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Right on target: using data from targeted stocks to reconstruct removals of bycatch species, a case study of longnose skate from Northeast Pacific Ocean

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A R T I C L E I N F O

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A B S T R A C T

Fisheries stock assessments rely heavily on historical catch information to understand how a stock responds to exploitation and make meaningful forecasts under alternative management and environmental scenarios. However, for many bycatch species historical removals are virtually unknown, as a large portion of the catch was discarded at sea. For example, historical discard of elasmobranch species such as skates and sharks have been reported as 95 percent of the total catch based on available data. The longnose skate is one the most abundant groundfishes on the continental slope of the U.S. Pacific Coast by biomass, and the most abundant skate species in the Northeast Pacific Ocean. We developed a method to estimate catch of longnose skate on the U.S. West Coast based on the catch of Dover sole, a co-occurring targeted species with which longnose skate is caught. This method allowed us to reconstruct historical longnose skate catches back to the beginning of the bottom trawl fisheries and improve stock assessment for this species. We also examined the impact of using our method versus other common methods of catch reconstruction to inform stock assessment models, and found that the target-based predictive method produced results that more accurately reflected the life history and typical stock dynamics of elasmobranch taxa. Our method is not limited to the specific case of longnose skate and could be easily adapted for other species and areas.

1. Introduction

Historical catch information is essential for fisheries stock assessment. Without knowing the catch history, it is difficult to understand how a stock responds to exploitation and make meaningful projections under alterative management and environmental scenarios (Hilborn and Walters, 2003; Branch et al., 2011; King, 2013). Throughout history and into current times, commercial fishery catch statistics have primarily consisted of the portion landed in port, originating from landing receipts, filled out by fish dealers or shoreside catch monitors. For highly prized, economically important fish species that are mostly retained, landings statistics can represent the vast majority of the catch and give a fairly accurate depiction of stock exploitation throughout time (Hilborn et al., 2003; Branch et al., 2011). Species that are not highly prized, but caught together with economically important species, are often discarded at sea, since investment in sorting, processing and cold storage may not be rewarded by high enough returns (Alverson et al., 1994; Kelleher, 2004; Pikitch et al., 1988; Punt et al., 2006; Rogers, 1994). For such species, landings statistics often provide a woefully incomplete or misleading picture of stock exploitation, and the history of actual fishery removals for many stocks is virtually unknown (Hammond and Trenkel, 2005; Harrington et al., 2005).

Elasmobranch species such as skates and sharks, have not been highly valued commercially in most areas around the world (King et al., 2017; Gertseva et al., 2019). With the exception of some sharks that were targeted by short but punctuated fisheries (for vitamin-A rich livers and shark fins, for example), elasmobranchs are primarily taken as bycatch in other fisheries (Bargmann, 2009, Gertseva and Taylor 2011, King et al., 2017). Lack of historical information on elasmobranch exploitation makes it challenging to reliably estimate the current status of a stock, describe its past dynamics and ensure long-term sustainable exploitation of these stocks (Compagno, 1990; Manire and Gruber,

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1990; Bonfil, 1994; Rose, 1996). At the same time, life histories of these species are characterized by slow growth, late maturation, low fecundity, and thus low intrinsic rate of increase, making them highly susceptible to overfishing and slow to recover from stock depletion (Smith et al., 1998; Dulvy and Reynolds, 2002; King and McFarlane, 2003; Matson and Gertseva, 2020). Progress in estimating historical catches of elasmobranch species is therefore necessary to enable reliable stock assessment and successful management of these vulnerable species.

Elasmobranch stock assessments have used different approaches to deal with the issue of lack of historical discard information, including assuming only landings to represent stock exploitation (ICES, 2019), and using a single discard rate throughout the time series, or time invariant discard rates applied within large time blocks (Gertseva and Schirripa, 2008). These approaches possess important shortcomings; from underestimating removals if relying only on landings to oversimplification, if applying time invariant discard ratios wholesale across large historical periods. Also, there are shark stock assessments, including the assessment of blue shark (*Prionace glauca*) in the North Pacific Ocean, that use fishing effort data from logbooks along with catch per unit effort estimates, to calculate total removals of the stock (Kai et al., 2014; Kai, 2016). Logbook data however, are often limited to relatively recent years in many regions and fisheries; this is problematic for assessments in which the modeling period spans back to the unfished equilibrium. Even when logbook records are available, reliability of data vary, depending on reporting rate, record details, and other factors (Sampson, 2002), which causes additional challenges.

Over the past several decades, there have been a number of fishery observer programs instituted around the World, in support of stock assessment, fishery management and conservation (King et al., 2015; Gertseva et al., 2019; ICES, 2019). These programs monitor commercial fishing and collect high-resolution data on discarded and retained catch, in order to estimate total fishing mortality. The observer programs' data have made it possible to explore relationships among catch of different species that co-occur and caught together as well as analyze additional information, such as depth, location and fishing gear, and also explore approaches to estimate historical discard of bycatch species. There have been attempts to estimate discard of elasmobranchs using statistical models developed based on observer data, while accounting for location, depth and duration of fishing (King et al., 2015). Such approaches, however, rely heavily on rich fishery information in order to function, which limits estimation of discard to a relatively recent, data-rich period, since historical catch records are commonly lacking additional details associated with catch.

In this paper, we present the method developed to reconstruct historical removals of longnose skate (*Beringraja rhina*) in the Northeast Pacific Ocean, which is a common bycatch species in the groundfish demersal trawl fishery on the West Coast of the United States. Our method relies on known catch records of targeted stocks to predict removals of an associated bycatch species with which it co-occurs, using a statistical relationship developed from data collected by the West Coast Groundfish Observer Program (WCGOP). The method enabled reconstruction of the total catch of longnose skate back to the beginning of the well-established groundfish trawl fishery on the U.S. West Coast. Here we describe the method, present the results and explore implications of using the new method, as well as alternative catch assumptions for stock assessment models. This new method is not limited to the specific case of longnose skate or elasmobranch species but can be adapted for other bycatch stocks lacking historical catch data.

2. Methods

2.1. Description of the species and fishery

Longnose skate is one of the most abundant groundfishes on the continental slope of the U.S. Pacific Coast by biomass (Tolimieri and Levin, 2006; Bizzarro, 2015) and the most abundant skate species in terms of biomass and abundance (Gertseva et al., 2019). It is broadly distributed in the Northeast Pacific Ocean, from the southeastern Bering Sea to southern Baja California and the Gulf of California (Snytko, 1987; Eschmeyer and Herald, 1983; Mecklenburg et al., 2002) but is most common off the U.S. Pacific Coast north of San Francisco at depth between 150 and 400 m (Tolimieri and Levin, 2006; Bizzarro, 2015). It is found mainly on soft (sand, mud) or mixed substrates (e.g., mud and cobble or boulder) (Bizzarro, 2015). This study considers the portion of the population that occurs off the coast of the United States from Southern California to the U.S.-Canadian border (Fig. 1). Having slow growth, late maturity, and low fecundity, longnose skates are classified as equilibrium strategists, who exhibit steady population dynamics over time and are slow to recover if overfished (Smith et al., 1998; King and McFarlane, 2003; Matson and Gertseva, 2020).

The groundfish demersal trawl fishery on the West Coast of the United States is an economically substantial, multispecies fishery with significant catch of numerous target and non-target species (Heery and Cope, 2014). The fishery first started off California in the early 20th century. With development of fishing technology and increased demands for protein food during World War II, the demersal trawl fishery quickly expanded toward Oregon and Washington, and to deeper waters (Harry and Morgan, 1961, Love 2002). By the late-1940s, the extent of effort by latitude and depth in the trawl fishery began to resemble that of the contemporary range.

Historically, skates caught on the U.S. West Coast have not been marketed as high-priced fishery products. Available information suggests that prior to the mid-1990s, processors primarily accepted only the skinned pectoral fins (often called "wings"), and most boats simply discarded skates as they did not want to process them on board since low ex-vessel prices would not justify the effort (Gertseva and Schirripa, 2008). The historical discard study conducted in the mid-1980s (Pikitch et al., 1988) indicated that longnose skate discard during that period was as high as 95 percent of total catch, and marketing problems were indicated as the main reason for the discard (Rogers, 1994). In the mid-1990s however, demand for whole skates increased in California and Oregon, and processors began accepting whole skates for landing; boats started to retain skates if they had space to hold them, which caused a substantial increase in retention rates and landed catch (Gertseva et al., 2019). This change in market is supported by lower skate discard observations from the mid-1990s (Sampson, 2002). After a few years the demand for whole skate decreased, and currently West Coast skates are marketed both whole and as wings, with skate wings sold fresh or fresh-frozen, as well as dried or salted and dehydrated.

