The use of Satellite Tags to Inform the Stock Assessment of a Data Poor Species: estimating vertical availability of Spiny Dogfish in the Gulf of Alaska

Peter-John F. Hulson (contact author)[1], Cindy A. Tribuzio[1], and Karson Coutre[2]

[1]Auke Bay Laboratories, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA

[2]Earth Resources Technology, Inc. Auke Bay Laboratories, 17109 Point Lena Loop Road, Juneau, AK USA 99801.

17109 Point Lena Loop Road, Juneau, AK USA 99801.
Phone number for contact author: 907-789-6060
Fax number for contact author: 907-789-6094
Email address for contact author: pete.hulson@noaa.gov
Other authors’ emails: cindy.tribuzio@noaa.gov, karson.coutre@noaa.gov

*Abstract

In Alaska, harvest specifications for many data-poor stocks are determined by using the product of estimated biomass from the Alaska Fisheries Science Center bottom trawl survey and a pre-specified fishing mortality rate. For Pacific spiny dogfish (*Squalus suckleyi*) in the Gulf of Alaska the bottom trawl survey biomass estimates are highly variable. In this study we used pop-up satellite archival tag data to estimate the vertical availability of spiny dogfish to the bottom trawl survey (the proportion of time spent under the headrope of the bottom trawl during survey operating hours) with the underlying goal of determining if the biomass estimates for this species from the bottom trawl survey can be improved. We estimated the vertical availability with two methods: one that assumed the bottom depth was the maximum depth recorded by the pop-up satellite tag in a 24 hour period, and the other that used the uncertainty in mean daily location estimates provided by a geolocation model to obtain bathymetric bottom depths around the mean daily location to compare with the depths recorded by the satellite pop-up tags. Using the satellite pop-up tag data we determined that the estimated vertical availability to the bottom trawl of spiny dogfish (that were either tagged or recovered in the Gulf of Alaska during the survey months) from the first method was 0.6, and from the second method was 0.03. Taken together, the availability of spiny dogfish to the bottom trawl survey in the GOA can be quite small which suggests that the biomass estimates from the bottom trawl survey are likely underestimated.

Keywords: spiny dogfish, pop-up satellite archival tags, bottom trawl survey, vertical availability

*Introduction

Stock assessment models commonly include a parameter for catchability (q) that is associated with population abundance indices integrated into the model. In simple terms, catchability is a parameter that scales the population abundance index data to enable the stock assessment model to estimate absolute abundance (e.g., Quinn and Deriso 1999). Cordue (2007) defines three components of catchability: (1) the area availability of the population to the survey (the proportion of the total population that is within the survey area), (2) the vertical availability (the average proportion of the biomass that is between the headrope and footrope of the net), and (3) the vulnerability to the survey gear (the average proportion of the biomass in front of the net that is actually caught, before horizontal herding). Catchability is a very influential parameter on stock assessment model results, in fact, some have considered it to be the most important parameter in stock assessment (Arreguín-Sánchez 1996). Often, catchability is either estimated within a stock assessment model or is assumed to be a fixed value (Wilberg et al. 2010). For example, it is a common assumption to set catchability equal to 1 for bottom trawl surveys that provide area-swept biomass estimates, which is currently the case for many data-limited groundfish species managed by the North Pacific Fishery Management Council (e.g., Tribuzio et al. 2015).

In Alaskan waters, the primary shark species (Pacific sleeper shark, *Somniosus pacificus*, salmon shark, *Lamna ditropis*, and Pacific spiny dogfish, *Squalus suckleyi*) are managed together as one complex with catch limits based on either a mean or maximum of a short catch history or estimates of biomass from trawl surveys. In the Gulf of Alaska (GOA) specifically, the shark complex stock assessment provides recommended catch limits for the complex as a whole, which are based on the sum of the individual species recommended limits. Spiny dogfish are the only species in the GOA shark complex for which catch limits are based on swept area biomass estimates from the Alaska Fisheries Science Center (AFSC) bottom trawl survey (Tribuzio et al. 2015, hereon called the 'bottom trawl survey' for brevity).

The bottom trawl survey uses a stratified random sampling design from which biomass for a number of species is estimated (Raring, 2011). An average catch per unit effort (CPUE) is calculated for each stratum and relative biomass estimates are calculated using stratum area weighted CPUE's which are summed over all stratum to obtain an overall GOA biomass estimate (a detailed description of how the survey biomass is estimated is outlined in von Szalay 2009). The bottom trawl survey in the GOA is conducted biennially in odd years and tows are made during the day (Raring 2011). A high-rise poly-Noreastern 4-seam bottom trawl is utilized in this bottom trawl survey with a 27.2 m headrope and a 36.8 m footrope. In the GOA, net heights are approximately 7 m off bottom (Nichol et al. 2007). The bottom trawl survey biomass estimates for spiny dogfish are highly variable through time and the confidence intervals for the biomass estimates from any given survey year are large, as a small number of large hauls often have dramatic influence on the estimated biomass (trawl survey biomass with 95% confidence intervals, CI, and the associated coefficient of variation, CV, is shown in Fig. 1). Further, the species tends to school and thus are patchily distributed (Tribuzio et al. 2015). For these reasons, the reliability of spiny dogfish biomass estimates from the bottom trawl survey is uncertain, both in the scale of the population estimates and in the ability to track trends in the population over time.

A growing number of field studies have been dedicated to providing auxiliary information to stock assessment models on catchability (e.g., Jones et al. 2011, Somerton et al. 2013, Carvalho et al. 2014, Carvalho et al. 2015). Of these, a small number of studies have used fish behavior inferred through pop-up satellite tag or archival tag data, to examine bottom trawl survey catchability (Nichol et al. 2007, Carlson et al. 2014). The hypothesis of Nichol et al. (and subsequently adapted in Carlson et al. 2014 and this study) was that demersal fish (in this case Pacific cod, *Gadus microcephalus*) would spend at least some portion of the day at the sea-floor. With archival tags that recorded depth it would then be possible to estimate the proportion of time the fish spent between the sea-floor and the headrope of the bottom trawl gear, thus, providing an estimate of vertical availability to the bottom trawl survey gear that could be used as an approximation of catchability. Carlson et al. (2014) used tagging data from another species of dogfish (*S. acanthias*) and determined that the species is not as demersal as previously thought and therefore not fully available to the bottom trawl surveys occurring in the western North Atlantic (the reader should note that the term “spiny dogfish” in this paper refers to the Pacific spiny dogfish, *S. suckleyi*, rather than a similar species, *S. acanthias*, which was used in the Carlson et al. study and also uses the common name spiny dogfish (e.g., Ebert et al. 2010).

During 2009 – 2013 spiny dogfish in the eastern North Pacific, primarily in the GOA, were tagged with pop-up satellite archival tags so that information on movement and behavior could be collected. Our objective in this study was to use the data from these pop-up satellite tags to estimate the vertical availability of spiny dogfish to the bottom trawl survey using methods similar to Nichol et al. (2007). In so doing we were also able to investigate the potential to improve the estimates of biomass from the bottom trawl survey for management of spiny dogfish in the GOA. The overarching goal of determining the vertical availability of spiny dogfish to the bottom trawl survey is to provide an auxiliary source for one of the three components of catchability (as defined by Cordue 2007) so that biomass estimates and associated catch limits provided to management could potentially be scaled to more accurate levels of population abundance.

*Materials and Methods

**Estimating location with pop-up satellite archival tags

During 2009 – 2013 pop-up satellite archival tags were deployed on spiny dogfish in the eastern North Pacific Ocean (Microwave Telemetry, Inc. X-tags, www.microwavetelemetry.com). The data recorded by the tags consisted of a date/time combination with associated depth from the surface and an observed daily location at noon. The observed location at noon was obtained based on light sensors in the pop-up tags which record the sunrise, sunset, and light intensity; these observations were then used to calculate the observed location at the sun's zenith, or 'noon' (these proprietary calculations were performed by Microwave Telemetry). However, the measurement error of the location provided by the tags is large enough that this location should more appropriately be considered as a mean daily location rather than a location precisely at noon, thus, from here forward we will refer to the recorded tag location as the observed mean daily location. Depth readings were recorded at 2, 15, 30 or 60 minute intervals during the time the tag was deployed. Tags with 2 minute interval data were tags that were physically recovered. The 15, 30 or 60 minute interval data was collected from satellite downloads and was dependent on the time at liberty of the tag; tags with longer time at liberty had longer intervals.

