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Examining size-sex segregation among blue sharks (*Prionace glauca*) from the Eastern Pacific Ocean using drift gillnet fishery and satellite tagging data[1]

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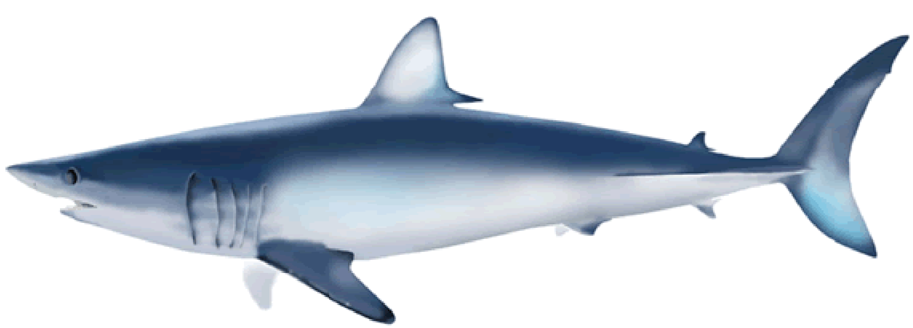

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Abstract

Biomass dynamic (BD) models assume that fishery captures are taken from a temporally stationary distribution of age and sex classes. Nakano (1994) described a blue shark population in the North Pacific Ocean that showed significant size and sex structure that may violate the assumptions of a BD model. Fishery-dependent size composition for the U.S West Coast drift gillnet fleet and electronic tag data were used to validate the spatial model of Nakano (1994) which does not extend to coastal waters. Results support the conclusions of significant size-sex structure in the North Pacific Ocean and thus it is recommended that the ISC Shark Working Group (SHARKWG) consider this when assessing blue shark stock status.

Introduction

At the May, 2012 meeting of the International Scientific Committee Shark Working Group (SHARKWG) it was decided to assess the status of blue shark (BS) in the North Pacific Ocean (NPO) using a biomass dynamic (BD) model. Advantages of the BD models are the relatively modest data requirements of total catch and an associated index of relative abundance. Stock dynamics are simplified to temporal estimates of an aggregated fishable population biomass or numbers. The model processes governing population production (growth, natural mortality and recruitment) are condensed into a single production process governed by the intrinsic growth rate (r). Population scale (often expressed as carrying capacity K) and r can be derived from an understanding of how catch created the population trend as described by the index of abundance.

Simplification of complex population dynamics is possible if strong model assumptions can be made. In the case of BD models, the primary assumption is that each unit of biomass removed through time has the same production equivalency. Another way of saying this is that a unit of removal in the first year has the same effect on the production function as a unit of removal in the last year (Crone & Sampson 1998, Pennington et al. 2002). Violations of this important assumption can be both biological and anthropogenic. Anthropogenic violations can be caused by changes in the fishery practices which affects the aggregate age or sex distribution removed (aggregate selection pattern). Biological violations can result from high recruitment variability, where the age distribution in the population varies widely as strong year-classes dominate the population and then disappear. Both causes can result in total removals having varied production impact (different age-sex distribution) that is not accounted for in simplified dynamic models. Due to modest fecundity of elasmobranchs, the anthropogenic violation is more likely to be an issue than the biological.

Violations of BD model assumptions are a special concern when the population shows spatial structure and/or the fishery has shown temporal changes in its distribution. Therefore, the assumption of production equivalency of the removals needs to be evaluated. One method to evaluate this assumption is through simulation of a hypothetical population which could be used to investigate the potential for assessment bias if spatial population structure is ignored. This hypothetical population would need to contain characteristics of the spatial characteristics of both the NPO BS stock and the fisheries which capture it.