2.2. Data sources used

Data on retained (and subsequently landed) catch of fish species caught in commercial fisheries on the West Coast of the United States are available from the Pacific Fisheries Information Network (PacFIN), which is a collaboration between NMFS and West Coast state agencies, that coordinates and manages information on landed catch from processors and port samplers along the U.S. West Coast. For many non-targeted species such as longnose skates, landed catch was historically reported as catch of all skates combined, and longnose skate landings have been reported separately only since 2009. Landings of longnose skate within the combined skate category for the period prior to 2009 have been recently estimated via coordinated efforts between NMFS and U.S. West Coast state agencies. This was accomplished using a combination of survey and fishery data, while accounting for changes in fishing depth over time, as well as interannual variability in the contribution of different skate species to total skate catch (Gertseva et al., 2019).

Recent discard information for the bottom trawl fishery is available from the WCGOP. The program was established in 2001 by NMFS' Northwest Fisheries Science Center (NWFSC). Over the years, it has expanded and currently it provides a widespread observer coverage of

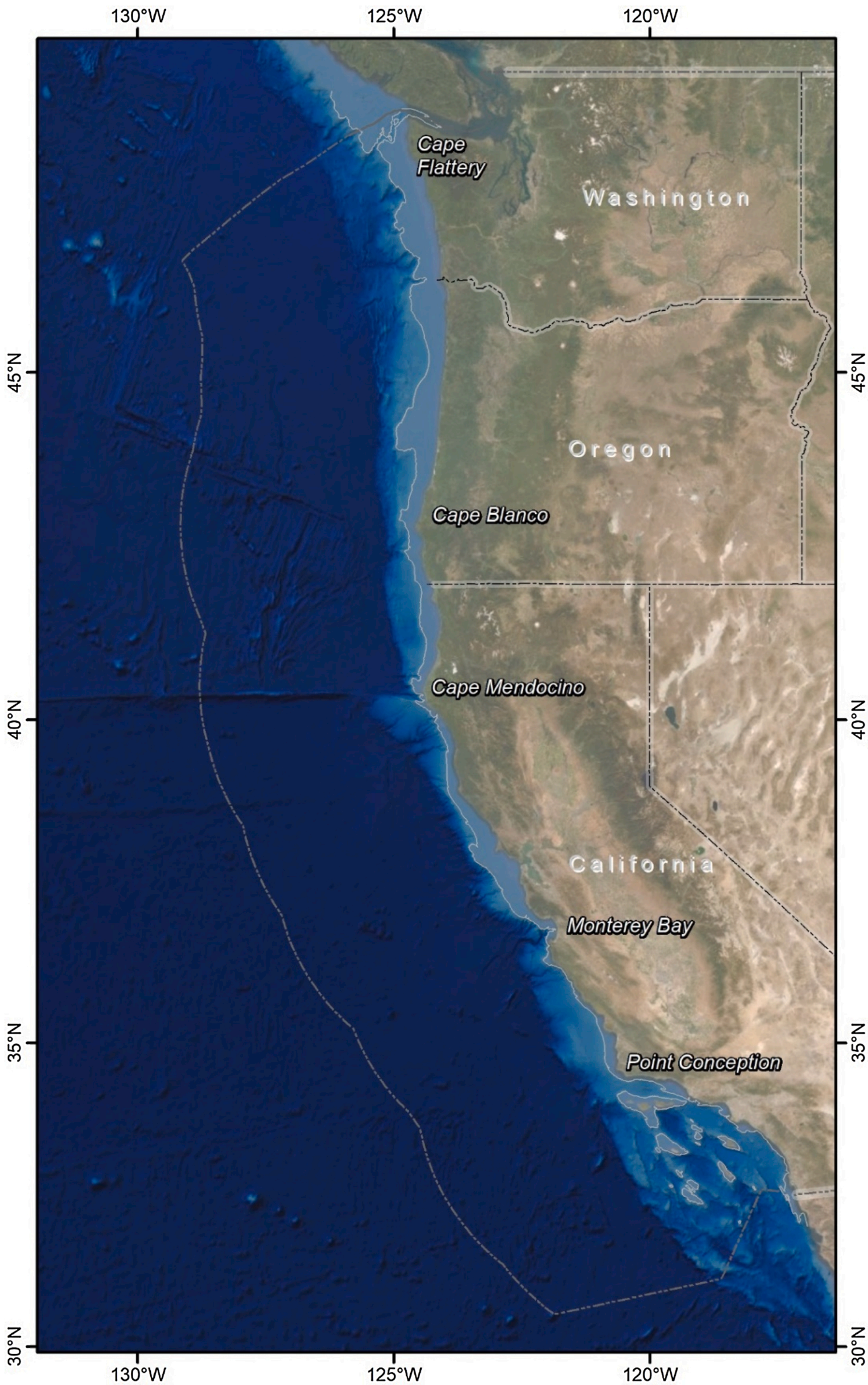

Fig. 1. Map of the area of the Northeast Pacific Ocean along the West Coast of the United States included in the study.

commercial vessels in all groundfish fishery sectors, operating in the U. S. Exclusive Economic Zone. The WCGOP collects haul-specific data on all species caught in commercial groundfish fisheries on the West Coast of the United States, in waters off Washington, Oregon, and California (Fig. 1), which includes discard amounts of groundfish species for observed hauls, along with haul duration, depth, location, gear type, and other details. The haul-specific data also include records of the intended "target" species of each haul as stated by the vessel captain. The WCGOP primarily focuses on the discarded portion of catch, but also collects haul-specific retained catch information. It cooperates with PacFIN to reconcile haul-level retained catch with trip-level fish ticket information in PacFIN and generates year-specific total mortality estimates for each species in commercial groundfish fisheries. These total mortality estimates represent the best available information of fishery removals within groundfish fisheries and are used to evaluate official harvest guidelines.

2.3. Method overview

A process-flow chart which overviews the method used to reconstruct historical longnose skate catch is shown in Fig. 2. Based on haul-specific WCGOP data, we identified several target species and complexes with which longnose skate has been reliably bycaught. Since multiple species co-occur within the same habitat and are caught together in the demersal groundfish fishery, each intended target (as stated by the vessel captain and reported by WCGOP) includes a combination of individual species. Therefore, we first identified target categories within which longnose skate is caught, and then explored the species composition of these target categories, to identify individual species with which longnose skate is consistently caught.

Then, using recent total mortality estimates from 2009 forward (without any assumption about discard survival), we screened several of the thus far qualifying target species for strong relationships with longnose skate catch, and developed statistical models to describe these relationships for the strongest cases. Next, we investigated which of the potential predictor stocks were mostly retained and had the longest and most reliable time series of historical catch records available. We also ensured that historical catch records of predictor species fell within the range of catches used to develop the statistical model to avoid potential extrapolative prediction errors, and that the spatial extent of the fishery for the historical period considered was similar to that of recent fishery data used to develop the statistical model. Finally, we used historical catch time series of predictor species selected to reconstruct historical removals of longnose skate using established relationship and estimated prediction intervals around the year specific predicted values of longnose skate historical catches.

2.4. Method validation

To validate results of our method, we compared the historical discard rates calculated within our study versus discard rates from the historical discard study by Pikitch et al. (1988). Pikitch et al. (1988) is the only historical study which collected species-specific information on retained and discarded catch of longnose skate within the groundfish demersal trawl fishery on the West Coast of the United States. Pikitch et al. (1988) was conducted between 1985 and 1987. The northern and southern boundaries of the study were 48°42′ and 42°60′ North latitude respectively (Pikitch et al., 1988; Rogers and Pikitch, 1992). Participation in the study included vessels using bottom, midwater, and shrimp trawl gears. Observers collected the data from normal fishing operations on commercial fishing vessels, estimated the total weight of the catch by tow and recorded the weight of each species retained or discarded in the sample.

We calculated longnose skate discard amounts between 1985 and 1987 (years when Pikitch et al. (1988) study was conducted) as the difference between total removals estimated from the target species based approach, and longnose skate landings obtained from Gertseva et al. (2019). Year-specific discard ratios were estimated as fractions of discarded catch to total removals. The year-specific discard rates from Pikitch et al. (1988) and uncertainty around those estimates were produced while accounting for species catch composition within observed trips and their geographical location.

