Using transdisciplinary science to improve fisheries management: ecology, economics, and equity of the US West Coast sablefish fishery

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**Abstract**300 words

Understanding and reducing bycatch is a major challenge for fishery managers. ?. Retrospective data from the US West Coast sablefish fishery were used to model the impact of economic and ecological drivers of gear choice and make inferences about fishermen behaviour under the influence of two management regimes: i) bi-monthly total allowable catches and ii) individual transferable quotas. Results indicate that ?.

**Keywords:** bycatch, catch share, governance, individual transferable quota (ITQ), risk pool, transdisciplinary

**Introduction**

Regulatory mechanisms to limit fisheries can involve regulating when, where, how, and how much fishermen can catch. Outcomes of management can depend, sometimes non-linearly, on multiple factors, and combinations of regulations can lead to outcomes unachievable by any single regulation (Deacon, 2012; Ono *et al*., 2013). Additionally, in assessing outcomes, it is often forgotten that the main task of fishery managers is to regulate fishermen, not fish. Consequently, appropriate solutions to fisheries management problems are contextual, dependent on human behaviour, and embedded in complex social-ecological systems (Hilborn, 2007; Kaplan *et al*., 2010).

Ecosystem based fisheries management (EBFM) attempts to account for the entire ecosystem, including humans, and recognizes that the effects of fishing extend well beyond the targeted fish population (Pikitch *et al*., 2004). According to Hilborn (2011), there are three ‘core’ aspects of EBFM: (a) the prevention of ecosystem-wide overfishing, (b) reduction of bycatch and discards, and (c) terminating habitat-destroying fishing methods. Implementation of (a) remains difficult as the definition of what constitutes ecosystem-wide overfishing remains unclear (Samhouri *et al*., 2010; Large *et al*., 2013). Conversely, literature suggests that implementing policies focused on reducing bycatch may be a more straightforward approach, specifically through the implementation of gear modifications, avoidance incentives, spatial or temporal closures, or some combination thereof (Hall and Mainprize, 2005). Bycatch commonly refers to catch that is not legally targeted by the fishery; more formally, the Magnuson-Stevens Fishery Conservation and Management Act (MSA), the primary source of fisheries legislation in the United States (US), defines bycatch as, “fish which are harvested in a fishery but which are not sold or kept for personal use, and includes economic discards and regulatory discards” (16 U.S.C. § 1802(2)).

Trawl fisheries, often multispecies in nature and characterized by gear with imperfect selection properties (e.g., bottom trawl), are known for being difficult to manage in terms of avoiding bycatch (Andrew and Pepperell, 1992; Kennelly, 1995). The chance that fishermen’s catches align with the proportions of species quota is almost non-existent. Fortunately, fishermen usually have at least a limited ability to control the ratio of species caught within their net (Beverton and Holt, 1957; Campbell and Nicholl, 1994; Quirijns *et al*., 2008), but most management systems fail to provide incentives or the flexibility to do so (Branch *et al*., 2006; Abbott and Wilen, 2009). Instead, fisheries run the risk of early closure when some quotas are filled before others (Patrick and Benaka, 2013) or suffer from economic discards (discarding when fishermen do not have markets, equipment, time, or economic returns to retain and process the catch) filling quotas such that profits are maximized (Hall *et al*., 2000).

Tools to manage bycatch can include bycatch taxes, which promote internal incentives for environmentally sustainable behaviour, but fail to guarantee that bycatch limits will be observed and may overly constrain the fishery when bycatch rates are uncertain (Herrera, 2005; Singh and Weninger, 2009). Conversely, total allowable catch (TAC) policies guarantee that bycatch limits are observed but promote inefficiency when quota for profitable species remains unfilled (Androkovich and Stollery, 1994; Holland, 2010). Additionally, open access TAC policies incentivize the ‘race to fish’, which often lead to increasing marginal costs and decreased safety (Criddle and Macinko, 2000; Emery et al., 2014). Individual transferable quotas (ITQs), where fishermen are allocated shares of the TAC, are thought to encourage fishermen to change their behaviour in a way that reduces catches of low-valued species and choke species (species in a multispecies fishery for which quota is scarce; Casey, 1995; Holland and Jannot, 2012). Under an ITQ system, time and area closures, as a measure to reduce bycatch, theoretically become self-regulated as quota becomes scarcer.