A state-space Kalman filter model was used with the observed mean daily location data from each tag to determine the most probable track (Sibert et al. 2003, hereon called the geolocation model) with the package analyzepsat operating in the R software environment (R

Core Team 2013). Bathymetry data with a spatial resolution of 1 minute were retrieved from the ETOPO1 Global Relief Model for the Gulf of Alaska and Bering Sea (Amante and Eakins 2009) in order to correct the estimated mean daily locations based on maximum daily depth recorded on each tag in relation to bottom depth. This ensured that the fish was not predicted to be in a location where maximum daily depth of the fish surpassed the known bathymetry on a given day (Teo et al. 2007). From the geolocation model we obtained estimated mean daily locations as well as the estimated uncertainty in the mean daily locations. The estimated mean daily locations were joined with the coverage for the bottom trawl survey using ArcGIS (version 10.2.1, www.esri.com) to categorize each estimated mean daily location as either "in" the survey area, or "out" of the survey area, and to determine which strata the mean daily location estimates were within. The bottom trawl survey splits the GOA region into forty-nine strata categorized by bathymetry, geographical area, and statistical management area boundaries (Raring 2011).

Only data from tags which were either released or recovered in the GOA during the summer were used (June – August, the time period in which the bottom trawl survey is conducted) to ensure that estimated mean daily locations were within the bottom trawl survey area of the GOA. Data was further filtered to remove any days of data in which the tag had released from the fish (either as programmed or prematurely) and was floating at the surface.

**Estimating vertical availability to the AFSC bottom trawl survey

We approximated the vertical availability of spiny dogfish to the bottom trawl survey by estimating the proportion of depth readings that were under the headrope of the bottom trawl, or, within 7 m of the bottom depth. We used two methods to estimate the vertical availability of spiny dogfish to the bottom trawl. The first method followed from the procedure presented in Nichol et al. (2007, hereon called the 'Nichol method'). For this method, the maximum depth observed by a tagged fish in a 24-hour period was assumed to be the bottom, and the proportion of time the fish spent within 7 m of this maximum depth during day-time hours (0600 – 1800) was computed. This proportion was computed as the number of times a depth reading was within 7 m of the bottom (in this case the deepest depth in a 24-hour period) divided by the total number of depth observations made by the tags during the day, resulting in daily estimates of vertical availability. The overall estimated vertical availability (pooled across years and for each individual year) was calculated as the mean of the daily vertical availability estimates and uncertainty was estimated from the upper and lower 95% percentiles of the daily estimates.

For second method (hereon called the ‘geolocation method’), rather than assume the maximum depth in a 24-hour period was the seafloor, the bottom depth was determined from the mean daily location estimates provided by the geolocation model. Bottom depths at the estimated mean daily locations were retrieved from the ETOPO1 Global Relief Model data described above. The uncertainty in the mean daily location estimates provided by the geolocation model were used to compute standard deviations (SD) in the latitude and longitude. These SDs in latitude and longitude were then used to generate random locations centered on the mean daily location to integrate uncertainty into the estimated mean daily locations. Using the normal distribution and the SDs, 10,000 random locations were generated for each mean daily location estimate, and the bottom depth for each random location was determined from the ETOPO1 Global Relief Model. These random locations were then filtered to locations that were within the AFSC bottom trawl survey area. Generated locations were removed from the analysis if the bottom depths were shallower than 11 m (the shallowest depth sampled in the trawl survey, which would also include locations on land), shallower than the minimum daily depth recorded by the pop-up tag (locations where the spiny dogfish could not have been in that day based on the depth data recorded), deeper than 1,000 m (the deepest depth the trawl survey samples), or if the generated locations were within inside waters that are not sampled by the bottom trawl survey (i.e., within Southeast Alaska, Prince William Sound, Cook Inlet, etc.). The remaining generated locations were used to compare between the depth of the bottom trawl headrope and the depth of the pop-up tag during the survey operating hours.

Vertical availability was estimated for the geolocation method by comparing the maximum daytime depth recorded by the pop-up tags to the trawl headrope depth during the daytime (7 m shallower than the bottom depth) with two cases: (1) if the maximum pop-up tag depth recorded during the daytime was shallower than the depth of the trawl headrope then the spiny dogfish was not vertically available to the trawl (the trawl was too deep) and (2) if the depth of the trawl headrope was shallower than the maximum daytime pop-up tag depth recorded then the spiny dogfish was, at some point during the day, vertically available to the bottom trawl at that location. The daily vertical availability was then estimated as the number of times that case 2 occurred (the number of times the spiny dogfish was available to the bottom trawl) divided by the total number of generated locations for that particular day that were within the survey area. The vertical availability for the geolocation method (both pooled across years and for each year) was computed as the mean of the daily vertical availability estimates and the uncertainty was estimated as the upper and lower 95% percentile of the daily vertical availability estimates. We also performed a sensitivity analysis to evaluate the estimated vertical availability from the geolocation method with respect to the depth of the headrope. Two cases were investigated in which the headrope height was doubled (14 m off bottom) and multiplied by 5 (35 m off bottom) and the vertical availability was re-estimated (both pooled across years and annually).

To further illustrate the vertical availability of spiny dogfish to the bottom trawl survey we performed a comparison between the depths recorded by the pop-up tags and several statistics from the bottom trawl survey with regard to survey depth strata (using depth strata as defined by the bottom trawl survey: 0-100 m, 101-200 m, 201-300 m, 301-500 m, 501-700 m, and 701-1000 m). The average across the years of the bottom trawl survey for the number of hauls performed within each depth strata, the average proportion of hauls with positive catches of spiny dogfish within each depth strata, and the average CPUE of spiny dogfish for the positive hauls within each depth strata were compared to the proportion of recorded depths from the pop-up tags within each depth strata. To further evaluate the vertical movement of spiny dogfish during a 24 hour period, not just the time spent under the headrope of the bottom trawl, we compared among the range of depths recorded by the pop-up tags at time intervals throughout the day (using 2 hour time periods). A concern was if the resulting depth changes through the day were a result of the spiny dogfish following the bottom or if the vertical movement was through the water column. To evaluate this, boxplots of depth readings from the pop-up tags were investigated for all the tags pooled, for tags that were over bottom depths less than 350 m based on the estimated mean daily location from the geolocation model (depths in which changes in depth readings could potential be from following the bathymetry, defined as “shallow” depths), and over bottom depths greater than 350 m (depths in which changes in depth readings were from movement through the water column, defined as “deep”).

*Results

Forty-six total pop-up tags met the criteria for inclusion in this study. There were 5 males, ranging from 69 – 80 cm pre-caudal length (PCL) and 41 females ranging from 66 – 103 cm (PCL – measured from the tip of the snout to the dorsal pre-caudal notch in a straight line); the release and recovery locations and dates, along with the sex and length of each spiny dogfish tagged and used in this analysis is shown in Table 1. The release and recovery locations for the 46 pop-up tags used in this analysis is shown in Fig. 2. Fig. 3A shows the results of the geolocation model estimated mean daily locations for the 46 tags used in this analysis. A total of 1,585 mean daily locations were estimated for these tags resulting in an average of 34 per tag (with a minimum of 7 and maximum of 82 mean daily locations across tags). The average SD in latitude of the mean daily location estimates that resulted from the geolocation model was 0.97° (with a maximum of 1.98°), and the mean SD in longitude was 1.09° (with a maximum of 2.42°). Thirty-eight of the 46 tags (~83%) resulted in at least one estimated mean daily location outside of the AFSC bottom trawl survey area in the GOA at some point during the summer (extent of trawl survey strata and management areas are shown in Fig. 3B). Additionally, around 40% of all the estimated mean daily locations across tags were located outside the AFSC bottom trawl survey area (pink circles Fig. 3C). Only those locations within the AFSC bottom trawl survey area were included in these analyses (green circles Fig. 3C).

The estimated vertical availability to the AFSC bottom trawl survey gear from the Nichol method was not significantly smaller than 1 for both pooled and annual estimates (Fig. 4A). From the Nichol method the estimated vertical availability was 0.609 using pooled data from all the tags (95% CI of 0.042 – 1, Fig. 4A, Table 2). Annual estimates of vertical availability from 2010 – 2013 using the Nichol method ranged from 0.519-0.736 (Table 2). The largest estimate of vertical availability occurred in 2013 and the smallest estimate occurred in 2010.