3. Results

The distribution of longnose skate catch by year among target categories (further referred to as "targets") as observed by WCGOP between 2009 and 2017 is shown in Fig. 3. This bycatch includes both retained

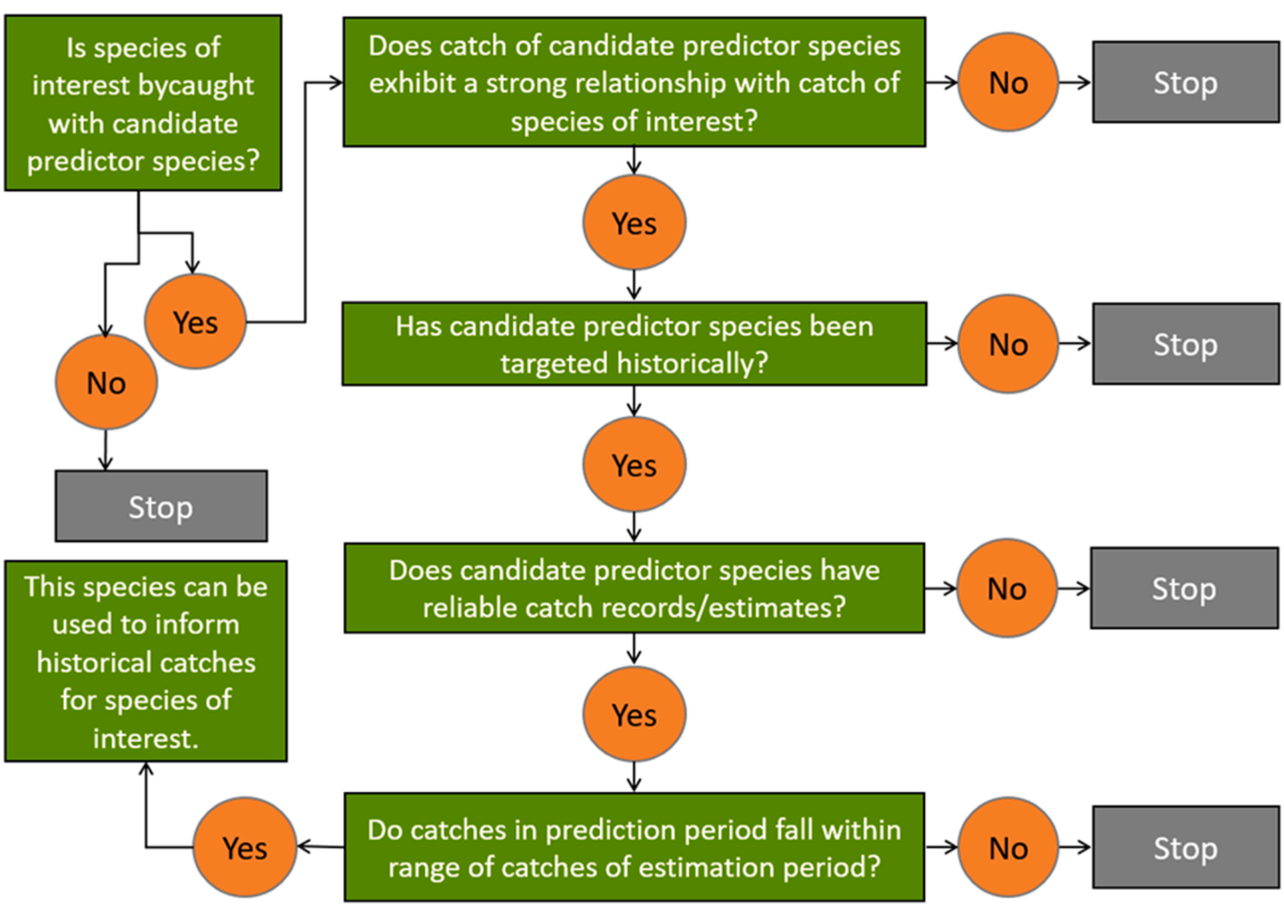

Fig. 2. Process-flow chart, overviewing screening method for reconstructing historical longnose skate catch.

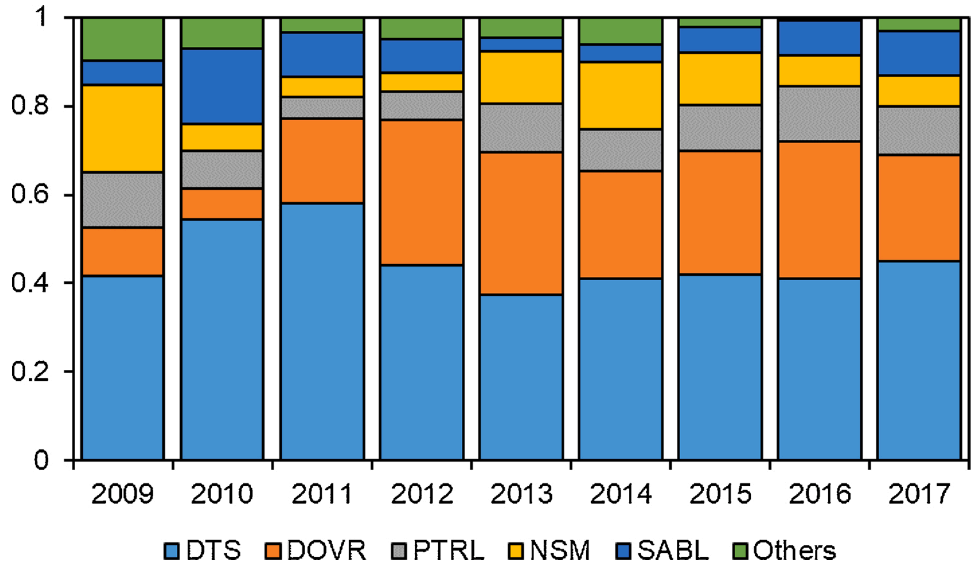

Fig. 3. Proportions of longnose skate catch observed by WCGOP by year, by target (DTS = Dover-Thornyhead-Sablefish complex, DOVR = Dover sole complex, PTRL = Petrale sole complex, NSM = nearshore mix and SABL = sablefish complex, Others = miscellaneous targets in which longnose skate is caught). For example, in any given year of the time series, 40 percent or more of the annual total catch of longnose skate was attributed to hauls in which the declared target was DOVR.

and discarded portions of longnose skate catch with no assumptions made about survival of the discard. More than 96 percent of longnose skate are caught within only a few targets, which include the Dover-Thornyhead-Sablefish (DTS) complex, Dover sole (DOVR) complex, Petrale sole (PTRL) complex, nearshore mix (NSM), and sablefish (SABL) complex. During this 9-year period, 70 percent of longnose skate catch each year was taken within DTS and DOVR, combined, while PTRL, NSM and SABL targets are each associated on average with ten, nine and seven percent of longnose catch, respectively. Only about four percent on average of the total longnose skate catch are caught with the other