ITQ fisheries are subject to their own problems (Copes, 1986): i) prohibitive entry costs (Copes and Charles, 2004), ii) social justice issues regarding allocation (McCay, 1995; Ecotrust, 2004), iii) resource consolidation (Dewees, 1998; Eythórsson, 2000), iv) high costs of enforcement (Copes, 1986), v) volatile quota markets (Newell *et al*., 2005), and vi) economic inefficiency (Abbott and Wilen, 2009). For example, when quota for choke species is difficult to obtain via often prohibitively expensive and sometimes volatile markets, fishermen’s ability to attain their quota for more profitable species becomes limited, potentially reducing overall yield or constraining it to a limited area (Branch, 2008).

Quota markets are an important method for rectifying the imbalance between fishermen’s catches and their annual quota. Theoretically, prices should reflect differences between expected price and cost on a per fish basis. Efficient markets are generally characterized by a large number of buyers and sellers, low transaction costs, and readily available price information (Fama, 1970; Stavins, 1995; Swinkels, 1999). Unfortunately, quota markets tend to be very thin and exhibit high transaction costs (Holland, 2013; Holland *et al.*, 2015). Markets are not the only option, as other mechanisms for balancing quota exist, such as rollover allowances, deemed value payments, species quota exchanges, retrospective balancing of quota, selective discarding, surrendering of catch, and species aggregating all of which may offer increased flexibility but come with a potential increased risk of overexploitation (Sanchirico *et al*., 2006). Risk pools, where fishermen pool their quota of non-target species, offer a potential means to mitigate financial risk and reduce transaction costs of quota markets while maintaining a high probability that catches will not exceed TACs. Risk pools often fulfil a similar function as a manager of a firm as they control aspects of members’ actions while achieving outcomes that are superior for the group (Deacon, 2012).Under the MSA, minimizing bycatch is required by law and an improved understanding of the contextual responses of fishermen to regulations and fish behaviour, e.g. the formation of risk pools or choice of gear, has the potential to increase management efficiency. Here, factors related to economics, ecology, and equity were used in an attempt to understand choices regarding gear type, a major driver of bycatch, while landing sablefish (*Anoplopoma fimbria*) in the US West Coast groundfish fishery. Censored (Tobit) mixed effects models were used to quantify changes in the yearly percentage of port specific landings caught using trawl versus fixed gear (pots and longline). Results provide insights relevant to the design and implementation of ITQ policies and have the potential to increase managers’ ability to implement EBFM while increasing economic efficiency. Additional information regarding challenges of data assimilation across multiple disciplines is also highlighted.

*History of the US West Coast sablefish fishery*

Today, sablefish is one of the most valuable fisheries in the US West Coast groundfish fishery, a federally managed multispecies fishery encompassing over 90 species but primarily targeting demersal species such as sablefish, Dover sole (*Microstomus pacificus*), shortspine thornyhead (*Sebastolobus alascanus*), Petrale sole (*Eopsetta jordani*), and Pacific whiting (Pacific hake, *Merluccius productus*). Reconstructed sablefish landings go back to the early 1900s, with the California Department of Fish and Wildlife documenting some of the first records in 1908. Prior to 1960, landings were primarily caught using hook and line (Figure 1), with later increases in the 1970s attributed to the development of a pot fishery, mainly comprised of foreign vessels (McDevitt, 1986). With the implementation of the MSA and the creation of the Pacific Fisheries Management Council (PFMC) Groundfish Fishery Management Plan (GMP), management authority switched from individual coastal states to the federal government, with the first federal regulation being coast-wide trip limits implemented in October of 1982 (Johnson *et al*., 2015).

Increasing effort and a decreasing stock size led to the implementation of seasonal management, gear specific allocations, and limited entry (LE) permits. By 1994, the fishery was apportioned 90.6% to the LE permit program, further split 58 – 42% between the LE trawl and the LE fixed gear sectors, and 9.4% to an open access fishery, for vessels that did not qualify for the LE program based on landing requirements met between July 11, 1984 and August 1, 1988. One permit was issued per vessel, though each permit could hold multiple gear endorsements. Additionally, management was divided at 36° N, with TACs being higher in the north as compared to the south.

Increasing concerns for fishermen safety associated with decreasing season lengths, just five days in 1996, led to a three-tier quota system based on historical landings. Seasons were still necessary such that the tiers did not represent an ITQ system, which were not allowed under the MSA moratorium on new ITQ programs. An exception to the moratorium was made for the sablefish fixed gear LE permit fishery on August 2, 2001 (PFMC, 2001), and despite the 2002 expiration of the moratorium, the trawl fishery was managed primarily through vessel bimonthly cumulative landing limits and spatial closures until 2011.

