation may help explain these data. Nevertheless, adult spatial distributions were also consistent with migrations between feeding and spawning grounds. Distinguishing the spatial structure of such life history connectivity, and how it interacts with fishing activity, is critical to refining the conservation measures necessary to rebuild large oceanic fisheries and restore marine ecosystems.

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1. Introduction

Recent international efforts to restore marine ecosystems and rebuild fisheries have concentrated on regulating exploitation rates through catch restrictions, gear modification and closed areas (e.g. Worm et al., 2009; Worm and Branch, 2012). Yet gauging the success of recovery efforts often depends on metrics taken prior to decline. Moreover, recovery is often related to the biology of the species, including life history and habitat (Hutchings and Reynolds, 2004). Identifying the spatially explicit structure of intact population life histories can be critical, in particular the areas that underpin the trajectories followed by successfully spawning fish (e.g. Sinclair, 1988; Ashford et al., 2012a,b). Reconstructing the spatial structure of these processes can be difficult after the collapse of a fishery. However, although invaluable, prior data are often unavailable.

For highly mobile species, the problem is compounded when life history trajectories straddle management regimes. In the southeastern Pacific Ocean, separate populations of Chilean jack mackerel (*Trachurus murphyi*) have been suggested for coastal and oceanic areas off western South America (e.g. Evseenko, 1987). In contrast, Serra (1991) hypothesized cyclic migrations that encompassed waters both in Exclusive Economic Zones (EEZs) regulated by national authorities and unregulated international waters. Thus, large concentrations of eggs and larvae found during November–December in surface waters north of the Subtropical Front are associated with an area of low wind intensity at the center of the South Pacific Gyre (Cubillos et al., 2008; Ashford et al., 2011). Young of the year move eastwards with the West Wind Drift, arriving on the Chilean shelf to recruit at ca. age 1–2. Adults migrate during summer after spawning, either onshore
to feed in productive coastal waters (Serra, 1991), or south of the Subtropical Front to feed on aggregations of copepods and euphausiids (Vinogradov et al., 1990), before returning to oceanic areas off central Chile to spawn.

The fishery for Chilean jack mackerel was until recently one of the largest worldwide (Suda et al., 1995; FAO, 2008). Within the Chilean EEZ, catches as large as ca. 4.2 million metric tons were taken during the mid-1990s by commercial purse-seiners. From the 1980s, large-scale mid-water trawlers from the former Soviet Union, Bulgaria, Cuba, South Korea, and Japan fished in international waters off the Chilean and Peruvian EEZ’s, and their total annual catch reached 2 million metric tons. The Chinese fishery began more recently in 2000, and the catch reached the peak value (160 thousands metric tons) in 2006 (Anon., 2012). Yet, despite its commercial importance, information about the biology of the species has been lacking (Suda et al., 1995). Early studies examined stock structure (Kalchugin, 1992), migration (Stepanenko, 1980), age and growth (Cubillos et al., 1995; Kaiser, 1973b; Kochkin, 1994), diet (Konchina, 1978, 1993; Konchina et al., 1996), and reproduction (Kaiser, 1973a; George, 1995; Kuroiwa, 1997). However, this early progress was not maintained and, in the years following, only a single report reviewing the population biology (Taylor, 2002) was published.

A call by the South Pacific Regional Fisheries Management Organization (Anon., 2008) highlighted the urgent need for more research, prompting recent activity examining population structure (e.g. Cardenas et al., 2009; Ashford et al., 2011). Yet the response so far has focused on national EEZs, and published data from international waters have been harder to obtain. Additionally, intense fishing can reduce abundance and spawning potential, modifying size structure and sex ratio among other measures (Garcia et al., 2003). In the Chilean jack mackerel fishery, rapid development may also have impacted stock structure and distribution (Canales and Serra, 2008). Stocks have declined precipitously since 2010, suggesting substantial further perturbation.

In the present study, therefore, we present a first analysis of data taken during a program sampling commercial catches from Chinese large-scale jack mackerel trawlers in international waters undertaken from 2000 to 2003, during the first years of the Chinese fishery. The objectives were (1) to provide historical information on length frequencies, length-weight relationships, sex ratios and diet as references for fishery recovery, and (2) to help understand the spatial biology of Chilean jack mackerel in international waters off Chile.

2. Materials and methods

A total of 7842 Chilean jack mackerel were sampled by scientific observers on board Chinese trawlers operating in international waters off central Chile (Fig. 1). Samples were taken from hauls each fishing day during June and July 2000, between July and October 2001, during August and September 2002, and January and February 2003. Observers measured fork length (FL), sex, body weight (BW) and dressed weight (DW, gutted weight) for each fish sampled, and recorded capture location and date.