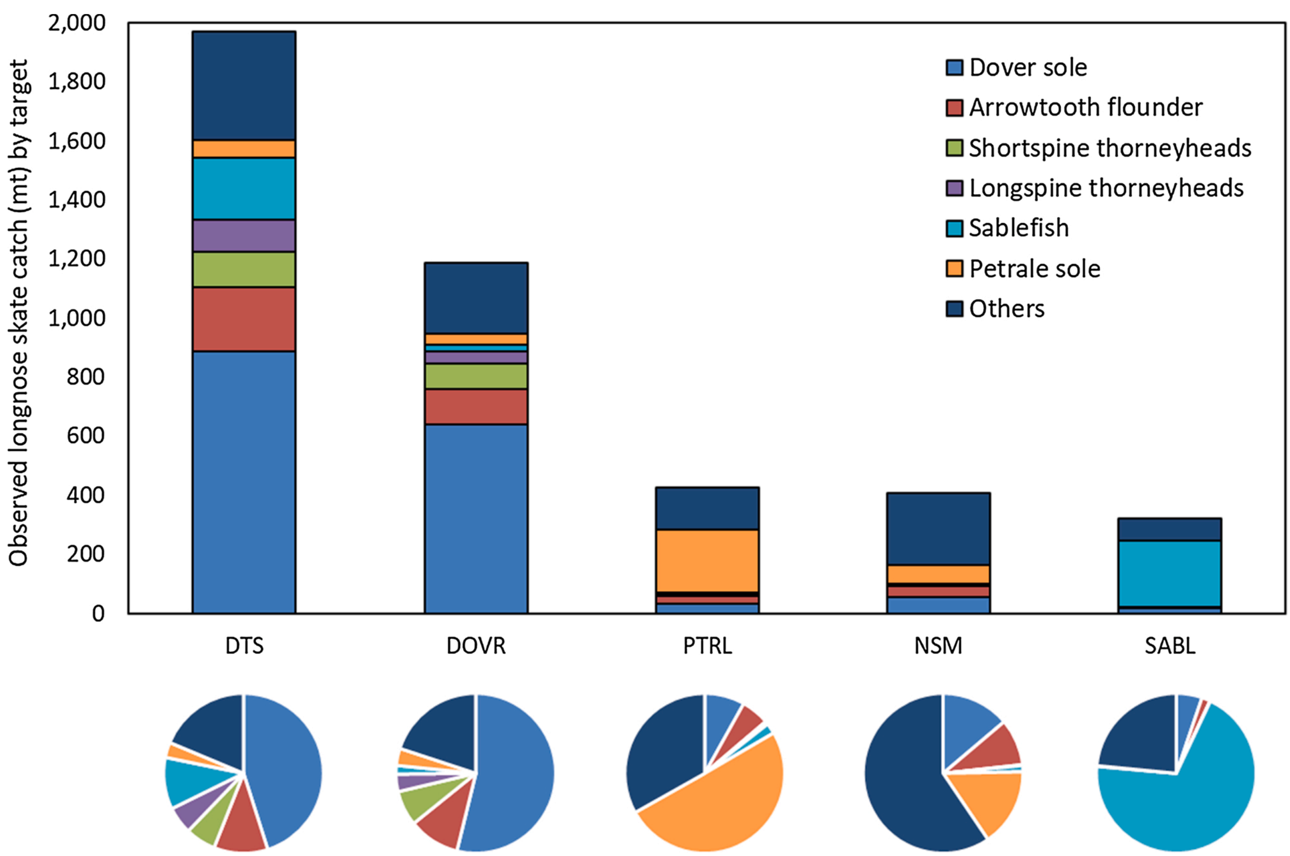

Fig. 4. Longnose skate total catch observed by WCGOP between 2009 and 2017, by declared target (DTS = Dover-Thornyhead-Sablefish complex, DOVR = Dover sole complex, PTRL = Petrale sole complex, NSM = nearshore mix and SABL = sablefish complex). The targets are broken down by the proportion of each species contributing to each target. The total height of the bar shows the catch of longnose skate in metric tons. The different colors within the bar show the species composition of each target, same as each pie underneath.

targets.

The total catch of longnose skate observed by WCGOP in each target category (DTS, DOVR, PTRL, NSM and SABL), with the targets broken down by percentage of species contributing to each target, is shown in Fig. 4. The targets where most longnose skate is caught (DTS and DOVR) are dominated by Dover sole, a shelf-slope flatfish species, which spatial distribution extends to over 1000 m offshore, and also include Arrowtooth flounder, longspine and shortspine thornyheads, sablefish as well as Petrale sole. The other targets that longnose skate is caught with include the same species (Dover sole, arrowtooth flounder, thornyheads, sablefish, Petrale sole) but in different proportions (Fig. 4). Survey observations also show that distributions of these six species over the range of U.S. West Coast substantially overlap with longnose skate distribution, as shown in Fig. 5, and we explored these species as potential candidates for estimating the total catch of longnose skate and predicting its historical removals.

A matrix of scatter plots illustrating relationships in annual total catch among potential target predictor species, versus longnose skate, is shown in Fig. 6. Longnose skate, Dover sole, arrowtooth flounder, thornyheads, and petrale sole are primarily caught by trawl gear. Sablefish on the other hand, is mostly taken with pots, and hook-and-line gear. For sablefish we used only the trawl caught portion to explore association with longnose skate catch. All candidate predictor species (except for Petrale sole) exhibit a linear relationship of varying strength with catch of longnose skate. Pearson's correlation values are shown, together with scatter plots and linear trend lines in Fig. 6 for each pair of species. The strongest relationship is observed between catch of Dover sole and longnose skate catch, with excellent predictive power (R^2 = 0.957) over the range of the Dover sole catches of 6500 to 12,500 metric tons. Shortspine and longspine thornyheads, arrowtooth flounder catches as well as trawl catches of sablefish also exhibited strong relationships with longnose skate catch, with slightly lower predictive power (Fig. 6). The weakest relationship was observed between catch of Petrale sole and longnose skate.

Based on the method overview diagram in Fig. 2, in addition to having a strong relationship with longnose skate catch, the predictor species needs to be targeted historically, so that the majority of its catch would be retained, maximizing reliability of historical catch records. Dover sole has been consistently targeted since 1950, and records of Dover sole landings are available from a variety of fishery sources (Hicks and Wetzel, 2011). The species has been mostly retained throughout history; discard rates have been minimal and stable, around 10 percent of total catch per year (Hicks and Wetzel, 2011). Therefore, Dover sole historical catch time series are considered quite reliable, which makes them suitable for predicting bycatch of longnose skate back to 1950. Unlike Dover sole, the market for arrowtooth flounder has been fairly limited throughout the history of demersal trawl fishery due to low flesh quality, and therefore this species was frequently discarded, likely at varying rates. Since discard rates of arrowtooth flounder have not been observed until recently, historical removals of this species are largely uncertain, and therefore cannot be used to reliable predict historical catch of another species (Kaplan and Helser, 2007). Landings of longspine and shortspine thornyheads have been reliable only in the last few decades. The first significant market for thornyheads began in northern California in the early 1960s. The fishery for thornyheads increased gradually during the 1960s and 1970s, but did not expand significantly until the late 1980s with the development of a market for smaller thornyheads. Initially, thornyheads were sold with other rockfish under a variety of names (Stephens et al., 2013; Taylor and Stephens, 2013). Even when separated from other species, landings of both thornyhead species were reported together until the mid-1980s (Karnowski et al., 2014). Historical discard rates for both species greatly varied from year to year, depending on the market. For example, longspine thornyhead discard rates have been estimated from as high as 46 percent to as low as 20 percent a year (Stephens et al., 2013). Therefore, neither longspine nor shortspine thornyheads would be a good choice for predicting historical longnose skate bycatch. Finally, catches of sablefish were primarily harvested by hook-and-line fisheries until the end of the 1960s

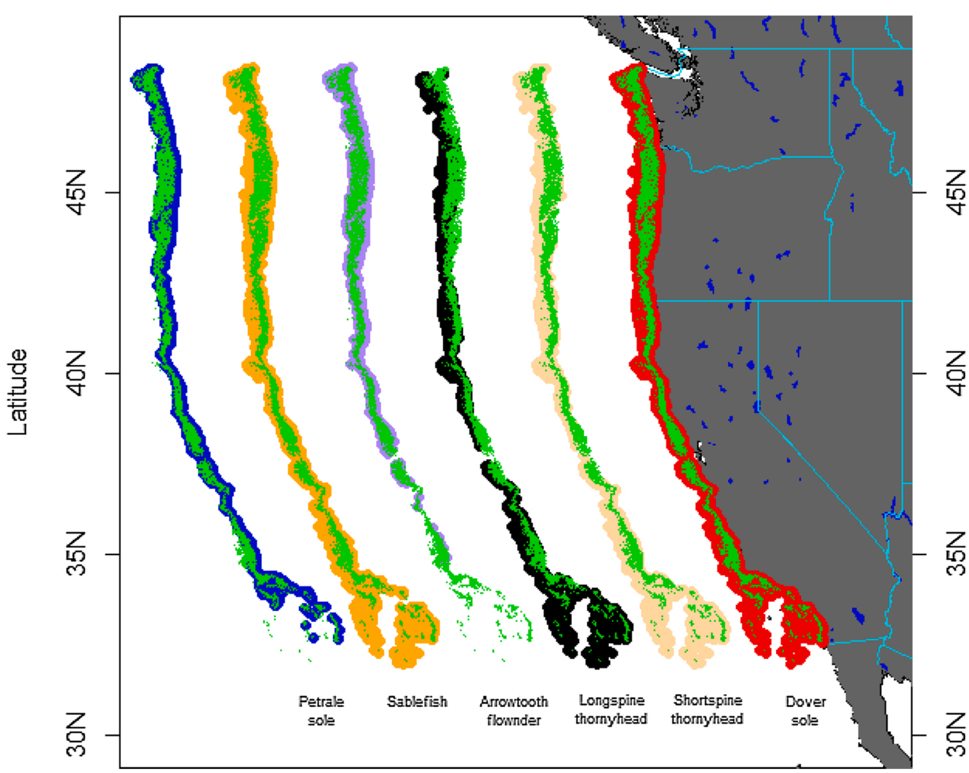

Fig. 5. Survey distribution of Longnose skate (bright green) along the coast of Washington, Oregon and California, overlain upon distribution of Dover sole (red, along the coastline); then from the far left: Petrale sole (blue), Sablefish (orange), Arrowtooth flounder (lavender), Longspine thornyhead (black), and Shortspine thornyhead (peach).