In 2011, an ITQ system was introduced for all participants of the US West Coast LE groundfish trawl fishery, with allocations based on historical landings. Currently, the ITQ system includes bycatch quotas for Pacific halibut (*Hippoglossus stenolepis*), an internationally managed species, five overfished species: (a) bocaccio (*S. paucispinis*; Field, 2013); (b) cowcod (*S. levis*; Dick and MacCall, 2014); (c) darkblotched rockfish (*S. crameri*; Gertseva and Thorson, 2013); (d) Pacific ocean perch (POP, *S. alutus*; Hamel and Ono, 2011); and (e) yelloweye rockfish (*S. ruberrimus*; Taylor and Wetzel, 2011). Quota share allocations for most bycatch species were based on bycatch rates applied to quota shares of target species (PFMC and NMFS, 2010). Furthermore, in 2011, bycatch quota became binding, whereas prior to the implementation of catch shares fishermen could continue fishing as long as all species for which they had reached their quota were discarded. Thus, incentives to reduce bycatch were potentially made stronger and individuals’ concerns about risk regarding reaching their bycatch quotas led to the formation of multiple formal and informal risk pools, though they were not required to publicly disclose information on rules, membership, or outcomes.

North of 36° N, gear switching was and still is allowed under a permit stacking program. Vessels can fish for their entire quota, of up to three permits, using any gear for which they hold an endorsement. As of 2013, 40 vessels holding sablefish endorsements have stacked permits with 164 permits issued in total (PFMC and NMFS, 2014). Six permits have endorsements for multiple gear types: four longline and pot, one pot and trawl, and one longline and trawl.

**Methods**

*Fishery-dependent data*

Landings and ex-vessel revenue data were obtained from the Pacific Fisheries Information Network (PacFIN) regional database, a compilation of sales receipts (i.e., fish-tickets) collected during the delivery of fish to processing plants in Washington, Oregon, and California (PacFIN, Pacific States Marine Fisheries Commission, Portland, Oregon, www.psmfc.org/pacfin). The PacFIN database contains information on landings by gear and market category, where sablefish represent a market category. Data on vessel characteristics were obtained from the Economic Data Collection (EDC) program, a mandatory component of the US West Coast groundfish trawl catch share program (www.nwfsc.noaa.gov/research/divisions/fram/economic). Since 2009, all catch share participants are required to provide information on operating costs, revenue, and vessel characteristics including: (a) length, (b) horsepower, (c) market value, (d) fuel capacity, (e) days at sea, (f) fishing speed, (g) variable and fixed costs, and (h) net revenue.

Nine strata were defined by latitudinal breaks (46°30’N, 45°N, 44°N, 43°N, 41°30’N, 40°30’N, 39°N, and 37°N; Figure ?) corresponding with fishing out of major ports and prominent biogeographic features at Cape Blanco, OR (42° 50’N) and Cape Mendocino, CA (40° 26’N): (a) Washington, (b) Astoria and Tillamook, (c) Newport, (d) Coos Bay, (e) Brookings and Crescent City, (f) Eureka, (g) Fort Bragg, (h) San Francisco and Bodega Bay , and (i) Monterey and Morro Bay. Strata were used to aggregate landings, ex-vessel revenue, and EDC data. Landings and ex-vessel revenue were summed by port group of landing and EDC data was either summed or averaged by port group, where within a given year each vessel was assigned to a single port group based on the port of highest ex-vessel revenue. For cases where there were not enough observations to ensure confidentiality, such that no value represented fewer than 3 entities, and no one entity represented 90% of any individual statistic (16 U.S.C. § 1881a), the data was withheld from the analysis.

*Fishery-independent data*

The Northwest Fisheries Science Center (NWFSC) Shelf-Slope survey collects annual data on hundreds of fish species along the US West Coast (Bradburn *et al*. 2011). Typically the survey contracts four commercial fishing vessels per year, although 2012 involved 2 contracts to a single vessel. Contracted vessels conduct standardized bottom trawl surveys at depths of 55 to 1280 m from Cape Flattery, Washington (48° 10’N) to the US-Mexico border (32° 30’N). The entire survey area is typically covered twice per year using a stratified random sampling design (based on three depth categories), with sampling extending from late May to late July for the first pass and from mid-August to late October for the second pass. Data are used as the primary source of information for most PFMC groundfish stock assessments. Specifically, relative indexes of abundance are generated using the spatially resolved (trawl mid-point) species-specific catches and delta generalized linear mixed-effects models (delta-GLMMs), which can account for vessel ‘catchability’, spatiotemporal variability, and uncertainty arising from small sample sizes or extreme catch events (Thorson and Ward, 2013).