Vertical availability to the AFSC bottom trawl survey gear was estimated from the geolocation method to be 0.031 (95% CI of 0 – 0.21, Fig. 4B) and was significantly smaller than

1. However, 0 was included in the CI for the pooled estimate and in 3 of the 4 annual estimates of vertical availability from the geolocation method. From the geolocation method annual estimates of vertical availability ranged from 0.020 – 0.037 (Table 2), but were not significantly different than the pooled estimate or among years (Fig. 4). The largest estimate of vertical availability occurred in 2012 and the smallest in 2011 from the geolocation method. Multiplying the headrope height by 2 resulted in vertical availability estimates that were on the same order of magnitude as the results of using the standard headrope height; the pooled vertical availability estimate was 0.046 (and was not significantly different than the pooled estimate of 0.031 using the standard headrope height) and ranged from 0.032 – 0.052 from 2010 – 2013 (Fig. 5B). Multiplying the headrope height by 5 did increase the estimates of vertical availability; the pooled vertical availability estimate resulted in 0.089, but was not significantly larger than the vertical availability estimate using the standard headrope height (Fig. 5C). Annual estimates of vertical availability after multiplying the standard headrope height by 5 ranged from 0.062 – 0.106.

On average, the number of hauls performed by the bottom trawl survey are in depths less than 200 m (Fig. 6A).The largest proportions of bottom trawl survey hauls that caught spiny dogfish (positive hauls) were in depth strata ranging from 0 to 300 m (Fig. 6B). Although, positive hauls have occurred in the 301 – 500 m depth strata (3.2%, with an upper 95% CI of 10%) and 501 – 700 m depth strata (2.4% with an upper 95% CI of 11%). The mean catch per unit effort (CPUE, in kg per km^2) of positive hauls by depth strata was the largest in the 0 – 100 m depth strata, the second largest mean CPUE was in the 501 – 700 m depth strata (Fig. 6C). The 301 – 500 m depth strata resulted in the largest variability in the mean CPUE (Fig. 6C). The large majority of the depth readings from the pop-up tags during the trawl survey operating hours were within 0 – 100 m depth strata (99.7%, Fig. 6D). The deeper strata had substantially lower proportions; 0.3% of the depth readings from the tags were within 101 – 200 m depth and <0.1% within 201 – 300 m depth. None of the pop-up tags used in this analysis recorded depths greater than 300 m, the greatest depth recorded during the trawl survey operating hours was 204 m (the greatest depth recorded during a 24-hour period was 274 m).

On average, the depths recorded by the tags during a 24-hour period were shallower during the night and deeper during the day (Fig. 7). For the time periods in which the AFSC bottom trawl survey operates (white-shaded boxplots in Fig. 7 between the vertical dashed lines), the median depths in the early morning periods were slightly shallower than the depths observed during the afternoon time periods. Overall, the depth distribution from animals over shallow (<350 m) or deep (>350 m) strata during the day was very similar (Fig. 7C – 7F); although, the pop-up tags over deep strata recorded some depths that were somewhat deeper than the pop-up tags over shallow strata during the day (comparing between Fig. 7D and 7F).

*Discussion

The results of tagging spiny dogfish with pop-up satellite tags indicate that the vertical availability of spiny dogfish to the AFSC bottom trawl survey in the GOA can be very limited. Indeed, the two methods we used in this study both resulted in estimates of mean vertical availability that were less than 1, which is the value currently assumed in the stock assessment for spiny dogfish in the GOA (Tribuzio et al. 2015). These results are not surprising. The stock assessment for the GOA shark complex states that the biomass estimates from the AFSC bottom trawl survey for spiny dogfish ‘is highly variable from year to year’ and ‘should be considered a minimum biomass estimate…’ due to issues with the highly migratory and pelagic nature of this species (Tribuzio et al. 2015). The results presented in this work also agree with the study by Carlson et al. (2014) who assessed the movement of a similar species, *S. acanthias*, in the Atlantic Ocean with pop-up satellite tags. They found that *S. acanthias* did not display movement characteristic of a demersal species. Instead, they used the entire water column, with greater vertical movement during daytime than at night. The authors suggested that *S. acanthias* are less available to trawl survey gear in the North Atlantic than previously thought, contributing to a potential underestimation of spiny dogfish abundance. We find that this is also likely the case in the AFSC bottom trawl survey.

In this study we have provided quantitative estimates of how efficiently spiny dogfish are sampled by the AFSC bottom trawl survey. This information enables assessment scientists to give more accurate advice to managers for determining shark catch limits in the GOA. Both methods used to estimate vertical availability to the AFSC bottom trawl survey have limitations, however. The primary assumption made with the Nichol method was that the maximum depth in a 24-hour period was the sea-floor, which is likely not true for some spiny dogfish (for example, the spiny dogfish that were over depths >350 m). Comparing depths inhabited by tagged spiny dogfish in shallow (<350 m) and deep (>350 m) water showed depth changes of the animals were very similar. This suggests that spiny dogfish inhabit consistent depth ranges and in many cases do not move to the bottom during any part of a 24-hour period (as would be true for the tagged spiny dogfish that were over bottom depths deeper than 350 m, which is deeper than any depth recorded by the pop-up tags). Further, studies of the diet of spiny dogfish in the eastern North Pacific Ocean have shown 80% of prey groups are from pelagic food sources (Jones and Green 1977, Tanasichuk et al. 1991, Tribuzio 2010). Our study and the diet evidence suggests spiny dogfish certainly spend a large amount of time off-bottom and could potentially be considered as primarily pelagic rather than demersal. The Nichol method estimate is likely an optimistic estimate of vertical availability to bottom trawl gear and in practical terms indicates the proportion of time that spiny dogfish inhabit depths close to their maximum daily depth rather than proximity to the sea-floor.

There are also several caveats when using the geolocation method to estimate vertical availability. The primary limiting factor was the large uncertainty in the estimated mean daily location from the geolocation model. For all the estimated mean daily locations the uncertainty overlapped large areas, areas that included land and areas that included depths beyond the bottom trawl survey area. We attempted to account for the uncertainty in this study by generating locations around the mean daily location estimate rather than using the mean daily location estimate itself, but in the future, development of tools to reduce the uncertainty in the estimated locations from satellite pop-up tag data so that the bathymetry can be related with greater certainty would be invaluable to this type of research. Another limitation was the coarseness of the bathymetry data used; a spatial resolution of 1 minute can include fairly variable bathymetry in Alaska and can vary by larger amounts than the headrope height of the bottom trawl. We tried to account for this limitation by including a sensitivity analysis to the headrope height, however, that analysis was also based on the same bathymetry data.

The range of values we estimated for vertical availability of spiny dogfish to the bottom trawl survey are similar to model-based catchability parameter estimates for several bottom trawl surveys from an assessment of spiny dogfish off the U.S. West Coast, which ranged from 0.05 to 0.55 (Gertseva and Taylor 2011). Further, with the pop-up satellite tag data we were able to estimate time-dependent vertical availability to the bottom trawl survey. Future research could investigate whether changes over time in vertical availability are due to oceanographic or environmental conditions (e.g., temperature or food availability). A number of methods exist to incorporate time-dependent catchability into stock assessment models (e.g., Wilberg et al. 2010), as well as estimating absolute abundance of spiny dogfish using prior estimates of catchability.

One of the goals of this study was to evaluate the reliability of the bottom trawl survey estimates of spiny dogfish biomass. The limited availability of spiny dogfish to the bottom trawl survey that resulted from this study does not invalidate the survey estimates of biomass, per se, but does question whether trends in abundance with such highly variable biomass estimates can be elucidated. An interesting result of this study when comparing between depths occupied by spiny dogfish and bottom trawl survey statistics by survey depth strata was that the bottom trawl survey captures spiny dogfish in strata whose bottom depths are deeper than the maximum depth observed by any of the pop-up satellite tags. Albeit, the proportion of total catch of spiny dogfish in the bottom trawl survey from strata whose depths are deeper than the maximum observed tag depth is small, around 2 – 5%. What this observation seems to imply is that the spiny dogfish caught in these strata are likely captured while the trawl gear is being deployed or retrieved, not when the gear is on-bottom. It is also possible that catch during trawl net deployment or retrieval could occur at times in shallower strata as well. Thus, we must ask: do some of the extreme catch events we observe for spiny dogfish during the bottom trawl survey, which make the survey biomass estimates so variable both within and between years, actually occur during deployment/retrieval of the trawl gear? It is not clear how to deal with this issue, making it a worthwhile topic for further investigations to reduce the variability in the bottom trawl survey estimates of biomass for spiny dogfish.