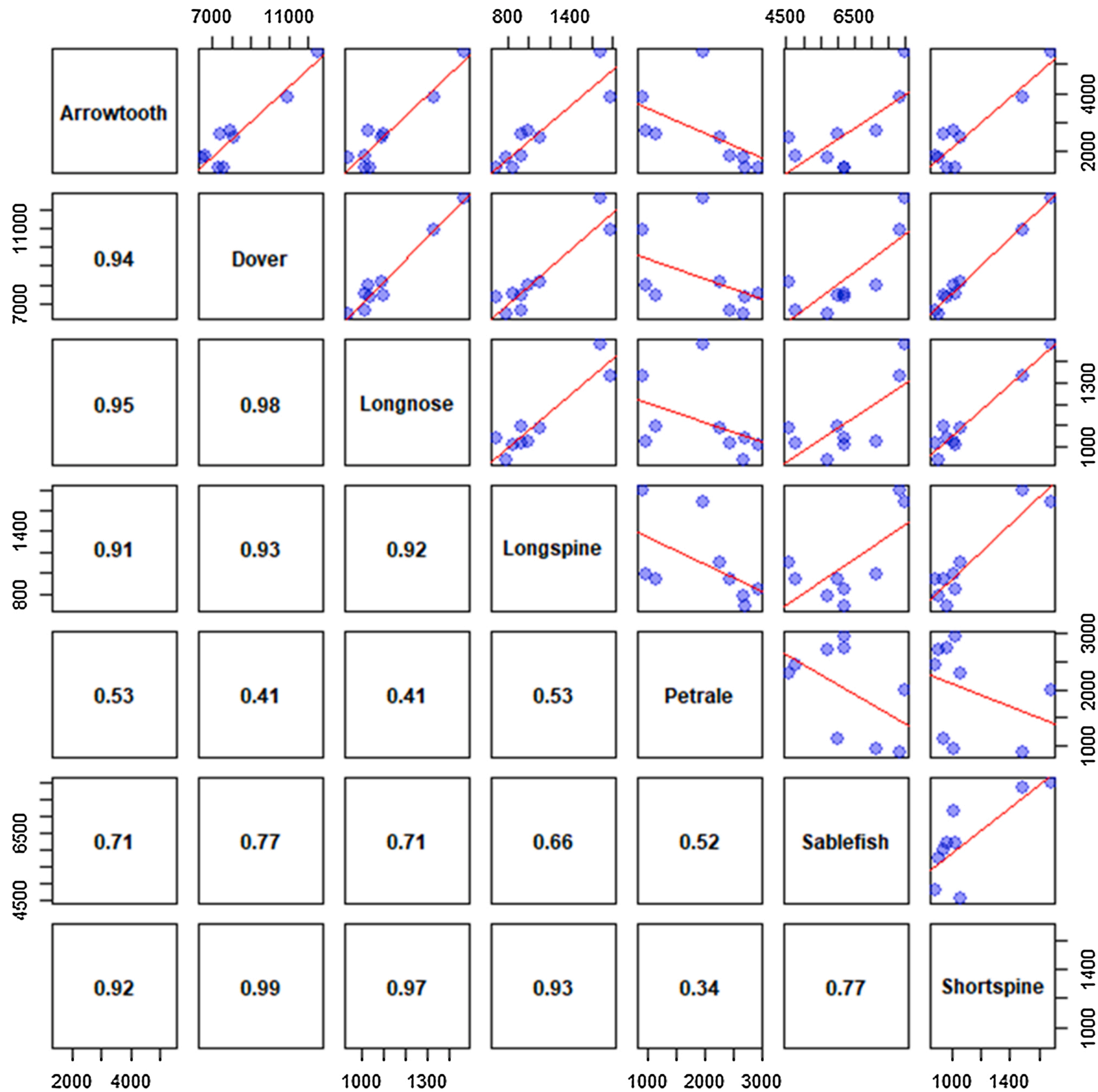

Fig. 6. Matrix of scatter plots illustrating relationships in annual total catch (mt), among potential target predictor species, from observer data, 2009-2017. Pearson's correlation coefficients appear in the lower panels, and scatterplots with linear trendlines (red) in the upper panels.

(Stewart et al., 2011), and historical prediction of longnose skate based on trawl catches of sablefish would be limited to more recent period only. Thus, of six candidate predictor species, which total catches exhibit strong relationships with catches of longnose skate, only Dover sole combines exclusive targeting by trawl gear, reliable landings records of sufficient duration, and stable discards rates that provide the ideal basis for predicting historical bycatch of longnose skate.

Catch time series of Dover sole were most recently compiled by Hicks and Wetzel (2011). In this study, we used catches for the period between 1950 and 2008, since the Dover sole fishery was well established and operated within the same depth and latitudinal ranges as current fishery (data from which were used to estimate the relationship between catch of two species) until the time when total catch of longnose skate become available from WCGOP. Dover sole catches within this period fall within the range of catches used to develop a relationship between Dover sole and longnose skate catches.

We used a generalized linear model (GLM), with a Gaussian family, to predict bycatch of longnose skate according to the relationship between Dover sole and longnose skate, and estimated accompanying 95 percent prediction intervals. Predicted longnose skate catches with 95 percent prediction intervals are shown in Fig. 7. A linear relationship was estimated with a $p(>|t|)$ value for the slope of 4.62×10^{-6}, and for the intercept of 0.000151. The R^2 value was 0.9577, calculated as 1-(deviance/null deviance), equal to simply the R^2 in the standard linear model (lm) in R. The model passed diagnostic tests for outliers, non-constant variance score, Durbin-Watson test for autocorrelation at multiple lags, and a global test of model assumptions (gvlma in R), including a global statistic, skewness, kurtosis, link function and heteroscedasticity (decision table reported "assumptions acceptable" for all), all with non-significant p-values ($p >> 0.05$). Predicted estimates and 95 percent confidence intervals were produced using the predict function in R.

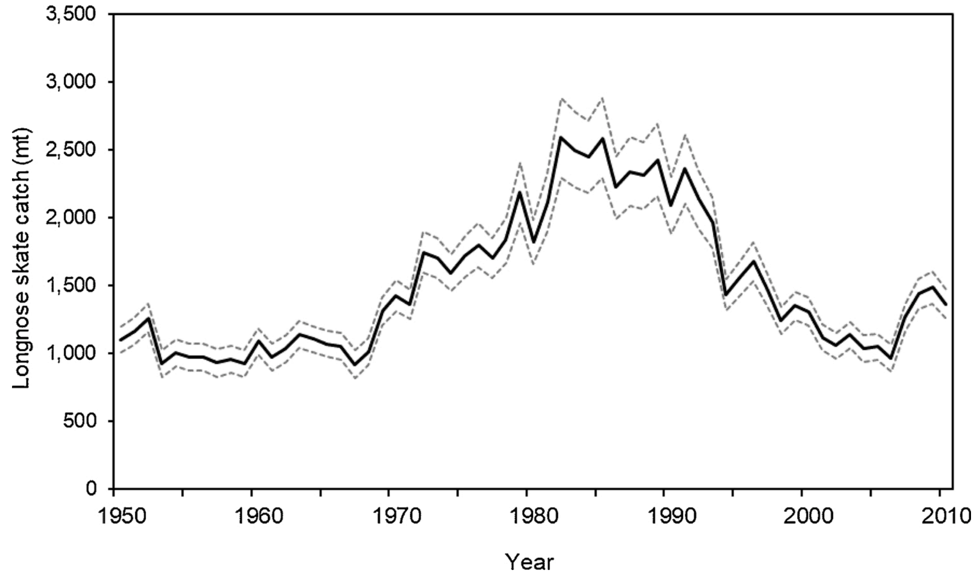

Fig. 7. Estimated total catch of longnose skate, based on Dover sole catches (solid line), with 95 percent prediction intervals (dashed lines).

3.1. Method validation

Only limited data are available on historical discard rates of longnose skate off the West Coast of the United States, which we can use to compare with values predicted by our approach and validate our method. The comparison between longnose skate historical discard rates observed within Pikich et al. (1988) and calculated using estimated catches within this study is shown in Fig. 8. The discard rates observed by Pikitch et al. (1988) are almost identical to discard rates estimated using target species based the approach presented here, with both sources indicating discard rates between 1985 and 1987 being between 95 and 99 percent of total catch, values supported by the available information about historical skate market (described earlier). Error bars on discard ratios calculated using Dover sole catch estimates only reflect prediction intervals from the linear model (Fig. 7), and not from other potential sources. Fig. 9 shows the entire time series of our estimated removals along with longnose skate landings obtained from Gertseva et al. (2019), and illustrates that our estimates are also consistent with market driven increase in skate retention observed in the mid-1990s (Sampson, 2002).