Size-sex segregation is a phenomenon commonly exhibited by BS in both the Atlantic and Pacific Oceans (Nakano 1994; Nakano and Seki 2003; Litvinov 2006). The size-sex segregation may include a depth component as well (Hazin et al. 1994). Based on Hawaii longline fishery data, both sizes (therefore presumably ages) and sexes show strong and differential patterns in distribution (Walsh and Teo 2012). A model of distribution and movement was proposed by Nakano (1994), where juveniles are found primarily in the northern NPO above 30^{o}N latitude. Above 35-40^{o}N latitude, juvenile females predominate, and are the only BS found above 45^{o}N. Mating takes place between 20-30^{o}N latitude. Adults of both sexes inhabit the entire NPO from 0-45^{o}N (Figure 1, hereafter referred to as N-S mode). One limitation of the Nakano model is it does not include the California Current were BS are taken in the DGN fishery.

The spatial population structure described by Nakano (1994) may provide a theoretical framework for developing a sex and age structured model to test the efficacy of BD modeling of BS in the NPO. The objectives of this work are to evaluate, using fishery-dependent data from the large mesh drift gillnet fishery (DGN) operating in U.S. EEZ waters, the sex-length spatial distribution model of Nakano (1994) and how this may or may not be reflected in coastal regions. In addition, we use electronic tagging data to enhance our understanding of eastern Pacific Ocean (EPO) movement with respect to the Nakano model.

Materials and Methods

U.S. DGN fishery data were collected by observers onboard fishing vessels from 1990-2010. The fleet historically operated along the entire US West Coast within the EEZ, however regulations imposed over the course of the fishery to reduce bycatch have dramatically reduced the temporal and spatial scope of the fishery. This dataset includes information on latitude, longitude, sex, and fork length for all observed BS caught within each set.

Satellite tagging data are also considered as an independent source of information about BS spatio-temporal distribution by sex and size. Satellite-linked radio telemeters (SLRT) were attached to the dorsal fin of sharks brought aboard vessels during research cruises from 2002-2012. SLRT locations were acquired from Argos, which provides an index of location quality with each location estimate. Most SLRT datasets included position outliers, and these outliers were filtered out using the R package ‘argosfilter’. Only SLRT tracks of at least 30 days were used to reduce the effect of tagging-site bias.

A size range at 50% maturity for male and female BS was agreed upon by the ISC SHARKWG, and the midpoint of their range was used to assign maturity status to DGN caught and satellite tagged sharks. Female BS were considered sexually immature if their fork length was less than 182.5 cm and sexually mature if their fork length (FL) was greater than or equal to 182.5 cm. Males were considered sexually immature if their fork length was less than 177.5 cm and classified as sexually mature if their FL was greater than or equal to 177.5 cm.

The geographic range of the study is the U.S. West Coast EEZ bounded to the North by Canada and to the South by Mexico. That range was divided into three latitudinal bands (Figure 2); band 1 = >40°N, 2 = 34.4°N - 40.0°N; 3 = <34.4°N. The breakpoints represent locations along the US West Coast where the California Current is deflected from a continuous along shore path (40.0°N is near Cape Mendocino, and 34.4°N is near Pt. Conception). Changes in the distributions of fishes are known to coincide with oceanographic changes around these locations (Burton 1998; Sivasundar and Palumbi 2010).

The three latitudinal bands we used to classify the fishery and tagging data also roughly coincide with the schematic of different BS distributions by sex and maturity proposed by Nakano (1994). Nakano (1994) proposed a schematic of BS population structure by sex and maturity status in the North Pacific Ocean (Figure 1, referred to as N-S model hereafter). The schematic segregates sub-adults, and includes parturition and nursery areas, in the northern extent of their range, with immature females occurring furthest north and immature males occurring further south. The three latitudinal blocks we used to classify the fishery and tagging data also roughly coincide with the schematic of different BS distributions by sex and maturity they proposed. Temporal structure (seasonality) is difficult to discern from the Nakano and Seki (2003) schematic, and thus seasonal structure is not tested in this analysis.