The primary objective of our study was to determine if pop-up satellite tag data could be used in the stock assessment for spiny dogfish and provide management with more accurate estimates of population abundance. This study provides a range of possible values of vertical availability that could be used to further evaluate catchability associated with the bottom trawl survey, and that would result in more accurate estimates of population size for spiny dogfish in the GOA. Further, this information can be directly integrated into the spiny dogfish stock assessment in the GOA to provide management with more appropriate harvest recommendations in a number of ways. We recommend model-based approaches, through the use of prior information on catchability, rather than directly scaling the estimated biomass from the bottom trawl survey for two reasons. First, the range in availability between the two methods can result in a large range in estimated absolute abundance. A single estimate would be desirable. Second, a model-based approach would allow for additional population abundance indices to be integrated with the bottom trawl survey index for stability, such as indices of abundance from longline surveys. Overall, the information provided by pop-up satellite tags has shown to be very useful, in this case, to aid in estimating vertical availability to a bottom trawl survey, and may in the future prove to be a valuable tool for stock assessment, especially for data-poor species.

*Acknowledgments

We would like to thank Chris Lunsford, Dana Hanselman, Jon Heifetz, and two anonymous reviewers for helpful comments and advice. The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the National Marine Fisheries Service, NOAA.

*References

Amante, C., and B.W. Eakins. 2009. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Tech. Memo. NESDIS NGDC-24. 19 pp.

Arreguín-Sánchez, F. 1996. Catchability: a key parameter for fish stock assessment. Reviews in Fish Biology and Fisheries. 6:221-242. doi:10.1007/BF00182344

Carlson, A.E., E.R. Hoffmayer, C.A. Tribuzio, and J.A. Sulikowski. 2014. The use of satellite tags to redefine movement patterns of spiny dogfish (*Squalus acanthias*) along the U.S. East Coast: Implications for Fisheries Management. PLoS ONE 9(7): e103384. Doi:10.1371/journal.pone.0103384.

Cordue, P. 2007. A note on non-random error structure in trawl survey abundance indices. ICES J. Mar. Sci. 64:1333-1337.

Ebert, D.A., W.T. White, K.J. Goldman, L.J.V. Compagno, T.S. Daly-Engel and R.D. Ward. 2010. Resurrection and rediscription of *Squalus suckleyi* (Girard, 1854) from the North Pacific; with comments on the *Squalus acanthias* subgroup (Squaliformes: Squalidae). Zootaxa. 2612:22-40.

Efron, B., and R.J. Tibshirani. 1993. An introduction to the Bootstrap. Chapman and Hall, New York. 436 pp.

Gertseva, V. and I.G. Taylor. 2012. Status of the spiny dogfish shark resource off the continental U.S. Pacific Coast in 2011. Pacific Fishery Management Council, 7700 NE Ambassador Place, Ste 101, Portland, Oregon 97220. 259 pgs. Available online: http://www.pcouncil.org/wp-content/uploads/Spiny_Dogfish_2011_Assessment.pdf

Jones, B.C. and G.H. Green. 1977. Food and feeding of spiny dogfish (*Squalus acanthias*) in British Columbia waters. J. Fish. Res. Board Can. 34:2067-2078.

Jones, D.T., C.D. Wilson, A. De Robertis, C. Rooper, T.C. Weber, J.L. Butler. 2011. Evaluation of rockfish abundance in untrawlable habitat: combining acoustic and complementary sampling tools. Fish. Bull. 110:332-343.

Nichol, D.G., T. Honkalehto, G.G. Thompson. 2007. Proximity of Pacific cod to the sea floor: Using archival tags to estimate fish availability to research bottom trawls. Fish. Res. 86: 129-135.

Quinn II, T.J., and R.B. Deriso. 1999. Quantitative fish dynamics. Oxford University Press, New York. 542 pp.

R Core Team. 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

Raring, N.W., P.G. von Szalay, F.R. Shaw, M.E. Wilkins, and M.H. Martin. 2011. Data report: 2001 Gulf of Alaska Bottom Trawl Survey. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-225. 179 pp.

Sibert, J.R., M.K. Musyl, and R.W. Brill. 2003. Horizontal movements of bigeye tuna (*Thunnus obesus*) near Hawaii determined by Kalman filter analysis of archival tagging data. Fish. Oc. 12(3):141-151.

Somerton, D.A., K.L. Weinbert, and S.E. Goodman. 2013. Catchability of snow crab (*Chinoecetes opilio*) by the eastern Bering Sea bottom trawl survey estimated using a catch comparison experiment. Can. J. Fish. Aquat. Sci. 70:1699-1708. doi:10.1139/cjfas-2013-0100.

Tanasichuk, R.W., D.M. Ware, W. Shaw, and G.A. McFarlane. 1991. Variations in diet, daily ration, and feeding periodicity of Pacific hake (*Merluccius productus*) and spiny dogfish

(*Squalus acanthias*) off the lower west coast of Vancouver Island. Can. J. Fish. Aquat. Sci. 48:2118-2128.

Teo, S.L., A. Boustany, H. Dewar, M.J. Stokesbury, K.C. Weng, S. Beemer, and B.A. Block. 2007. Annual migrations, diving behavior, and thermal biology of Atlantic bluefin tuna, *Thunnus thynnus*, on their Gulf of Mexico breeding grounds. Mar. Bio. 151(1):1-18.

Tribuzio, C.A. 2010. Life history, demography, and ecology of the spiny dogfish (*Squalus acanthias*) in the Gulf of Alaska. Ph.D. dissertation. University of Alaska Fairbanks. 183 Pgs.

Tribuzio, C.A., K. Echave, C. Rodgveller, and P.-J.F. Hulson. 2015. Assessment of the Shark stock complex in the Gulf of Alaska. In Stock assessment and fishery evaluation report for the groundfish fisheries of the Gulf of Alaska. North Pacific Fishery Management Council, 605 W 4th Avenue, Suite 306, Anchorage, AK 99510.

von Szalay, P.G., C.N. Rooper, N.W. Raring, and M.H. Matrin. 2011. Data Report: 2010 Aleutian Islands Bottom Trawl Survey. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-215. 153 pp.

Wilberg, M. J., J.T. Thorson, B.C. Linton, and J. Berkson. 2010. Incorporating time-varying catchability into population dynamic stock assessment models. Rev. Fish. Sci. 19(1):7-24. doi: 10.1080/10641260903294647

*Tables

Table 1. Sex (M – male, F – female), length (PCL, in cm), release and recovery dates and locations for the 46 tagged spiny dogfish used in this analysis (sorted by release date).