4. Discussion

Reconstructing historical removals is one of the main challenges for stock assessments of bycatch species, such as elasmobranchs, for which catch is mostly discarded at sea (King et al., 2015; Gertseva et al., 2019; Taylor et al., 2019). Improving catch estimates is therefore an important management priority, addressing which could markedly improve assessments of many fishery stocks. Recently instituted fisheries observer programs provide high quality data on discarded and retained catch and make it possible to explore relationships among catch of species that co-occur and are caught together, and predict historical removals of bycatch species from documented catch of targets stocks. We developed an approach that outlines necessary screening steps, and predicts historical removals of bycatch stocks from target stocks (Fig. 2); and we used this approach to predict historical removals of longnose skate in the

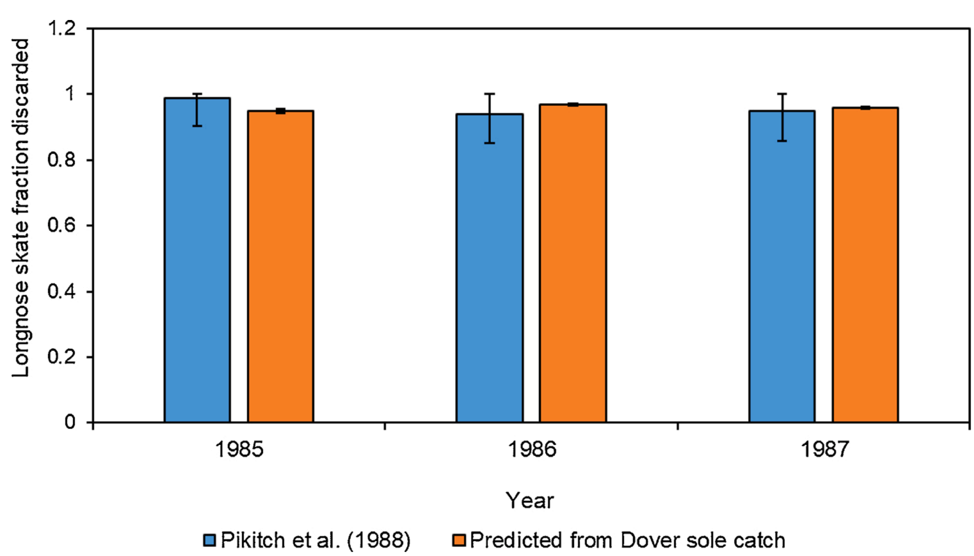

Fig. 8. Predicted longnose skate discard rates, compared with discard rates calculated from actual catch observed in the Pikitch study, conducted between 1985 and 1987 (observer-based, longnose skate-specific estimates). Error bars on catch estimates predicted from Dover sole catch only reflect prediction intervals from the linear model, and not from other potential sources.

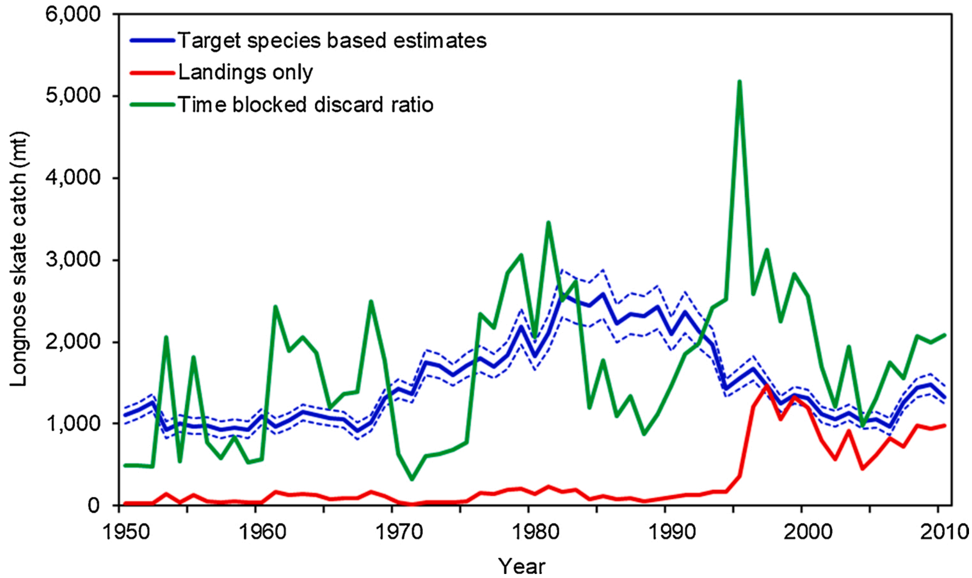

Fig. 9. Comparison of reconstructed longnose skate catch among methods; using target species based predictive method (blue, dashed 95 percent confidence intervals), landings only assumption (red), and time blocked discard ratio (green).

Northeast Pacific Ocean back to the beginning of a well-established groundfish trawl fishery on the West Coast of the United States.

We identified six species that longnose skate is consistently caught with, which included Dover sole, shortspine and longspine thornyheads, arrowtooth flounder, sablefish and Petrale sole. Heery and Cope (2014) and Cope and Haltuch (2012) used a variety of cluster techniques to analyze WGGOP database as well as data from research surveys on the U.S. West Coast also found that longnose skate cluster together with Dover sole, arrowtooth flounder, shortspine thornyheads, and sablefish. The species that longnose skate is consistently caught with share the same habitat preferences, and their distributions over the range of U.S. West Coast substantially overlap with longnose skate distribution. Fig. 5 illustrates survey distribution of longnose skate along the coast of Washington, Oregon, and California, overlain upon that of Dover sole, shortspine thornyhead, longspine thornyhead, arrowtooth flounder, sablefish, and Petrale sole, showing varying degrees of overlap in distribution of longnose skate with other candidate species. Longnose skate shows an especially high degree of overlap with Dover sole, a dominant flatfish species on the continental shelf. Although several other candidates, for instance sablefish, show nearly as high a degree of overlap visually, Dover sole showed the strongest statistical relationship with catch of longnose skate in the fishery, and had the necessary long history of catch records available to support making historical catch predictions using relationships estimated from relatively recent observer data. The weakest relationship was observed between catch of Petrale sole and longnose skate. This is not surprising, because unlike other candidate species, Petrale sole shows a distinct spawning migration pattern between shelf and slope; during summer months it stays in shallower waters to feed, but during the winter it travels to spawn at several discrete deep water sites (Hart, 1988; Love, 1996). Petrale sole fishing effort shows a seasonal pattern while following the migrating fish, which makes it deviate from larger aggregate fishery patterns, targeting other groundfish species.

The predicted catch of longnose skate is consistent with what we know about progression of the bottom trawl fishery on the U.S. West Coast, with catches growing through the 1980s and 1990s and then generally decreasing since 2000 with the implementation of increasing management restrictions coinciding with rockfish stock depletion and area closures (Love et al., 2002). In the last decade, groundfish catches started to grow again, following successful rebuilding of several Pacific rockfish. Predicted catches are also consistent with the biology of longnose skate, a slow growing, late maturing and low productive organisms (King and McFarlane, 2003; Matson and Gertseva, 2020), for which we do not anticipate high punctuated recruitment events that would be translated into large peaks in fishery catches.

The reconstructed time series shows narrow estimated prediction intervals (Fig. 6) due to the very tight relationship between catch of Dover sole and longnose skate catch (Fig.5). These intervals however, cannot account for all potential sources of uncertainty; for example, uncertainty in historical landings records or discard rates of Dover sole. Despite this, our approach is a substantial advancement compared with commonly used assumptions regarding catch histories previously used for this species, and other elasmobranchs elsewhere.

Given the lack of historical estimates for elasmobranch species, it has been common practice to either to assume landings to represent historical stock exploitation (ICES, 2019), or to apply a single discard rate (calculated from limited historical data and anecdotal evidence) throughout the time series to account for discards (Gertseva and Schirripa, 2008, Gertseva 2009). In Fig. 9, we plotted our estimated catches of longnose skate from the target stock based approach along with landings from Gertseva et al. (2019) and catches calculated while using time invariant bycatch ratios within two large time blocks, as used in Gertseva and Schirripa (2008). For the last scenario, a 95 percent discard ratio is assumed prior to 1996, based on Pikitch et al. (1988) and 50 percent discard rate from 1996 forward (Sampson, 2002), to reflect known changes in the periodic skate fishery. It is evident that a scenario when only landings represent the total catch grossly underestimates removals, which is particularly hazardous in its resulting effects on estimates of stock status, as elasmobranch species are known to be highly susceptible to overfishing and slow to recover from stock depletion. The scenario in which total catch is estimated using a single discard ratio across large blocks results in a chaotic and unrealistic inflation of total catch with slight increases in landings, which is not representative for an equilibrium species such as longnose skate (Matson and Gertseva, 2020) and not consistent with the general degree of stability in trawl effort, from one year to the next.