A null hypothesis and four alternative hypotheses with respect to spatial distributions by sex and maturity status were constructed from the N-S model and tested with the DGN dataset. The hypotheses are below.

H_0: There is no difference between the proportions of BS by sex and maturity status in different latitudinal bands.

H_1: Maturity
H_{1A}: The proportion of immature BS is significantly greater than expected by chance in latitude block 1.
H_{1B}: The proportion of mature BS is significantly greater than expected by chance in latitude block 3.

H_2: Sex
H_{2A}: The proportion of female BS is significantly greater than expected by chance in latitude block 1.
H_{2B}: The proportion of male BS is significantly greater than expected by chance in latitude block 3.

To test these hypotheses, the observed proportion of BS catch by sex and maturity status was calculated for each DGN set. The catch composition observations of each set were then randomly reassigned to fishing locations, and proportions were recalculated. A distribution of expected proportions was constructed with 10,000 randomizations, and the absolute value of difference between the observed proportion and the randomized proportion was used as a one-tailed test statistic for each permutation. The proportion outside alpha (0.05) was used as a measure of significance (p-value).

Results

Spatial structure of BS catch by sex and maturity state in the DGN fishery by season is visually apparent in Figure 2. The null hypothesis of equal distribution by sex and maturity status was rejected.. Figure 3 demonstrates the differences in the observed and expected distributions and these differences are quantified in test statistics below.

H_{1A}: $t=0.0285$, $p<<0.01$
H_{1B}: $t=0.0058$, $p<<0.01$

H_{2A}: $t=0.2011$, $p<<0.01$
H_{2B}: $t=0.0276$, $p<<0.01$

Each of the four alternative hypotheses were accepted (Figure 4). This indicates strongly non-random patterns by sex and maturity in DGN catches.

Satellite tagging data (Figure 5) show several sexually immature females during the winter and fall in the area defined as a nursery ground in the N-S model which corresponds to band 1. In addition, sexually mature males were observed in the N-S model breeding ground during winter and spring which corresponds to band 3. Furthermore, sexually mature males were most prevalent in latitude block 3 during all seasons (Figure 5).

Discussion

An examination of the temporal and spatial patterns of immature and mature males and female BS caught and tagged in the EPO reveal spatial patterns in the distribution in the EPO These results support the argument that different sex and age classes of BS are not random but are structured across latitude. This type of structure implies that fishing at different latitudes is likely to result in catches that have different biological characteristics. The tagging data generally corroborate the fishery data although tagging site bias should be considered in the interpretation of the observations (most animals were tagged near the boundary of blocks 2 and 3, and a few were tagged in block 1).

The information used in this analysis was taken from fishery-dependent sources. Although the data are a very good description of the biological characteristics of the catch, it is less clear how good they are as a measure of the population characteristics. Fishing effort in the gillnet fishery has changed across time due to management, particularly time/area closures to minimize sea turtle catch. It is unknown how these regulations may have affected the catch composition. We note that the majority of the observations in our study were of immature individuals, and as such we likely do not have a good measure of adult patterns. The lack of adult fish in the gillnet catch may be related to fishing processes or may indicate that the California Current system is made up primarily of juvenile sharks. Further investigation of fishing practices (e.g. depth) and associated catch may be instrumental in understanding how gear deployment may have affected the biological characteristics of the catch. Integration of these data with other data sources would be beneficial for improving our understanding of BS in the NPO. A comparison of observer data across periods where regulations changed may provide some insight into how changes in fisheries operations may have impacted catch composition.

Our results are broadly consistent with patterns of sex, and to a lesser extent index of maturity, to those outlined in the model of Nakano (1994). The authors note that latitudinal bands used in this study were developed based on known bio-geographical boundaries. Our boundaries therefore did not precisely conform to the graphical model from Nakano (1994), which may have weakened our test.