Relative indexes of abundance by port group for sablefish and four of the overfished species were created using delta-GLMMs implemented with an open source software package (Thorson and Ward, 2013) in the R statistical software environment (R Core Team, 2015). Cowcod was not included because spatial management (Rockfish Conservation Areas) have been successful in decreasing their bycatch and as a species they represent the smallest (sometimes zero) percent of bycatch within the sablefish fishery (NMFS, 2004). The use of the delta-GLMM facilitates the inclusion of vessel:year interactions as random effects, which is necessary because vessels were not consistent across years (Helser *et al*., 2004). Gamma error structures were used for model components representing positive catches and a Bernoulli error structure was assumed for all presence/absence components. Stratum, vessel, and year effects were investigated, leading to five model structures for each species:

Model 1: strata and year as fixed effects and the interaction of year and vessel as random effects;

Model 2: strata and year and the interaction between strata and vessel as fixed effects;

Model 3: strata and year as fixed effects and the interactions between year and vessel and strata and vessel as random effects;

Model 4: strata and year as fixed effects; and

Model 5: strata and year as fixed effects with correlated interactions between year and vessel and strata and vessel.

Furthermore, all models included survey pass as a covariate to account for incomplete sampling during the second pass of the 2013 survey where stations south of 37°N were not sampled. Model goodness of fit was evaluated using Bayesian posterior predictive checks and model selection was performed using deviance information criterion (Spiegelhalter *et al*., 2002).

*Statistical analysis*

Generalized linear mixed effect models were used to determine the drivers of gear switching in the US West Coast sablefish fishery (Pinheiro and Bates, 2000). GLMMs are extensions of linear models, , with an added random component, . Random components are needed for hierarchical data that lack independence, therefore violating the standard assumptions of homogeneity in linear models. GLMMs provide the flexibility needed to model the statistical means of the data (as in the standard linear model) and their variance and covariance. Using matrix notation,

, 1

is the vector representing the dependent variable, represents the fixed portion of the model such that denotes the () design matrix of fixed effects and denotes a vector of length holding the fixed intercept and slopes, is the vector of length holding the random intercept and slopes, is the (). A random effect term with repeated measures over time was included in all models allowing for variations among port groups. To account for correlation between years temporal random effects could have been included, though this was not investigated here.

The dependent variable, percent of sablefish landings caught by the trawl fishery, was bounded between zero and one, thus a two-limit Tobit model was deemed appropriate:

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where is normally distributed with a mean of zero and a variance of and is a latent variable that is not observed for values less than zero and greater than one (Long, 1997; Greene, 2012). Predictor variables included in the fixed effect structure were modelled using linear relationships and included: (a) vessel count, (b) average horsepower, fuel capacity, and fuel consumption by sablefish trawl vessels, (c) fixed and variable costs of sablefish trawl vessels, (d) fixed and variable costs of sablefish fixed gear vessels, (e) index of abundance for each modelled species, and (f) an indicator variable for before and after the implementation of catch shares. Not all possible fixed effects were included in each model run, as some are highly correlated. Analyses were performed using the *censReg* package (Henningsen, 2013) in R (R Core Team, 2015).

Akaike’s Information Criterion (AICc) was used to select the best model among the *a priori* hypothesized set of models (Burnham and Anderson 2002). AIC differences of less than two were seen to have a similar fit.