Examining FL distributions, we addressed issues raised by Wolff (1989) and Erzini (1990) in the selection of FL interval (FLI) by using Snedecor’s method and Sturge’s method to calculate the fork length class intervals (Ye, 1964):

\[ FLI(\text{Snedecor}) = \frac{\text{Range}}{(\text{Range}/\text{S.D.}) \times 4} \]  

(1)

and

\[ FLI(\text{Sturges}) = \frac{\text{Range}}{(1 + 3.322 \log N)} \]  

(2)

where, Range = the range of FL values sampled, S.D. = standard deviation, N = sample size, FLI = fork length interval. Because Snedecor’s method generates a lower FLI than Sturges’ method (Ye, 1964), the values were averaged to obtain FLI = 20 mm. FL distributions were tested for differences between sexes using a two-sample Kolmogorov–Smirnov test (K-S test).

Within each year, a sub-sample of fish was taken to assess the relationship between dressed weight and body weight using linear regression. The length-weight relationship was quantified as well, using the exponential regression equation

\[ W = ah^b e^c, \quad e \sim N(0, \sigma^2), \]  

(3)

where W is the body weight (gram), h the fork length (FL) (mm), b the growth exponent or length-weight factor, and a is a constant. The parameters a and b, the coefficient of determination (r²) and the standard error of b (SEb) were estimated over the entire period by least squares regression using the log-transformed weights and sizes. Regression analyses were performed separately for sub-samples of males and females taken each year, and t-tests used to test for differences between sexes. Additionally, Analysis of Covariance (ANCOVA) was used to examine differences in the length-weight relationship between sexes, and the hypothesis of isometric growth (Ricker, 1975) was tested by t-test (α = 0.05) (Sokal and Rohlf, 1987).

Sex ratio was estimated as the proportion of males by size class. For each FL class, chi-square tests were used to test for any significant difference to the theoretical ratio of 1:1. Stomach fullness was determined from a sub-sample of 1101 fish using a 0–4 point scale (Tanabe, 2001): 4 for full stomachs, 3 for 3/4 full, 2 for 1/2 full, 1 for traces of food, and 0 for empty stomachs. A two-factor contingency table was constructed and analyzed for differences in stomach fullness between FL classes (α = 0.05).

3. Results

Fork lengths ranged between 116 and 618 mm and their distributions showed significant differences between female and male fish (two-sample Kolmogorov–Smirnov test; Z = 1.656, P = 0.008). Mean FL for females was 348.2 (SD ± 70.7) mm and for males it was

![Fig. 1. Sampling area.](image-url)
Table 1
Fork length of Chilean jack mackerel in the high seas off Chile during June 2000 to February 2003.

<table>
<thead>
<tr>
<th>Period</th>
<th>Area</th>
<th>Mean FL (mm)</th>
<th>SE (mm)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>June–July 2000</td>
<td>38°01′S–40°36′S, 78°18′E–81°32′E</td>
<td>326.7</td>
<td>1.4</td>
<td>2638</td>
</tr>
<tr>
<td>July–October 2001</td>
<td>32°28′S–38°59′S, 79°11′E–85°30′E</td>
<td>301.6</td>
<td>0.7</td>
<td>3625</td>
</tr>
<tr>
<td>August–September 2002</td>
<td>30°46′S–36°36′S, 80°15′E–86°36′E</td>
<td>272.6</td>
<td>1.1</td>
<td>1287</td>
</tr>
<tr>
<td>January–February 2003</td>
<td>34°48′S–38°49′S, 81°15′E–86°37′E</td>
<td>259.0</td>
<td>1.1</td>
<td>292</td>
</tr>
</tbody>
</table>

$FL$, fork length; $SE$, standard error; $n$, sample size.

Fig. 2: The fork length distribution of Chilean jack mackerel in the high seas off Chile (by sex and pooled data).

365.6 (SD ± 81.1) mm (Fig. 2). FL also differed significantly between years (Kruskal–Wallis test $\chi^2 = 1029.512$, $P < 0.0001$) when fish were pooled by year (Table 1, Fig. 3).

The relationship between dressed weight and body weight was highly significant ($P < 0.0001$) with $r^2 = 0.998$ (Fig. 4). For males, the length-weight relationship was $BW = 0.00000781 FL^{1.0383}$ ($r^2 = 0.987$, $SE_b = 0.0145$); for females, it was $BW = 0.00000716 FL^{1.0579}$ ($r^2 = 0.985$, $SE_b = 0.0164$) (Fig. 5). The slope was significantly different between sexes ($t$-test: $t = 17.7521$, $P < 0.0001$), and significantly higher than $b = 3$ for both males ($t$-test: $t = 64.3861$, $P < 0.0001$) and females ($t$-test: $t = 81.0001$, $P < 0.0001$). However, the ANCOVA indicated no significant difference in weight between sexes when differences in length distributions were taken into account ($F = 0.825$, $P = 0.364$). As a result, the length-weight data were pooled for all fish from both sexes and expressed as the relationship $BW = 0.00000652 FL^{1.0708}$ ($r^2 = 0.9869$, $SE_b = 0.0044$). The slope was significantly higher than $b = 3$ ($t$-test: $t = 7.988$, $P < 0.0001$) indicating positive allometric growth.

More males were present than females in 13 of the 18 fork length classes with a trend toward greater predominance with length: in all size classes of 420 mm and larger, the proportion of males was larger than females (Table 2). Of the total number of fish subsampled, 228 (20.7%) had empty stomachs; very few (ca. 1%) had stomachs that were full; and ca. 60% were classified as Stage 1 or Stage 2 (Fig. 6). Stomach fullness differed significantly among fork length classes ($\chi^2 = 96.929$, $P < 0.0001$).