Given that this work supports spatial patterning of BS demography in the NPO and the spatial shifts in the DGN fishery, the SHARKWG should give consideration of the implications to assessing the population status. The Working Group needs to consider if proportional fishing effort by latitude has changed, as any changes may result in meaningful temporal differences in the biological characteristics and production equivalent of the catch.

We therefore suggest that the Nakano model may provide a reasonable hypothesis to build simulation models to test the validity of results from a BD model.

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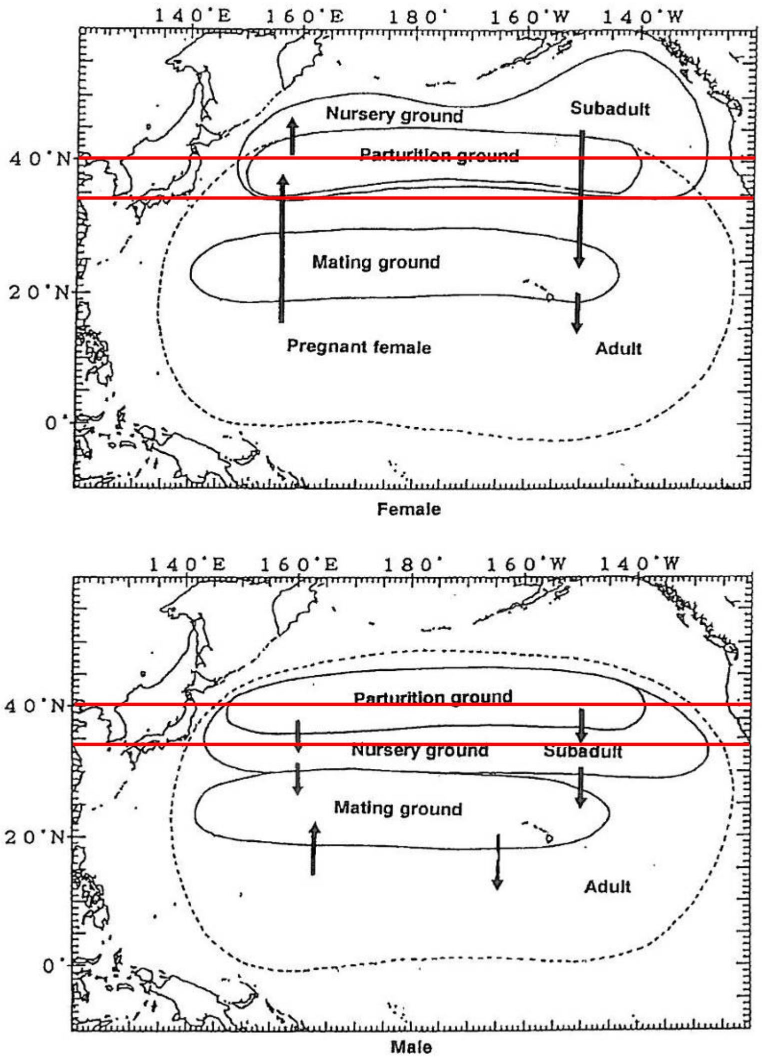

Figure 1. Schematic of the N-S model from Nakano and Seki (2003). Females are in the top panel, males in the lower panel. In each panel, latitudes higher than 40°N (top red line) are latitude block 1, latitudes below 34.4°N (lower red line) are latitude block 3, and latitudes between 34.4°N and 40°N (between red lines) are block 2.