4.1. *Implications for stock assessment*

To further illustrate the importance of estimating fishery removals reliably, we explored the effect of different assumptions about catch histories shown in Fig. 8 upon dynamics of the fishery stock and estimation of its stock status. To accomplish this, we used the most recent stock assessment model of longnose skate on the West Coast of the United States (Gertseva et al., 2019), developed using the Stock Synthesis modeling framework that has been applied in a wide variety of fish assessments globally (Methot and Wetzel, 2013). This assessment is currently used to inform management measures and harvest specifications of this stock on the U.S. West Coast. We ran the assessment model assuming different scenarios of catches, including our target species based catch estimates, longnose skate landings only, and applying time blocked discard rates, with a single ratio being used for the period before 1996 and a second ratio for the period from 1996 forward. For all the discarded portion of the catch, we assumed 50 percent survival, the assumption used in the longnose skate stock assessment (Gertseva et al., 2019). Fig. 10 shows time series of relative spawning stock biomass ($\frac{SSB_t}{SSB_0}$), as the ratio of the stock size in each year (SSB_t) relative to unfished state (SSB_0) with these three model runs. Fig. 10 also shows management reference points used for the longnose skate stock on the West Coast of the U.S. by the Pacific Fishery Mangement Council that include an overfished threshold equal to 25 percent of SSB_0 and management target equivalent to 40 percent of SSB_0, the latter is used as a proxy measure of B_{MSY} for most groundfish on the West Coast of the united States. The model run with landings representing the entire catch resulted in the stock being estimated to stay stable and near the unfished stock size until the mid-1990s when landings were minimal and vast majority of the catch was discarded. After 1996, with an increase in landings the stock began exhibiting a gradual decline. As a result of lighter exploitation under the landings-only scenario, the estimated stock size relative to unfished state throughout the time series was substantially higher than the other two scenarios. In the model run for the scenario in which total catch is calculated through application of a longnose discard-to-landed-catch rate, which is blocked within two discrete time periods, stock status exhibited a more dynamic trajectory. This variability reflects the peaks and valleys in removals resulting from unrealistic sensitivity of estimated total catch to slight changes in landings. This scenario resulted in a more depleted stock, and its dynamics reflected the higher removals and inability of a low productivity stock to quickly recover from punctuated large catches. Although under all scenarios, the stock remained above the management target and threshold, the scenarios produced substantially different pictures of past stock dynamics as well as understanding of its current status. Estimates of current status are translated into different management specifications and catch limits, which impacts both the current fishing industry and prospects of achieving the sustainability of fishery resources.

There is most likely uncertainty associated with our estimates of longnose skate catch, beyond the prediction intervals calculated from the statistical relationship between catch of target and bycatch species. This uncertainty can be explored in stock assessments in multiple ways. First, thorough sensitivity testing should be conducted to evaluate how sensitive the assessment model output is to varying degrees of deviations from assumed fishery removals time series. Also, modeling frameworks, such as Stock Synthesis used for longnose skate assessment model, are gradually progressing in developing options to incorporate uncertainty associated with fishery catches into the assessment model, one of them is through estimating additional parameters that allow adjustment to the catch over a variety of time blocks within the assessment model. The

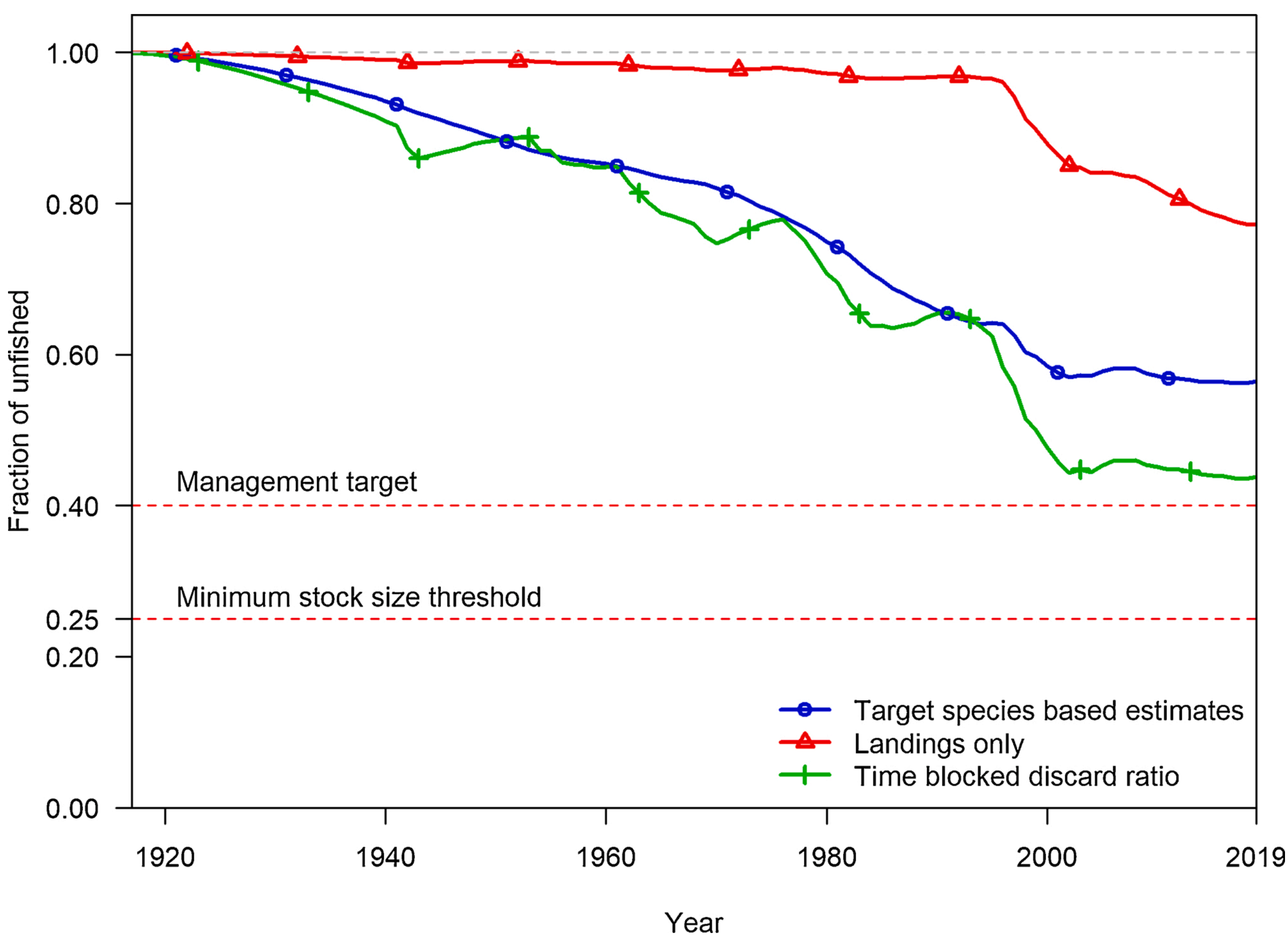

Fig. 10. Comparison of assessment model results, as relative stock depletion (relative to unfished biomass) using three different time series of reconstructed historical catch, illustrating the functional importance or accurate catch reconstruction to inform stock assessment; target species based model predicted estimate (blue), landings only (red), and time blocked ratio-based estimator (green).

further development and exploration of these new modeling options would help address uncertainty in historical catches.

In conclusion, we developed a method that enables reconstruction of historical removals of a bycatch stock based on records of target species removals, applying it to the case of the longnose skate stock in the Northeast Pacific Ocean, on the West Coast of the United States. This approach is a substantial advancement versus commonly used assumptions about catch histories previously used for this species, as well as elasmobranchs elsewhere. Our results benefited from validation with available historical observations of skate discard. Our approach is particularly valuable because it leverages high resolution, recent-era fishery data to identify a reliable predictor species and empower historical data that would otherwise go underutilized, to dramatically improve accuracy of current stock assessment. Although motivated by the case study of longnose skate, the method presented here is not inherently limited to a particular species or elasmobranch taxon, but can be easily adapted for other species and areas around the World.

Declaration of Competing Interest

None.

References

Alverson, D.L., Freeberg, M.H., Murawski, S.A., Pope, J.G., 1994. A Global Assessment of Fisheries Bycatch and Discards, Vol. 339. Food and Agriculture Organization, Rome.

Bargmann, G.G., 2009. A history of the fisheries for spiny dogfish along the pacific Coast from California to Washington. In: Gallucci, V.F., McFarlane, G.A., Bargmann, G.G. (Eds.), Biology and Management of Dogfish Sharks. American Fisheries Society, pp. 287–297.

Bizzarro, J.J., 2015. Comparative Resource Utilization of Eastern North Pacific Skates (*Rajiformes: Rajidae*) with Applications for Ecosystem–based Fisheries Management. Ph.D. Dissertation. University of Washington, Seattle, WA.

Bonfil, R., 1994. Overview of World Elasmobranch Fisheries, Vol. 341. Food and Agriculture Organization, Rome.

Branch, T.A., Jensen, O.P., Ricard, D., Ye, Y., Hilborn, R.A.Y., 2011. Contrasting global trends in marine fishery status obtained from catches and from stock assessments. Conserv. Biol. 25 (4), 777–786.