**Results**

**Discussion**

* In 2011, correlation between fishermens' allocated QP of bycatch species and catch was low (Holland2012).
* Unexplained decrease in number of sablefish landings occurring in Washington state since 2002 (PFMC and NMFS, 2014).
* Looking at things from the margins. Establish the worst and best case scenarios that fishermen can perform under the combination of management available to them and decide if the outcome will be sustainable within the fishery.
* Lack of data on sociological indicators made it a problem to analyse economics, biology, and equity in a single framework.
* Drivers of change outside of the governmental system may be more influential than what is typically accounted for.
* If information was available on risk pools we hypothesize i) that risk-pools will have a higher probability of establishment closer to areas with higher abundances of choke species, ii) risk-pool members will have higher economic revenue compared to non risk-pool members, and iii) vessels participating in risk-pools will have a higher probability of landing 100% of their allotted TAC for target species than non risk-pool vessels.
* The question is especially compelling because it incorporates a perspective on governance, namely non-governmental organization (NGO) involvement, which cannot be evaluated by using only economic and biological data.
* whether there is a link between the spatial abundance of overfished species and the creation of risk pool associations.
* whether participation in a risk-pool helps to achieve a greater percent attainment of the yearly TAC for target species.
* Incorporating social information can help managers predict outcomes of proposed management frameworks.
* Implementing EBFM requires clear societal goals, identification of alternative ways of achieving those goals, and interdisciplinarily evaluating societal trade-offs inherent in each alternative (McConkey, 1983).
* Bycatch reduction may not be internally consistent with the activities of a fishing industry, where the main goal is facilitating profit maximization for individual fishermen, due to avoidance costs or reduced catches of targeted species (Abbott and Wilen 2009, Singh and Weninger 2009).
* When fishing strategies are highly variable among participants, adverse selection may increase thereby decreasing the potential advantages of risk pools. Studies in Common Pool Resource (CPR) management find individuals who are members of cooperatives are more likely to subordinate self-interest for the sake of managing a resource in the community’s interest (Fehr and Leibbrandt, 2010). With gear specific bycatch rates that can vary spatially and temporally, it is not always clear when risk pools are advantageous compared to a competitive quota market. Thus, how risk pools are designed and choices available to fishermen may impact their success (Holland and Jannot, 2012).

TNC entered the West Coast groundfish fishery prior to the management change to an ITQ fishery, with the intent on not harvesting their purchased quota. Currently, instead of holding their quota they lease out quota pounds to members of the California risk pool, in return for having a say in how fishing occurs, mainly what practices are used. In turn TNC has helped implement a geographic information system that combines the best available science and technology with fishermen’s knowledge, historical fishery data, and habitat information to identify zones that contain overfished species as well as areas with voluntary closures. According to TNC, , the California Risk Pool has reduced bycatch of overfished species, increased harvest of target species, and improved the tracking and sharing of fishing information (The Nature Conservancy 2014). Risk pool managers found that the overall trawl-based groundfish fleet caught more than 30% of TAC for overfished species, in contrast to 2.1% for the California Risk Pool (FBGA et al. 2011). Results that were not apparent in our analysis.

Outcomes of risk pools depend on fishing behaviour, social networks (information sharing), locally developed fishing plans and their enforcement. Furthermore, outcomes of the fishery depend to a large extent on how many fish are available. Thus, we plan on moving forward with the analysis to combine measures of biology, economics, and social capacity to inform managers when and where risk pools should be formed and how information regarding life history and abundance can inform policy.

**Outlook**

1. Risk pools form within a social-ecological system. Future research could identify key enabling social and biological factors that contribute to their formation.

* What are the key social factors? Are pre-existing community-based fishery organizations a necessary condition for forming risk pools?

2. What are the dynamics among members in the risk-pools?

* What are the incentives to join or leave a risk pool;
* What are perceived benefits and challenges of risk pools among risk pool members and non risk pool members?
* What are the dynamics between risk-pool and non-risk pool participants in the fishery (e.g. information sharing with fishermen outside risk pool, intention to reach out to non risk pool members in case the risk pool reached deficit for overfished species, would they buy TAC for those species from other fishers?);

3. What are perceived benefits and challenges of the co-management governance   
 arrangement?

* How is power shared among the members on the management board?
* What are perceived benefits and challenges of the co-management arrangement?
* What outcomes have been achieved due to the co-management approach?

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Table 1. Factors that affect the relative benefits of maintaining individual bycatch quotas as compared to creating a risk pool (Holland and Jannot, 2012).

|  |  |
| --- | --- |
| **Favors maintaining individual quotas** | **Favors risk pool** |
| Species caught frequently | Species only rarely caught |
| Low variance, normally distributed catch events | High variance, positively skewed catch events |
| High number of fishing events per vessel | Low number of fishing events per vessel |
| Bycatch risk correlated with expected profits | Bycatch risk uncorrelated with expected profit |
| Bycatch risk heterogeneous across vessels | Bycatch risk homogenous across vessels |
| Real-time information sharing not useful for avoidance | Real-time information sharing useful for avoidance |