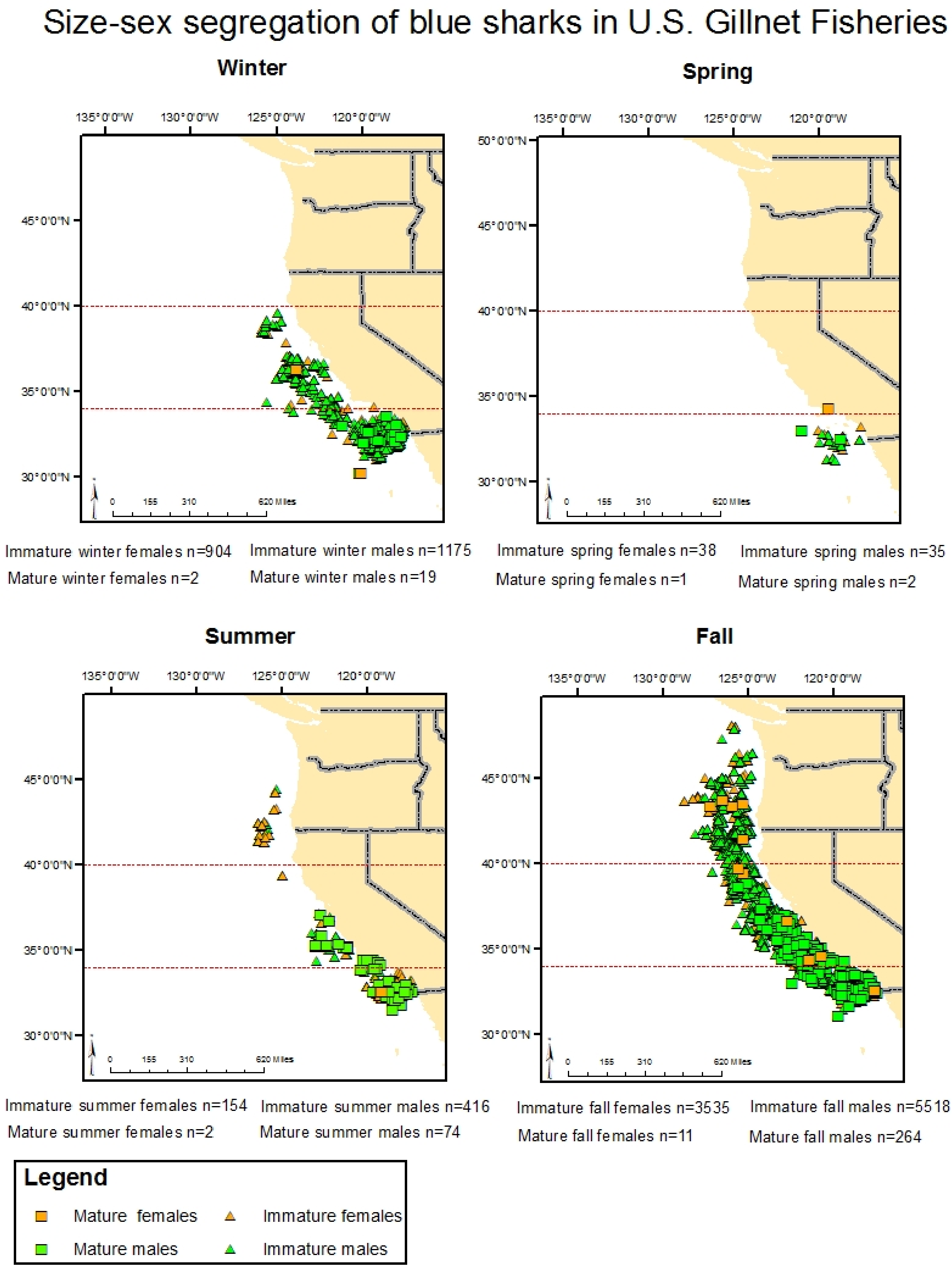

Figure 2. Locations of seasonal DGN catch from 1990-2010. Red lines represent latitude blocks previously described.

