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Insights into the reproductive biology and fisheries of two commercially exploited species, shortfin mako (*Isurus oxyrinchus*) and blue shark (*Prionace glauca*), in the south-east Pacific Ocean

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ABSTRACT

In 2005 and 2010, 1241 *Isurus oxyrinchus* and 1153 *Prionace glauca* were collected from 178 longline sets in a ship-board observer programme in coastal waters off Caldera, Chile (27°S). Catch composition was significantly biased towards *I. oxyrinchus* in 2005, but both species were caught in the same proportion in 2010. The sex ratio for *I. oxyrinchus* and for *P. glauca* did not differ significantly from unity within or between years. Sharks matured (L_{50}) at a total length of 190.3 cm for male and 199.2 cm for female for *P. glauca*, and 180.2 cm for male *I. oxyrinchus*. Size-at-maturity for female *I. oxyrinchus* was not determined due to the near absence of mature specimens examined. Generalised additive models (GAMs) were used to examine catch per unit effort (CPUE) in relation to sea surface temperature, wind speed, time of day, hook depth and soak time. The GAMs revealed a significant effect of depth on *P. glauca* CPUE, and depth and wind speed for *I. oxyrinchus* CPUE. The predominance of small, immature sharks caught in the coastal, artisanal fishery indicates that both species may use the area as a pupping, and possibly a nursery zone during spring and summer. National data on catch composition and annual landings provide evidence of an increasing trend to land *P. glauca*, possibly to satisfy the international shark fin trade. Conservation measures, such as the introduction of a minimum capture size for sharks to protect the recruitment into the population, conservative fishing quotas and delimitation of fishing areas are necessary to ensure the sustainability of both species in the region.

1. Introduction

There is global concern about the impact of depletion and possible loss of apex predator fishes in marine ecosystems (Dulvy et al., 2003; Myers et al., 2007; Ferretti et al., 2010). This concern is of particular relevance in relation to sharks as their biological characteristics make them particularly vulnerable to over-exploitation (Stevens et al., 2000; Cailliet et al., 2005). Downward trends in pelagic shark catches have been documented in many oceanic fisheries, for example, in the north-east Atlantic (Pawson and Vince, 1999; Baum et al., 2003; Dulvy et al., 2008), off southern Africa (Petersen et al., 2009), Japan (Nakano, 1999) and in the Mediterranean Sea (Ferretti et al., 2008).

The shortfin mako shark, *Isurus oxyrinchus* Rafinesque, 1810, is an important component of pelagic shark community, ranging through most tropical and temperate oceans of the world (Compagno et al., 2005). In the south-east Pacific, *I. oxyrinchus* is caught in commercial oceanic longline and gill-net fisheries that target swordfish (*Xiphias gladius* Linnaeus, 1758), as well as being caught in the coastal, artisanal longline fishery that operates in northern Chile and southern Peru (Acuña et al., 2001; Gilman et al., 2007). The latter is the only Chilean artisanal fishery that target sharks. In addition to *I. oxyrinchus*, this fishery has a bycatch of blue shark, *Prionace glauca* (Linnaeus, 1758) and to a lesser extent, porbeagle, *Lamna nasus* (Bonnaterre, 1788) (Lamilla et al., 2010).

In Chilean waters (and outside of the Exclusive Economic Zone) the directed shark fishery, and the associated shark bycatch, has grown substantially in recent years due primarily to a declining abundance of valuable teleost species and management restrictions placed on these teleost fisheries (Cerna and Licandeo, 2009). In contrast to the oceanic fishery, the coastal artisanal fishery has discrete operational boundaries; these are mainly related to the limited autonomy of vessels that restricts the length of trips and hence, fishing areas. This 'subsistence fishery', that started in 1979, is focused on the coastal zone from southern Peru (Gilman et al., 2007) to 35°S in Chile where boats of 9–18 m length explore coastal temperate water-masses of about 18–21 °C which are associated with a relatively large abundance of sharks (Acuña et al., 2001).

While there are legal minimum sizes for pelagic sharks (which includes *I. oxyrinchus* and *P. glauca*) caught in Peruvian waters, the

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only regulation of shark fishing in Chilean waters is in the types of gear allowed to be used (Lamilla et al., 2010), despite the fact that Chile has a National Plan of Action to promote the conservation and management of sharks. While *I. oxyrinchus* is retained by both oceanic and coastal fisheries, *P. glauca* is generally discarded after finning which has resulted in under reporting of the latter species in official landings records (Lamilla et al., 2008). Commercial shark landings in the decade 1999–2009 increased fourfold for *I. oxyrinchus*, from 237 to 950 tonnes and almost sixty-fold for *P. glauca*, from 7 to 408 tonnes (SERNAP, 2009).

I. oxyrinchus reproduces by oophagic viviparity (Lamniform oophagy), with an average of 12 pups per litter and a 15- to 18-month gestation period (Gilmore, 1990; Snelson et al., 2008). There is a large sexual difference in the size and age at maturity, with males maturing at about 195 cm total length (L_T) at 6 years of age, and females at 265–280 cm L_T at 16 years of age (Stevens, 2008; Semba et al., 2009). While segregation among the developmental stages (Nakano and Nagasawa, 1996) and geographical sexual segregation (Mucientes et al., 2009) have been reported, little is known about stock structure or genetic diversity (Heist et al., 1996) due to the species' large, diffuse, and highly dispersive populations (Schrey and Heist, 2003).