4. Discussion

Data from commercial catches taken by Chinese trawlers indicated that activity was concentrated in international waters near 40°S, moving northwards along the boundary of the Chilean EEZ where it encompasses the Juan Fernandez Islands. We found a broad length distribution overall in which sampled fish occupied FL classes from 240 mm to 600 mm, with modes of 320 mm for females and 340 mm for males. However, there was a consistent decline in mean FL from 2000 to 2003 that corresponded with both the disappearance of larger fish and a shift downwards in the mode for each year. Body weight was closely related to length, and the growth

Fig. 3: The fork length distribution of Chilean jack mackerel in the high seas off Chile.

Fig. 4: The relationship between body weight and dressed weight of Chilean jack mackerel in the high seas off Chile.
The length-weight relationship of Chilean jack mackerel in the high seas off Chile.

<table>
<thead>
<tr>
<th>FL (mm)</th>
<th>Sex</th>
<th>Percentage of females</th>
<th>Chi-Square</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>220–240</td>
<td>9</td>
<td>12%</td>
<td>1.923</td>
<td>0.166</td>
</tr>
<tr>
<td>241–260</td>
<td>36</td>
<td>25%</td>
<td>1.984</td>
<td>0.159</td>
</tr>
<tr>
<td>261–280</td>
<td>62</td>
<td>50%</td>
<td>0.000</td>
<td>1.000</td>
</tr>
<tr>
<td>281–300</td>
<td>37</td>
<td>44%</td>
<td>0.605</td>
<td>0.437</td>
</tr>
<tr>
<td>301–320</td>
<td>67</td>
<td>58%</td>
<td>0.648</td>
<td>0.421</td>
</tr>
<tr>
<td>321–340</td>
<td>59</td>
<td>76%</td>
<td>2.418</td>
<td>0.120</td>
</tr>
<tr>
<td>341–360</td>
<td>49</td>
<td>49%</td>
<td>0.000</td>
<td>1.000</td>
</tr>
<tr>
<td>361–380</td>
<td>46</td>
<td>53%</td>
<td>0.495</td>
<td>0.482</td>
</tr>
<tr>
<td>381–400</td>
<td>37</td>
<td>31%</td>
<td>0.373</td>
<td>0.541</td>
</tr>
<tr>
<td>401–420</td>
<td>42</td>
<td>37%</td>
<td>0.316</td>
<td>0.574</td>
</tr>
<tr>
<td>421–440</td>
<td>25</td>
<td>33%</td>
<td>1.103</td>
<td>0.294</td>
</tr>
<tr>
<td>441–460</td>
<td>25</td>
<td>28%</td>
<td>0.170</td>
<td>0.680</td>
</tr>
<tr>
<td>461–480</td>
<td>9</td>
<td>18%</td>
<td>3.000</td>
<td>0.083</td>
</tr>
<tr>
<td>481–500</td>
<td>10</td>
<td>20%</td>
<td>3.333</td>
<td>0.068</td>
</tr>
<tr>
<td>501–520</td>
<td>3</td>
<td>13%</td>
<td>6.250</td>
<td>0.012</td>
</tr>
<tr>
<td>521–540</td>
<td>6</td>
<td>6%</td>
<td>0.000</td>
<td>1.000</td>
</tr>
<tr>
<td>541–560</td>
<td>2</td>
<td>6%</td>
<td>2.000</td>
<td>0.157</td>
</tr>
<tr>
<td>561–580</td>
<td>2</td>
<td>6%</td>
<td>2.000</td>
<td>0.157</td>
</tr>
<tr>
<td>581–600</td>
<td>1</td>
<td>9%</td>
<td>6.400</td>
<td>0.011</td>
</tr>
<tr>
<td>601–620</td>
<td>0</td>
<td>1%</td>
<td>0.000</td>
<td></td>
</tr>
</tbody>
</table>

* P < 0.05.
FL, fork length class.
national trawler fleets, but the differences may also be explained by spatio-temporal effects generated by the feeding and spawning movement described by Serra (1991). Similarly, the predominance of males in the sex ratios we found was in accordance with Taylor (2002), but other studies have shown a ratio of about 1:1 for male to female (Andrianov, 1985; George, 1995) and the differences may reflect spatial distributions during seasonal movement.

These data provide historical information on important biological variables as a reference for future fishery recovery, and highlight critical gaps in our understanding of the spatial biology of Chilean jack mackerel in the Southeastern Pacific Ocean. More research is needed to test between competing population structure hypotheses and resolve potential confounding between long-term stock trends and distributions at different spatial, inter-annual and seasonal scales. Analyses of diet composition as well as stomach fullness may further clarify feeding differences between areas. Our results indicate that critical life history trajectories could well have played an important role in supporting fishing activity prior to fishery decline. Understanding their spatial structure, and how they interact with fishing activity, can assist better targeting of the conservation measures necessary to rebuild fisheries and restore marine ecosystems.

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