Tag	Sex	PCL	Release date	Release location	Recovery date	Recover location
1	F	74	7/20/2010	59.56 N, -139.82 W	9/27/2010	58.8 N, -143.75 W
2	F	81	7/20/2010	59.56 N, -139.82 W	1/20/2011	46.47 N, -124.6 W
3	F	77	7/20/2010	59.56 N, -139.82 W	1/20/2011	59.1 N, -148.26 W
4	F	70	7/20/2010	59.56 N, -139.82 W	3/20/2011	59.2 N, -147.83 W
5	F	81	7/20/2010	59.56 N, -139.82 W	3/22/2011	58 N, -139.01 W
6	F	73	7/20/2010	59.56 N, -139.82 W	1/11/2011	59.29 N, -147.12 W
7	F	75	7/20/2010	59.56 N, -139.82 W	1/31/2011	56.03 N, -154.42 W
8	F	79	7/20/2010	59.56 N, -139.82 W	5/20/2011	59 N, -138.56 W
9	M	70	6/26/2011	54.57 N, -158.65 W	7/17/2011	55.54 N, -156.88 W
10	F	93	6/26/2011	54.57 N, -158.65 W	3/28/2012	35.26 N, -122.46 W
11	M	69	6/29/2011	55.64 N, -155.85 W	10/24/2011	55.33 N, -159.95 W
12	F	77	7/10/2011	55.93 N, -134.9 W	1/10/2012	56.85 N, -136 W
13	F	73	7/10/2011	55.93 N, -134.9 W	12/8/2011	57.04 N, -134.57 W
14	F	73	7/10/2011	55.93 N, -134.9 W	3/10/2012	56.41 N, -135.63 W
15	F	82	7/10/2011	55.93 N, -134.9 W	11/29/2011	49.45 N, -126.85 W
16	F	66	7/10/2011	55.93 N, -134.9 W	4/13/2012	56.39 N, -135.61 W
17	F	88	7/12/2011	56.38 N, -135.49 W	11/18/2011	49.95 N, -127.58 W
18	F	81	7/12/2011	56.38 N, -135.49 W	4/13/2012	38.32 N, -123.59 W
19	F	81	7/12/2011	56.38 N, -135.49 W	5/12/2012	40.6 N, -126.05 W
20	F	74	7/29/2011	59.75 N, -143.59 W	1/29/2012	59.07 N, -147.71 W
21	F	82	8/5/2011	59.52 N, -146.96 W	1/5/2012	59.23 N, -147.32 W
22	F	74	6/24/2012	54.37 N, -160.25 W	5/24/2013	45.37 N, -137.25 W
23	F	89	6/25/2012	54.5 N, -159.26 W	12/27/2012	45.53 N, -132.58 W
24	F	70	6/25/2012	54.5 N, -159.26 W	12/5/2012	53.22 N, -163.53 W
25	F	86	6/25/2012	54.5 N, -159.26 W	2/26/2013	42.16 N, -145.65 W
26	F	92	6/26/2012	54.63 N, -158.57 W	1/2/2013	42.46 N, -129.61 W
27	F	73	6/26/2012	54.63 N, -158.57 W	1/28/2013	41.55 N, -125.7 W
28	F	88	6/26/2012	54.63 N, -158.57 W	4/27/2013	42.68 N, -141.48 W
29	F	81	6/29/2012	55.64 N, -155.85 W	12/30/2012	54.18 N, -132.35 W
30	F	103	7/5/2012	54.65 N, -132.84 W	5/6/2013	44.56 N, -149.31 W
31	F	85	7/5/2012	54.65 N, -132.84 W	7/5/2013	53.2 N, -131.69 W
32	F	90	7/24/2012	59.42 N, -140.93 W	7/21/2013	58.49 N, -138.26 W
33	F	73	7/25/2012	58.69 N, -140.64 W	2/26/2013	59.4 N, -149.98 W
34	F	70	7/25/2012	58.69 N, -140.64 W	10/17/2012	59.79 N, -145.89 W

Table 1. Continued

Tag	Sex	PCL	Release date	Release location	Recovery date	Recover location
35	F	76	7/25/2012	58.69 N, -140.64 W	6/25/2013	58.97 N, -138.5 W
36	M	70	7/28/2012	59.55 N, -142.58 W	7/29/2013	57.65 N, -142.48 W
37	F	84	7/29/2012	59.75 N, -143.59 W	4/2/2013	36.49 N, -122.66 W
38	M	69	7/29/2012	59.67 N, -143.39 W	11/10/2012	56.11 N, -153.96 W
39	F	72	8/5/2012	59.52 N, -146.96 W	8/9/2013	59.86 N, -144.19 W
40	F	71	8/5/2012	59.52 N, -146.96 W	8/5/2013	58.42 N, -138.53 W
41	F	72	8/26/2012	55.75 N, -156.2 W	8/26/2013	59.66 N, -145.98 W
42	F	90	6/26/2013	54.63 N, -158.57 W	6/28/2014	56.51 N, -154.71 W
43	F	74	6/28/2013	55.24 N, -156.67 W	6/28/2014	44.25 N, 151.27 W
44	M	80	6/29/2013	55.64 N, -155.85 W	6/29/2014	56.61 N, -151.8 W
45	F	86	8/5/2013	59.52 N, -146.96 W	8/9/2014	59.2 N, -153.99 W
46	F	82	8/5/2013	59.52 N, -146.96 W	8/5/2014	60.29 N, -152.37 W

Table 2. Pooled (across years) and annual mean vertical availability estimates (VA) from the Nichol method and geolocation method with associated standard deviations (SD).

	Number of days	VA (Nichol)	SD in VA (Nichol)	VA (Geolocation)	SD in VA (Geolocation)
Pooled	1585	0.609	0.341	0.031	0.071
2010	261	0.519	0.329	0.021	0.019
2011	269	0.619	0.345	0.020	0.069
2012	670	0.551	0.325	0.037	0.069
2013	385	0.736	0.328	0.035	0.092

*Figures

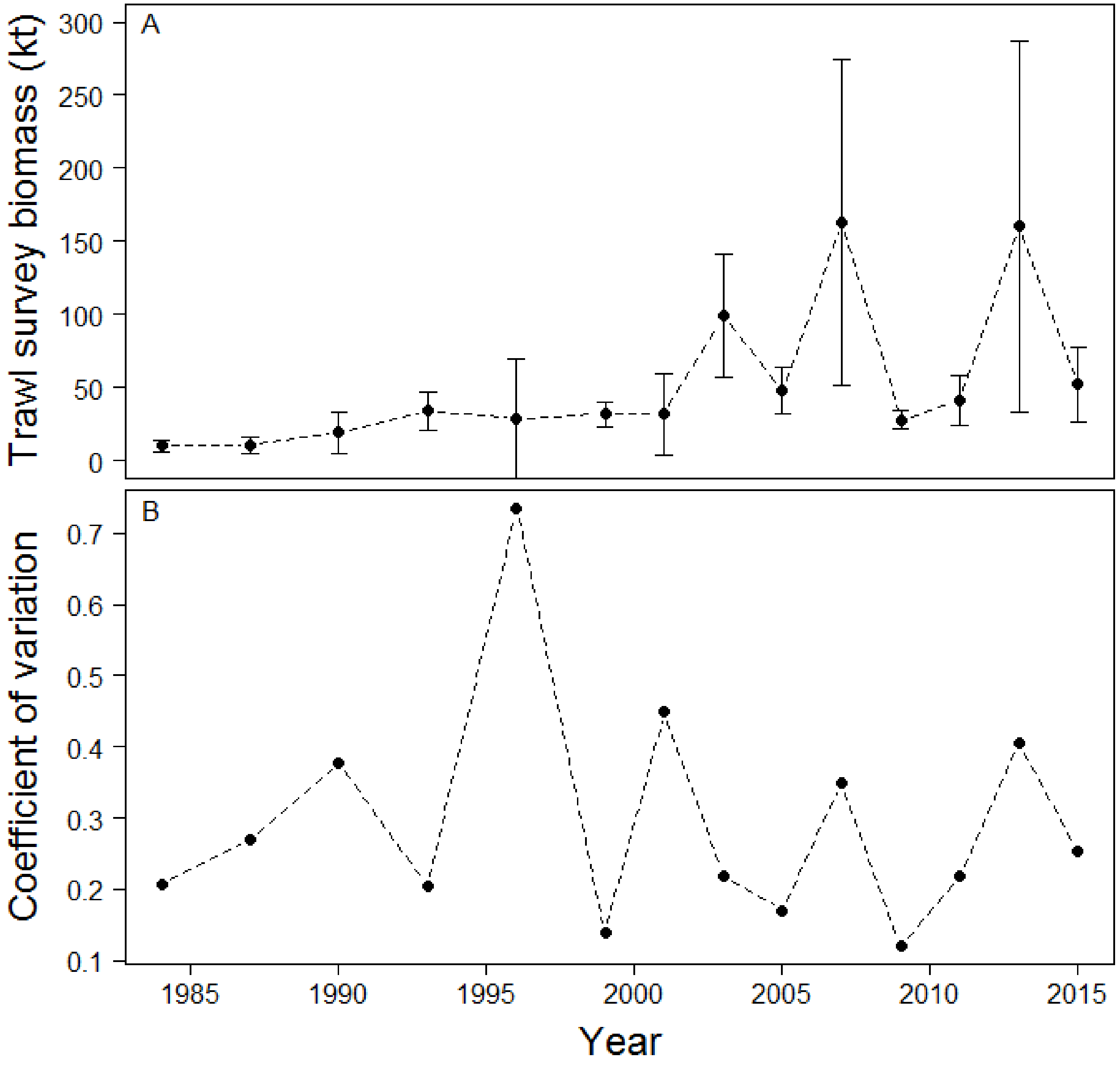

Figure 1. Gulf of Alaska spiny dogfish estimated biomass from the Alaska Fisheries Science Center (AFSC) bottom trawl survey (A) with the coefficient of variation in the trawl survey biomass (B).