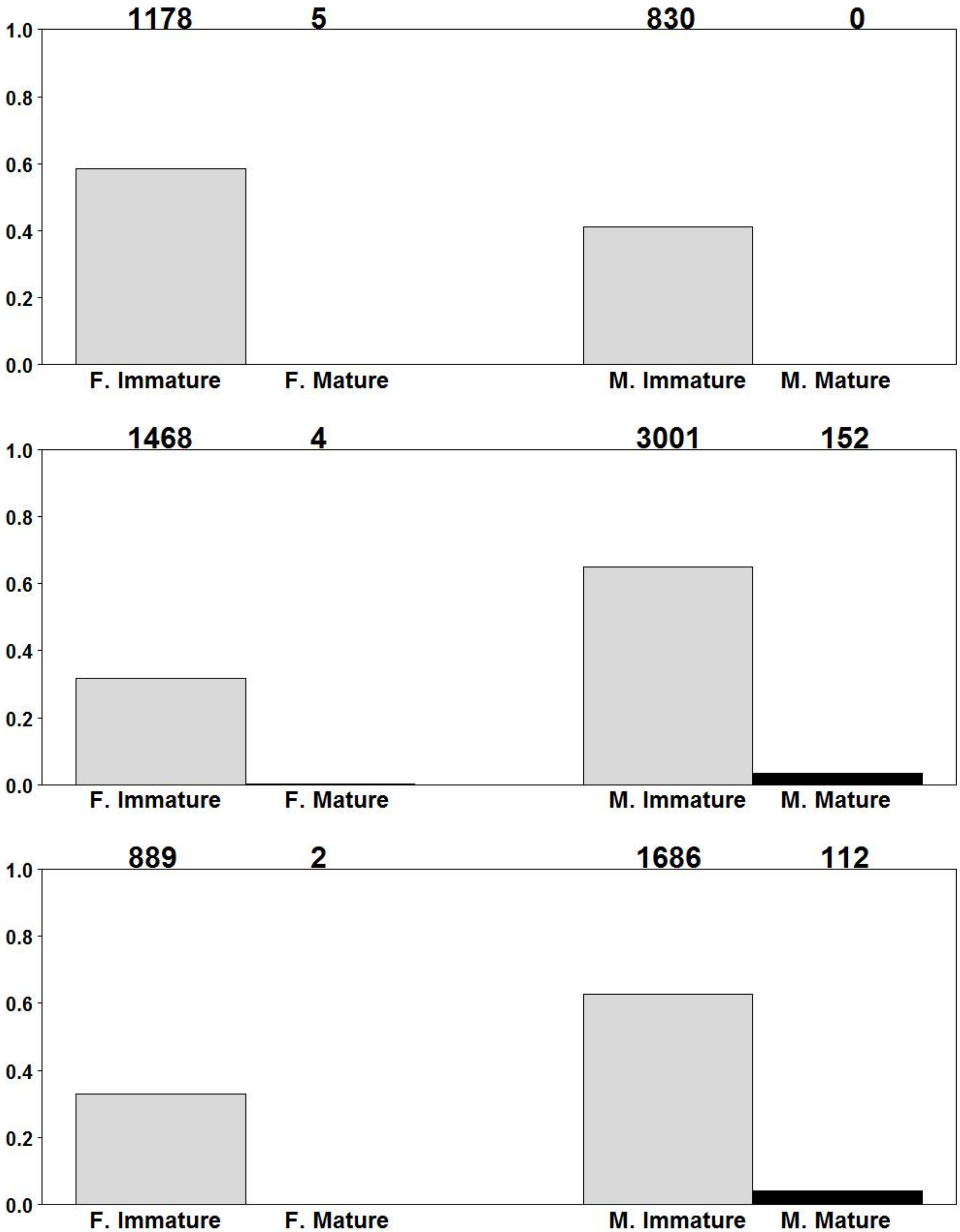

Figure 3. Proportions of blue shark caught by sex and maturity status during the Fall quarter in each latitude block (sample sizes at top of each histogram). Panels are arranged by latitude blocks (top panel=block 1, middle panel=block 2, bottom panel=block 3).