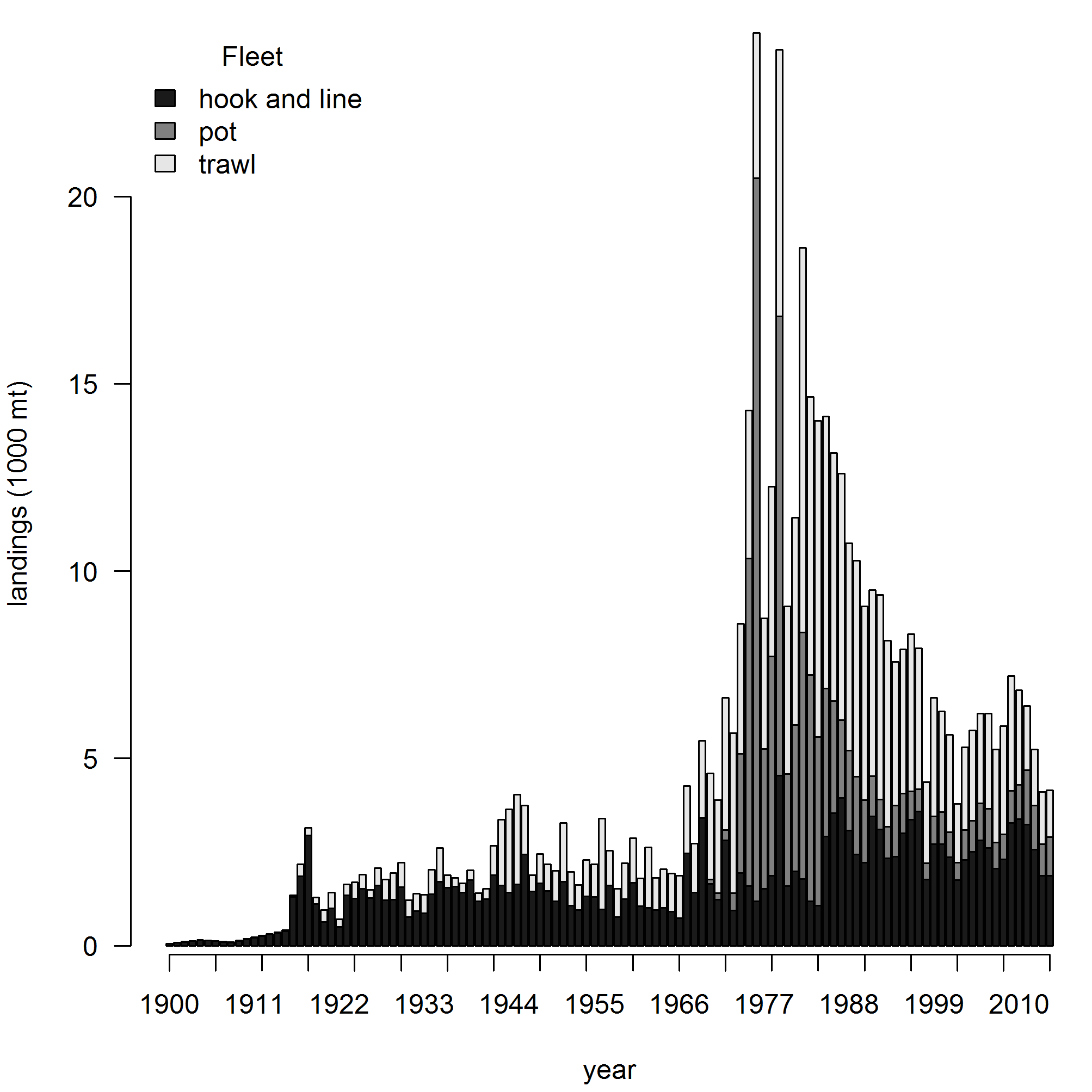


Figure 1. Reconstructed sablefish landings from 1900 to 2014. Landings include those from foreign vessels, which are largely responsible for the peak landings in 1976 and 1979. Fleet names indicate gear type.

Figure 2. The geographical extent of the survey area with latitudinal lines depicting strata used to separate between port groups. Unique port groups from north to south include: (a) Washington; (b) Astoria and Tillamook; (c) Newport; (d) Coos Bay; (e) Brookings and Crescent City; (f) Eureka; (g) Fort Bragg; (h) San Francisco and Bodega Bay; and (i) Monterey and Morro Bay.