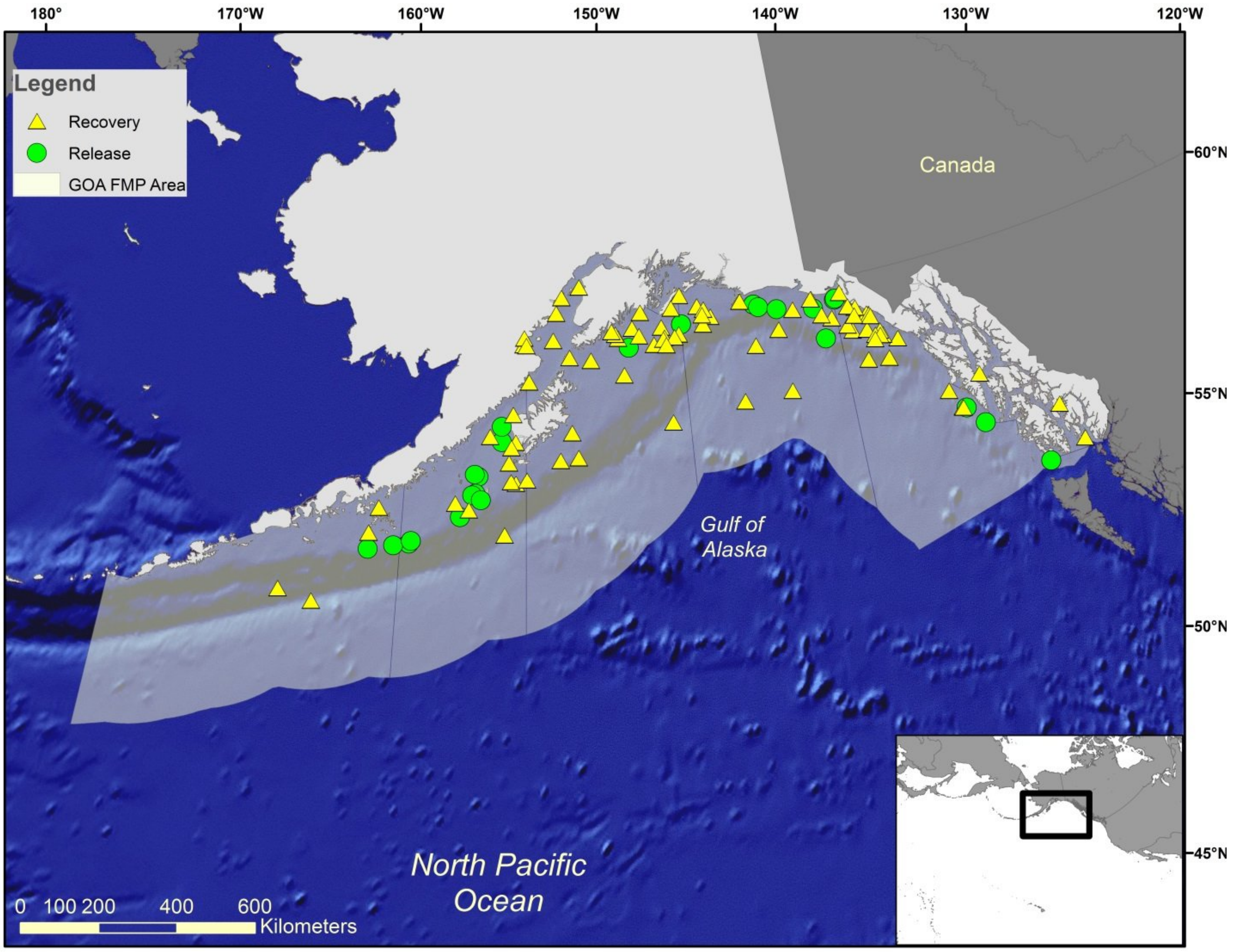

Figure 2. Release and recovery locations for tags in the Gulf of Alaska (GOA) used in this study to estimate bottom trawl availability. The shaded polygon represent the GOA fishery management plan area.

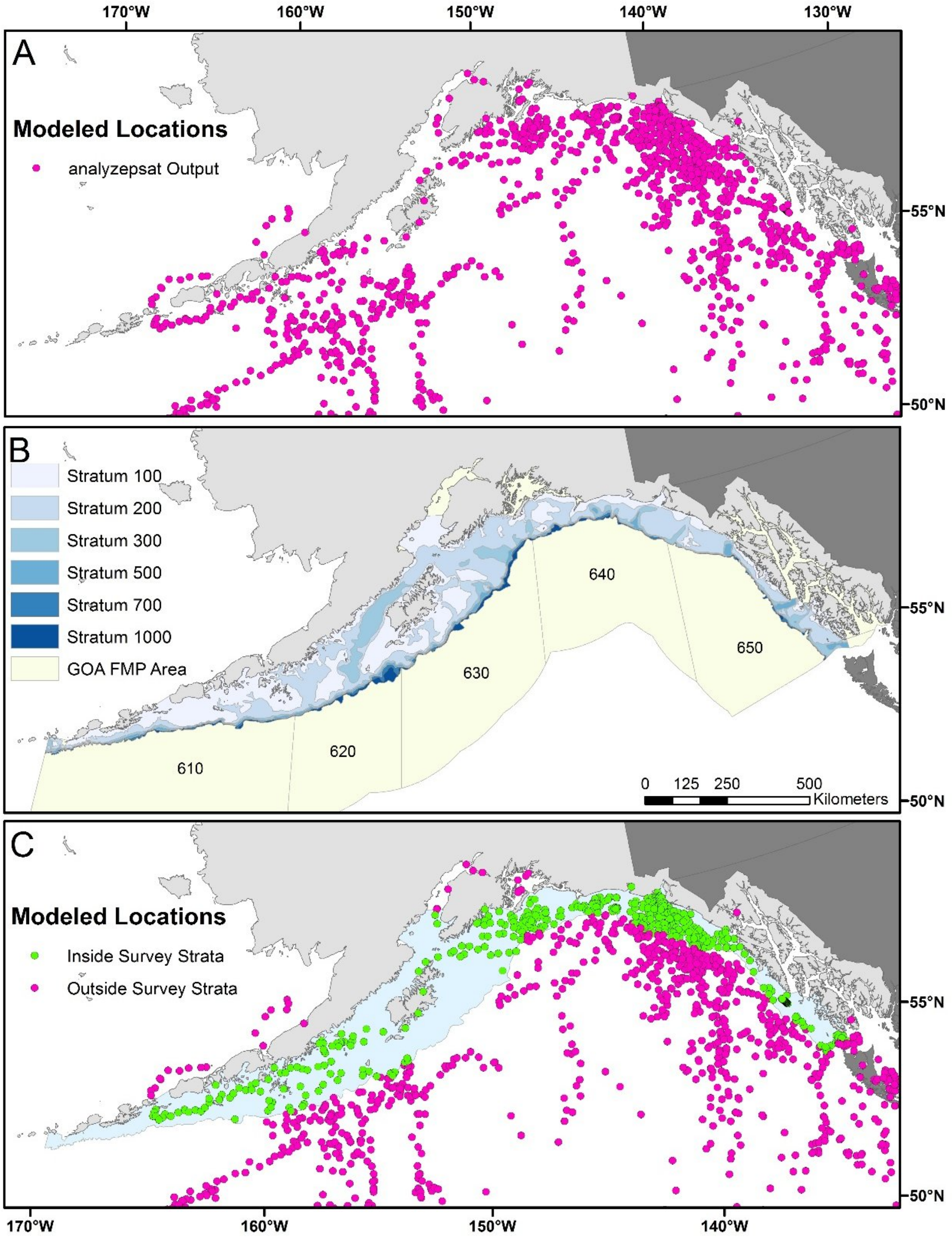

Figure 3. (A) Estimated model locations from the geolocation model, (B) AFSC bottom trawl survey strata (blue shaded) and GOA management areas (green shaded), and (C) color coded locations within the AFSC bottom trawl survey area (green circles) and outside the AFSC bottom trawl survey (pink circles).