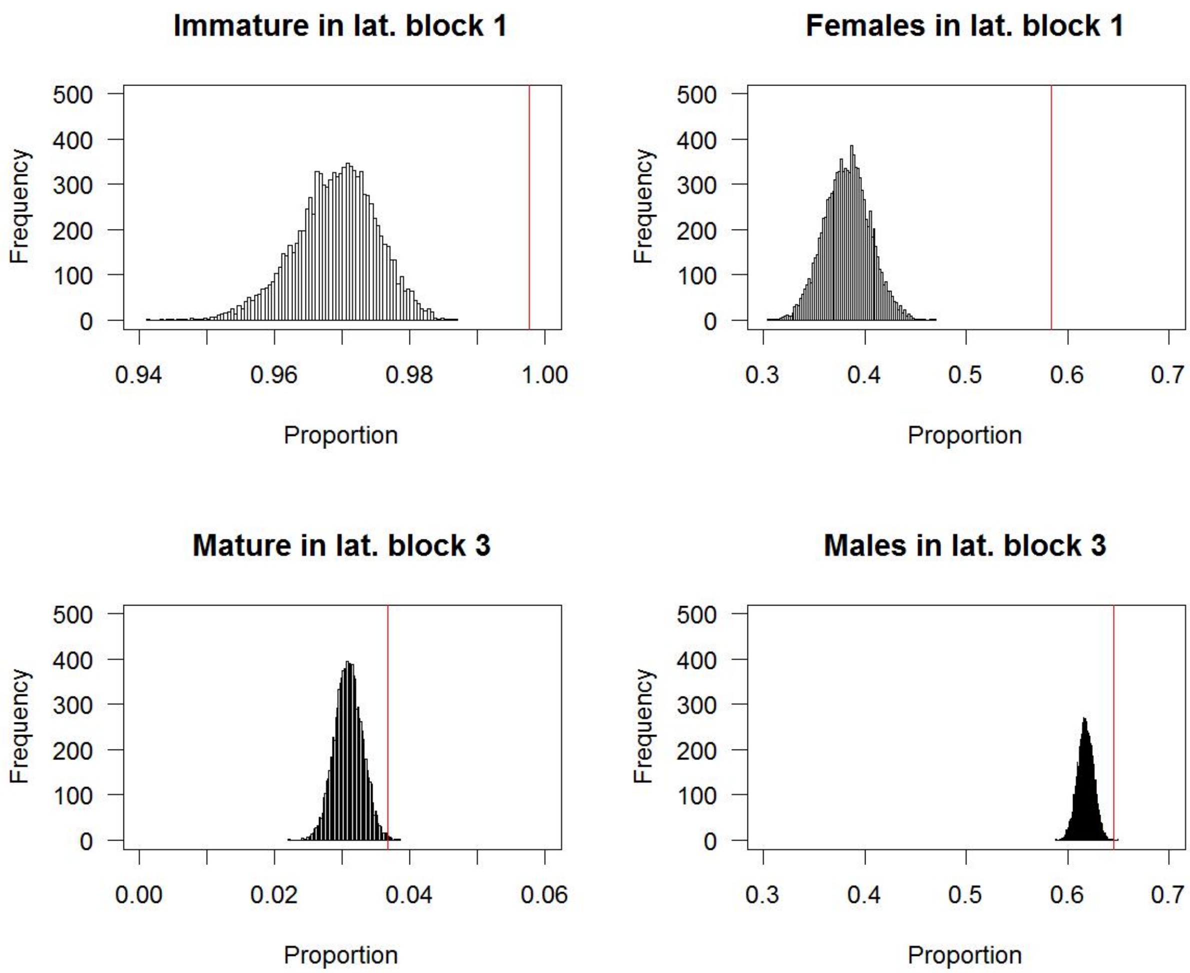

Figure 4. Proportions of blue sharks caught in the DGN fishery by sex and latitude block. Histograms are the ‘expected’ proportions from 10,000 randomizations, and the red line represents the ‘observed’ proportion.