Compagno, L.J.V., 1990. Shark exploitation and conservation. In: Pratt, H.L., Gruber, S. H., Taniuchi, T. (Eds.), Elasmobranchs as Living Resources: Advances in the Biology, Ecology, Systematics, and the Status of the Fisheries. Technical Report NMFS 90. National Oceanic and Atmospheric Administration, Washington, D.C, pp. 391–414.

Cope, J.M., Haltuch, M.A., 2012. Temporal and spatial summer groundfish assemblages in trawlable habitat off the west coast of the USA, 1977 to 2009. Mar. Ecol. Prog. Ser. 451, 187–200.

Dulvy, N.K., Reynolds, J.D., 2002. Predicting extinction vulnerability in skates. Conserv. Biol. 16 (2), 440–450.

Eschmeyer, W.N., Herald, E.S., 1983. A Field Guide to Pacific Coast Fishes of North America From the Gulf of Alaska to Baja California. Houghton Mifflin, Boston.

Gertseva, V.V., Schirripa, M.J., 2008. Status of the Longnose Skate (*Raja Rhina*) Off the Continental US Pacific Coast in 2007. Pacific Fishery Management Council, Portland, OR.

Gertseva, V.V., Matson, S.E., Taylor, I.G., Bizzaro, J., Wallace, J.R., 2019. The Next Link Will Exit From NWFSC Web Site Stock Assessment of the Longnose Skate (*Beringraja Rhina*) in State and Federal Waters Off California, oregon and Washington. Pacific Fishery Management Council, Portland, OR.

Hammond, T.R., Trenkel, V.M., 2005. Censored catch data in fisheries stock assessment. ICES J. Mar. Sci. 62 (6), 1118–1130.

Harrington, J.M., Myers, R.A., Rosenberg, A.A., 2005. Wasted fishery resources: discarded by-catch in the USA. Fish Fish. Oxf. (Oxf) 6 (4), 350–361.

Harry, G., Morgan, A.R., 1961. History of the trawl fishery, 1884-1961. Oregon Fish Commission Research Briefs. 19, 5–26.

Hart, J.L., 1988. Pacific fishes of Canada. Bull. Fish. Res. Bd. Canada. 180, 1–730.

Heery, E., Cope, J.M., 2014. Co-occurrence of bycatch and target species in the groundfish demersal trawl fishery of the US west coast; with special consideration of rebuilding stocks. Fish. Bull. (Wash. D. C.) 112 (1), 36–48.

Hicks, A.C., Wetzel, C., 2011. The Status of Dover Sole (*Microstomus Pacificus*) Along the US West Coast in 2011. Pacific Fishery Management Council, Portland, OR.

Hilborn, R., Walters, C.J., 2003. Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. Springer.

Hilborn, R., Branch, T.A., Magnusson, E., Minte-Vera, C.V., Scheuerell, M.D., Valero, J.L., 2003. State of the world's fisheries. Annu Rev Env Resour. 28 (1), 359–399.

ICES, 2019. Workshop on Incorporating Discards Into the Assessments and Advice of Elasmobranch Stocks (WKSHARK5). ICES Scientific Reports.

Kai, M., 2016. Update of Japanese Catches for Blue Shark Caught by Japanese Offshore and Distant Water Longliner in the North Pacific (No. ISC/16/SHARKWG-1/11). National Research Institute of Far Seas Fisheries.

Kai, M., Shiozaki, K., Ohshimo, S., Yokawa, K., Takahashi, N., Kanaiwa, M., 2014. Update of Japanese Abundance Indices and Catch for Blue Shark *Prionca Glauca* in the North Pacific. ISC/13/SHARKWG-3/01.

Kaplan, I.C., Helser, T.E., 2007. Stock Assessment of the Arrowtooth Flounder (*Atheresthes Stomias*) Population Off the West Coast of the United States in 2007. Pacific Fishery Management Council, Portland, OR.

Karnowski, M., Gertseva, V.V., Stephens, A., 2014. Historical Reconstruction of Oregon's Commercial Fisheries Landings. 2014-02. Oregon Department of Fish and Wildlife, Newport, Oregon.

Kelleher, K., 2004. Discards in the World'S Marine Fisheries-an Update, Vol. 470. Food and Agriculture Organization, Rome.

King, M., 2013. Fisheries Biology, Assessment and Management. John Wiley & Sons.

King, J.R., McFarlane, G.A., 2003. Marine fish life history strategies: applications to fishery management. Fisheries Manag Ecol. 10 (4), 249–264.

King, J.R., Surry, A.M., Garcia, S., Starr, P.J., 2015. Big Skate *(Raja binoculata)* and Longnose Skate (R. rhina) stock assessments for British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2015/070. ix + 329 p.

King, J.R., McFarlane, G.A., Gertseva, V.V., Gasper, J., Matson, S.E., Tribuzio, C.A., 2017. shark interactions with directed and incidental fisheries in the northeast pacific Ocean: historic and current encounters, and challenges for shark conservation. In: Larson, S., Lowry, D. (Eds.), Northeast Pacific Shark Biology, Research, and Conservation, Part B. Academic Press, London, pp. 9–44.

Love, M.S., 1996. Probably More Than You Want to Know About the Fishes of the Pacific Coast. Really Big Press, Santa Barbara.

Love, M.S., Yoklavich, M., Thorsteinson, L., 2002. The Rockfishes of the Northeast Pacific. University of California Press, Berkeley.

Manire, C.A., Gruber, S., 1990. Many sharks may be headed toward extinction. Conserv. Biol. 4, 10–11.

Matson, S.E., Gertseva, V.V., 2020. Resolving associative patterns in life history parameters among marine fish stocks in the Northeast Pacific Ocean. J. Sea Res.156, 101837.

Mecklenburg, C.W., Mecklenburg, T.A., Thorsteinson, L.K., 2002. Fishes of Alaska. American Fisheries Society, Bethesda, Maryland.

Methot Jr., R.D., Wetzel, C.R., 2013. Stock synthesis: a biological and statistical framework for fish stock assessment and fishery management. Fish. Res. 142, 86–99.

Pikitch, E.K., Erickson, D.L., Wallace, J.R., 1988. An Evaluation of the Effectiveness of Trip Limits As a Management Tool. NWAFC Processed Report 88-27. Northwest and Alaska Fisheries Center, National Marine Fisheries Service, US Department of Commerce.

Punt, A.E., Smith, D.C., Tuck, G.N., Methot, R.D., 2006. Including discard data in fisheries stock assessments: two case studies from south-eastern Australia. Fish. Res. 79 (3), 239–250.

Rogers, J.B., 1994. Assemblages of Groundfish Caught Using Commercial Fishing Strategies Off the Coasts of Oregon and Washington From 1985-1987. Ph.D. Dissertation. Oregon State University, Oregon.

Rogers, J.B., Pikitch, E.K., 1992. Numerical definition of groundfish assemblages caught off the coasts of Oregon and Washington using commercial fishing strategies. Can. J. Fish. Aquat. Sci. 49 (12), 2648–2656.

Rose, D.A., 1996. An Overview of World Trade in Sharks and Other Cartilaginous Fishes. TRAFFIC International, Cambridge, United Kingdom.

Sampson, D.B., 2002. Analysis of Data From the At-sea Data Collection Project. Final Report to the Oregon Trawl Commission. Oregon State University, OR.

Smith, S.E., Au, D.W., Show, C., 1998. Intrinsic rebound potentials of 26 species of Pacific sharks. Mar Freshwater Res. 49 (7), 663–678.

Snytko, V.A., 1987. New data on the distribution of some species of fish in the North Pacific. J. Ichthyol. 27, 142–146.

Stephens, A., Taylor, I.G., Draft, P.S., 2013. Stock Assessment and Status of Longspine Thornyhead (*Sebastolobus Altivelis*) Off California, oregon and Washington in 2013. Pacific Fishery Management Council, Portland, OR.

Stewart, I.J., Thorson, J.T., Wetzel, C., 2011. Status of the US Sablefish Resource in 2011. Pacific Fishery Management Council, Portland, OR.

Taylor, I., Stephens, A., 2013. Stock Assessment of Shortspine Thornyhead in 2013. Pacific Fishery Management Council, Portland, OR.

Taylor, I.G., Gertseva, V., Stephens, A., Bizzarro, J., 2019. . Status of Big Skate (*Beringraja binoculata*) Off the U.S. West Coast, 2019. Pacific Fishery Management Council, Portland, OR.

Tolimieri, N., Levin, P.S., 2006. Assemblage structure of eastern Pacific groundfishes on the U.S. Continental slope in relation to physical and environmental variables. T Am Fish Soc. 135, 115–130.