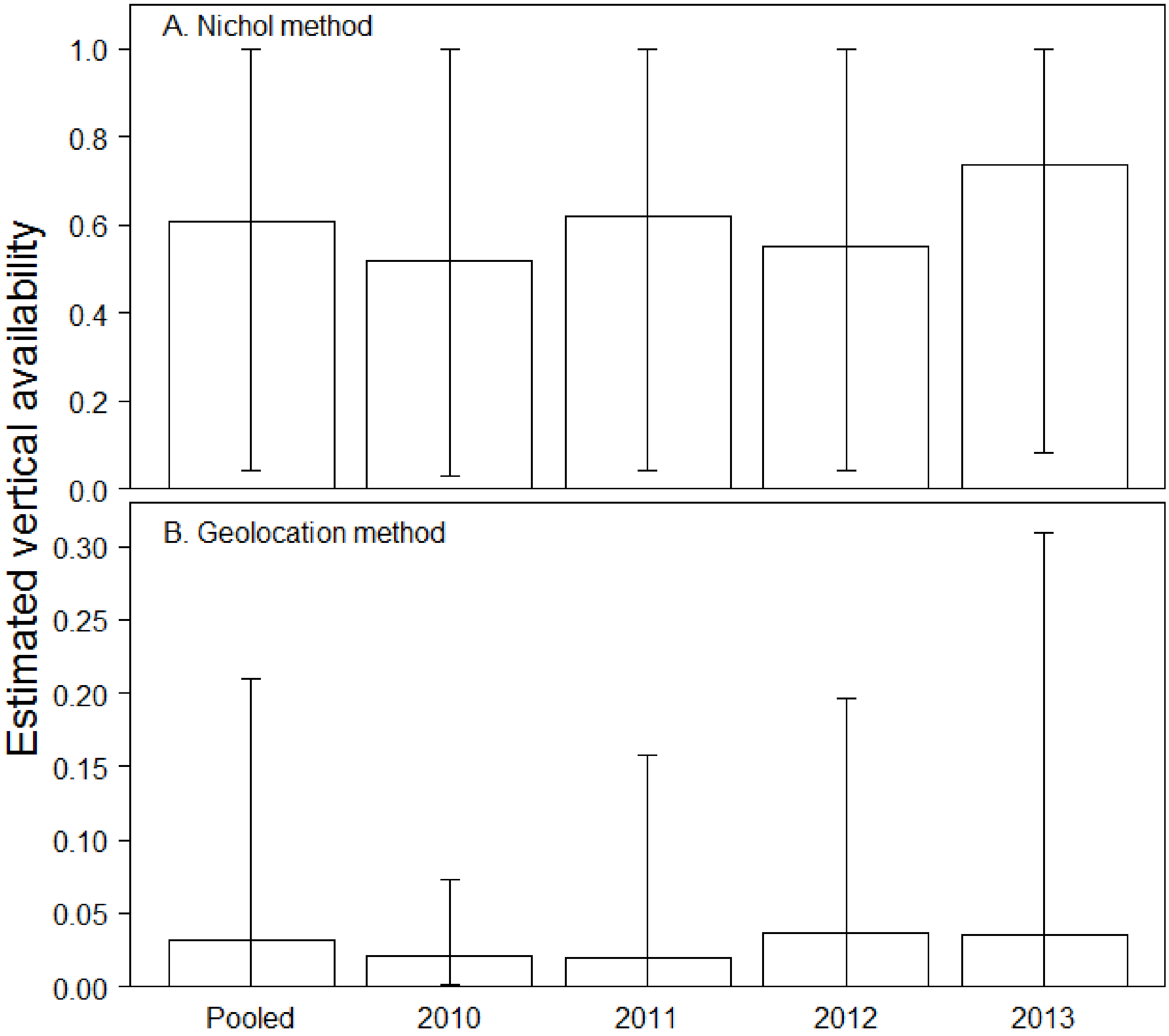

Figure 4. Estimated vertical availability to the AFSC bottom trawl survey in the GOA (i.e., proportion of time within 7 m of the bottom) from the Nichol (A) and geolocation (B) methods with 95% confidence intervals in the daily vertical availability estimates.

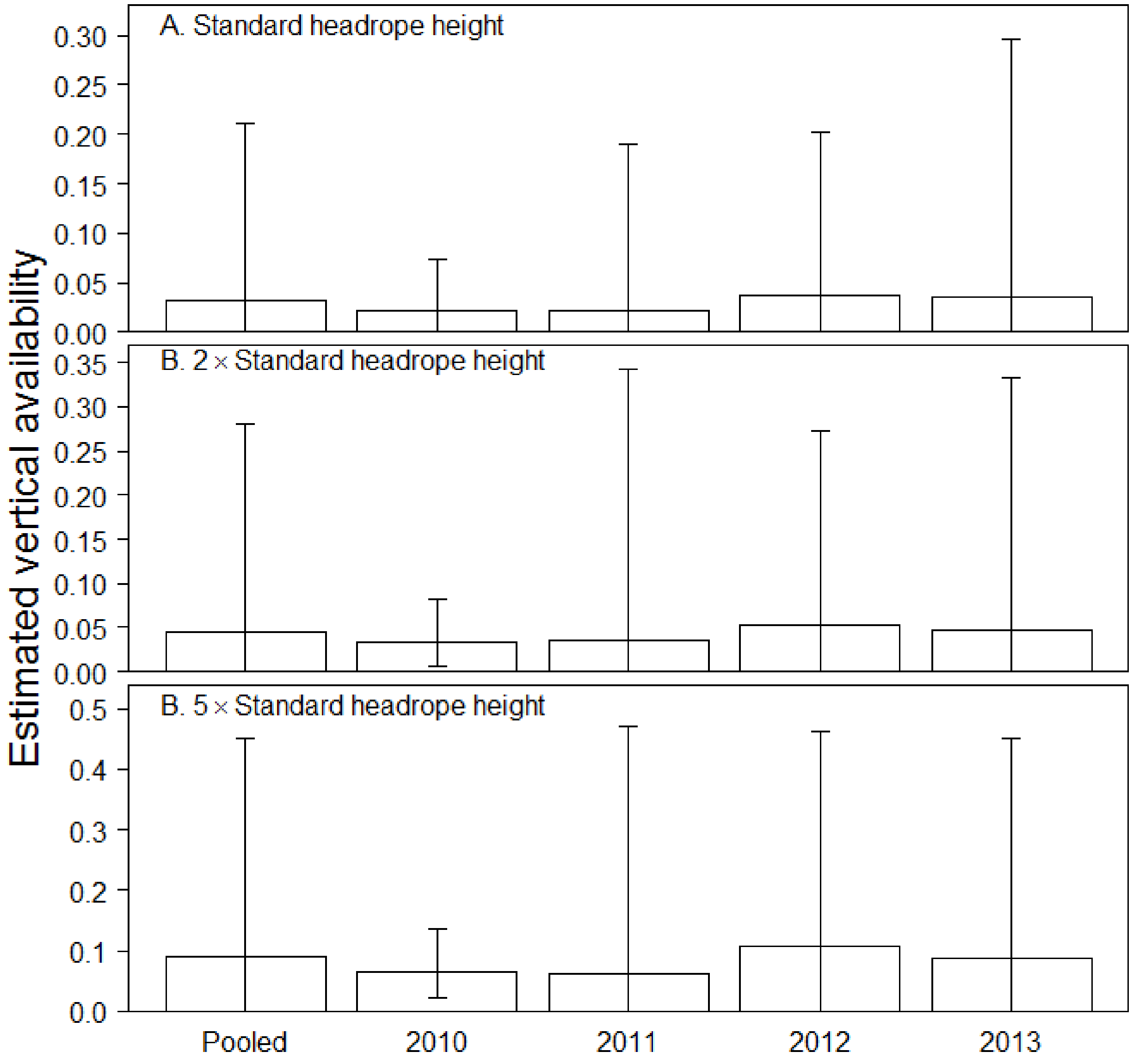

Figure 5. Sensitivity of the estimated vertical availability from the geolocation method to headrope height. (A) Standard headrope height (7 m), (B) twice the standard headrope height (14 m), and (c) five times the standard headrope height (35 m).