P. glauca reproduces by placental viviparity, gives birth to an average of 30 pups after a 9- to 12-month gestation period (Henderson et al., 2001), and females may breed every year (Stevens, 1984; Hazin et al., 1994). Birth usually occurs in spring and summer, with pupping and nursery areas seemingly located in intermediate-latitude oceanic convergences with high prey availability (Nakano and Stevens, 2008). Growth is relatively rapid, with males maturing at 4–6 years and females at 5–7 years of age (Lessa et al., 2004; Manning and Francis, 2005). Distinct sex and size segregation is evident, with size generally decreasing with increasing latitude (Henderson et al., 2001). Blue sharks are a major bycatch of longline and gill-net oceanic fisheries, but because of poor reporting the magnitude of the catch and mortality is not reflected by official statistics (Nakano and Stevens, 2008). Additionally, recent population assessments indicate a moderate to large declining trend in both abundance and size of blue sharks in north-west Atlantic (Baum et al., 2003), central Pacific (Ward and Myers, 2005) and the Mediterranean (Ferretti et al., 2008).

To properly manage and conserve pelagic shark species it is necessary to have adequate information on their life-histories in order to understand the ecology and susceptibility to over-exploitation (FAO, 2003; Garcia and Cochrane, 2005). Various analyses suggest that both sharks *I. oxyrinchus* and *P. glauca* may have undergone significant declines in abundance over parts of its distribution (Nakano, 1999; Pawson and Vince, 1999; Baum et al., 2003; Ward and Myers, 2005; Dulvy et al., 2008; Ferretti et al., 2008; Cailliet et al., 2009). Due to estimated and inferred declines, probable increases in fishing pressure, and considering the life history characteristics of *I. oxyrinchus*, the Indo-west Pacific and Atlantic subpopulations have recently been classified as Vulnerable on the IUCN Red List of threatened species; the north eastern Pacific subpopulation as Near Threatened; while the south Pacific population remains without conservation assessment (Cailliet et al., 2009). *P. glauca* is listed as Near Threatened globally (Stevens, 2000).

In the south-east Pacific, age and growth (Cerna and Licandeo, 2009) and habitat use (Abascal et al., 2011) of *I. oxyrinchus*, and the reproductive cycle of *I. oxyrinchus* and *P. glauca* (Acuña et al., 2001) have been examined, although information of the species' reproductive biology in the region is incomplete. The aims of the present study are to estimate life-history traits, including size-at-maturity, sex ratios and catch composition, as well as to describe the species' environmental preferences in Chilean waters. Annual landings and shark fin exports are discussed in relation to fishing practices and factors involved in the commercial fishery of pelagic sharks in Chile.

2. Methods

Specimens of *I. oxyrinchus* and *P. glauca* were collected during on-board observer surveys in the artisanal longline fishery targeting *I. oxyrinchus* based in Caldera, Chile (27°04′S, 70°51′W) in the Southern Hemisphere summer fishing season (January and February) in two different years (2005 and 2010). Sharks were collected from 78 fishing trips made by 18 vessels of 12–17 m length using 5.5 km monofilament longline gear with wire traces and M/K No. 2 hooks. Sets comprised 200–350 hooks, each suspended from surface buoy spaced every 180–200 m. Hooks were baited using fresh and/or dry-salted chub mackerel (*Scomber japonicus* Houttuyn, 1782) or Chilean jack mackerel (*Trachurus murphyi* Nichols, 1920). Maximum soak time was 240 min, with sharks hooked during the longline deployment removed, the hook rebaited, and the capture time recorded.

2.1. Biological data

Data recorded at the time of collection included sex, maturity and total length (L_T). Measurements were made to the nearest centimetre (cm) in a straight line with the shark lying on its ventral surface (Francis and Duffy, 2005). Left clasper post-cloacal length (L_C) was also recorded.

Three reproductive-stage classifications were determined for each sex as juvenile, adolescent and adult. Changes in the reproductive organs were used to further assess the onset of maturity (Mollet et al., 2000). Males were considered to be adult when the claspers were elongated and the terminal cartilage elements were calcified. Adolescent individuals were those whose claspers extended beyond the posterior edge of the pelvic fins, but lacked calcification of the terminal cartilage elements. Juveniles had short, flexible claspers that did not extend beyond the posterior edge of the pelvic fins. Internally, coiling of the epididymides and testes development were also indicators of maturation (Stevens, 1983). Females were determined to be mature if they demonstrated one or more of the following characters: presence of pups *in utero*; large vitellogenic ova; and an oviducal gland distinctly differentiated from the uterus. Adolescent individuals had smaller ovaries, with some differentiation and no mature ova; undeveloped oviducal gland and uteri strap-like in appearance. Juveniles lacked any differentiation of the ovaries, and the oviducal gland was not differentiated from the uterus (Mollet et al., 2000).

Chi-square goodness-of-fit (χ^2) (Sokal and Rohlf, 1987) was used to test for significant sex bias between males and females proportion of each species within each year and between the 2 years sampled. Binomial maturity data (immature 0, mature 1) were determined by sex using 10 cm size class intervals. Size at 50% maturity was calculated by fitting the following logistic curve (by minimisation of the least squares), to the relationship between the fraction of mature males or females and L_T,

$$\text{as a function of } L_T, \quad Y = [1 + e^{-(a+bX)}]^{-1}$$

where Y is the fraction of mature individuals in length class X, and a and b are the model coefficients. The ratio a:b represents the size at which 50% of the sharks were mature (Mollet et al., 2000). In addition, the relationship between L_T and L_C were used to further assess the onset of first maturity (Restrepo and Watson, 1991). Comparisons of median L_T for males and females for each species were performed using the Mann–Whitney U test with significance accepted at $P < 0.05$.