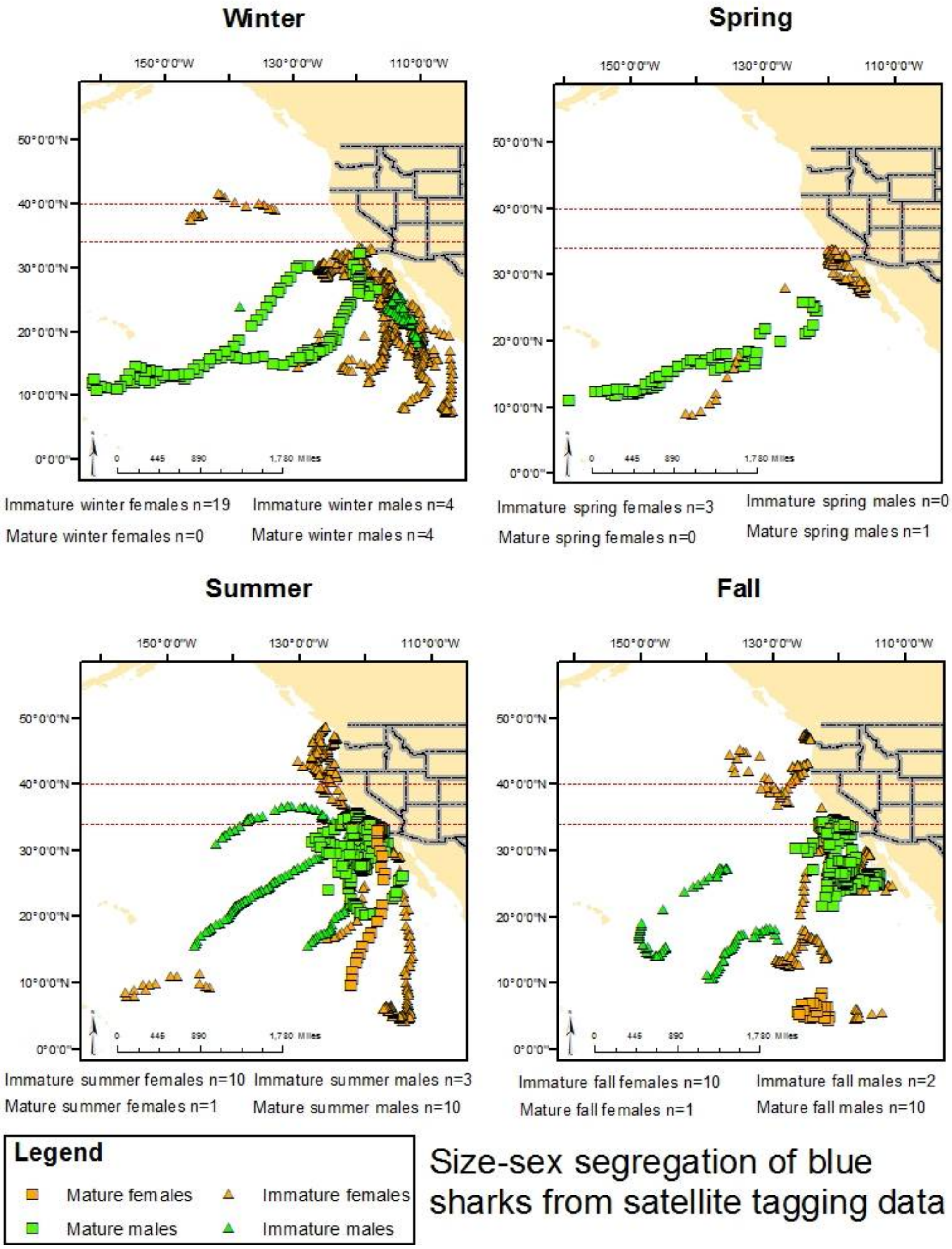

Figure 5. Satellite tagging data collected from 2002-2010, by season. Red lines represent latitude blocks previously described.