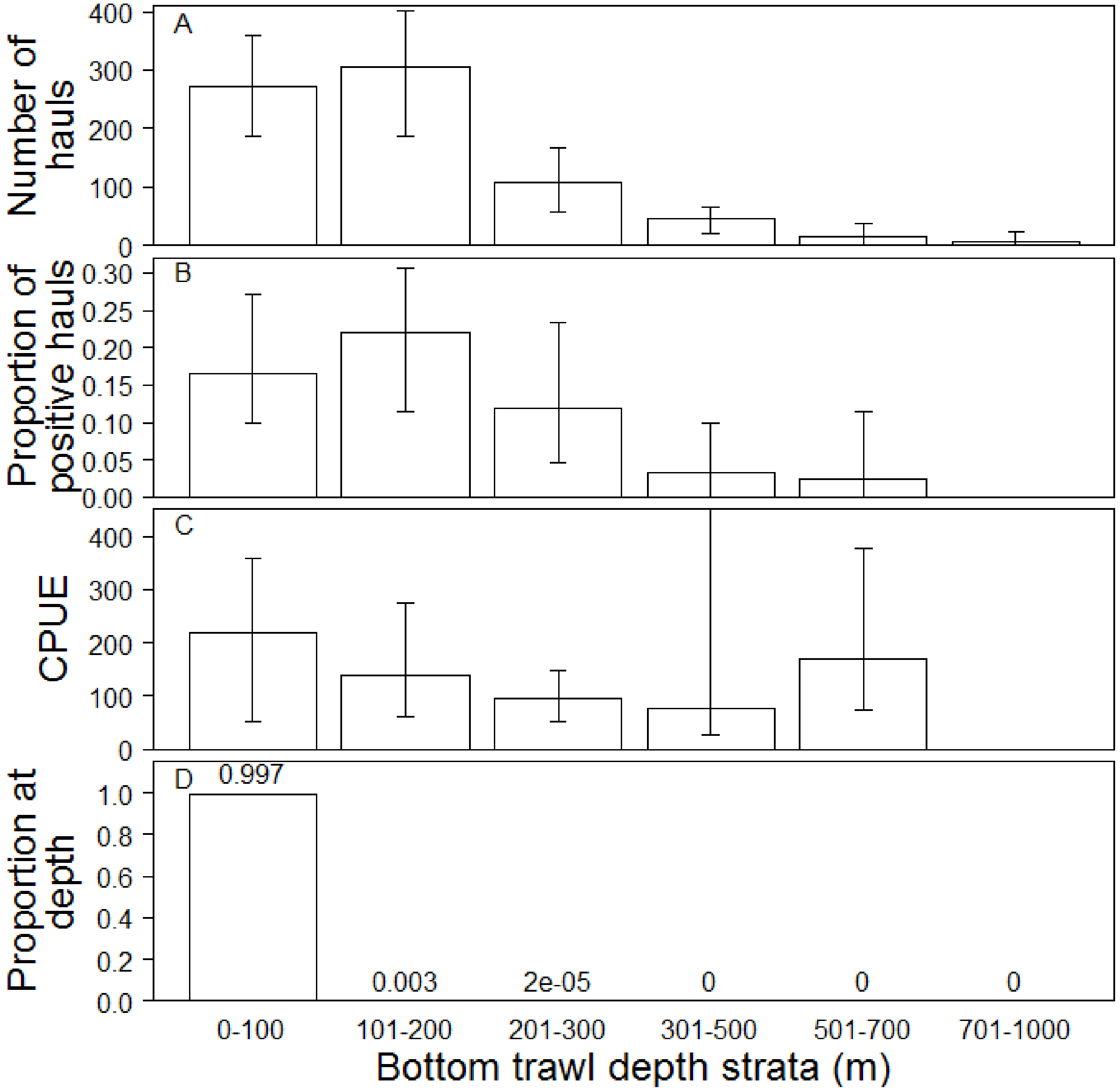

Figure 6. Mean number of hauls in the AFSC bottom trawl survey by depth strata (A), mean proportion of hauls that caught spiny dogfish in the AFSC bottom trawl survey by depth strata (positive hauls, panel B), average catch per unit effort (CPUE, in kg per km^2) of positive hauls by depth strata (C), and proportion of time spent within depth strata from the pop-up satellite tags (during trawl survey operating hours, D).

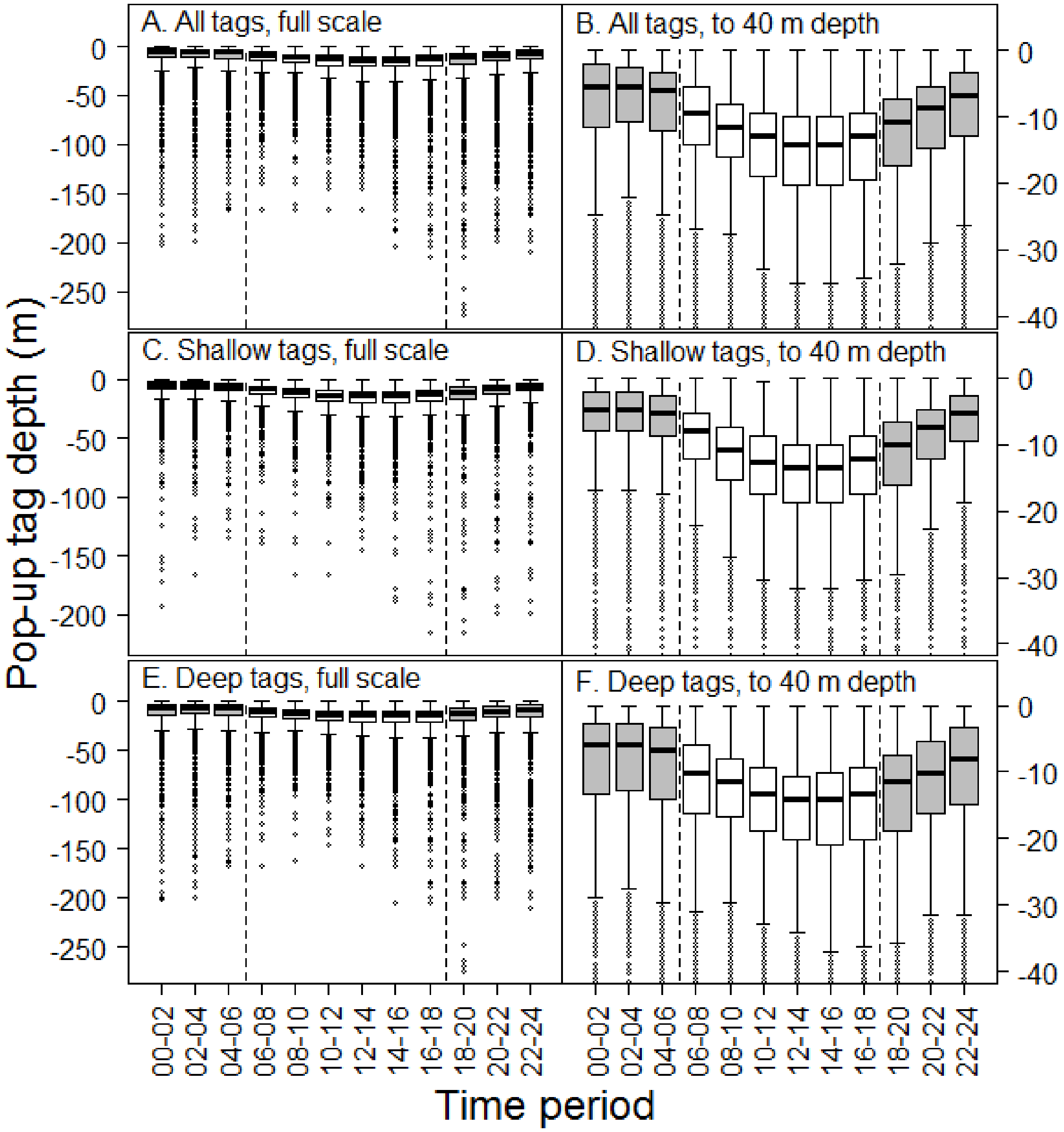

Figure 7. Boxplots of observed pop-up tag depth by time period during a day for all tags pooled (A and B), tags over shallow depths (<350 m, C and D) and tags over deep depths (>350 m, E and F). Time periods during which the AFSC bottom trawl survey operates are shaded in white between the dashed vertical lines.