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A comparison of methods to spatially represent pelagic longline fishing effort in catch and bycatch studies

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Abstract

Bycatch in fisheries has been recognized as a threat to many endangered populations of sea turtles, sea birds and marine mammals. Interactions between pelagic longline fisheries and critically endangered populations of leatherback sea turtles (*Dermochelys coriacea*) have led to temporary closures of the Hawaiian pelagic longline swordfish fishery and severe bycatch quotas. The negative impact of these events on both the populations of certain endangered species and the economic livelihood of the fishermen has resulted in a strong push from all sides to better understand bycatch events. Typically, analyses of longline catch and bycatch have examined fishing effort summarized over large areas (≥1°). Although aggregation of effort to this level may be necessary to account for uncertainty, confidentiality concerns, or to make comparisons across regions, it specifically limits the researcher's ability to characterize the local oceanographic factors that may drive individual bycatch events. Higher resolution analyses must be undertaken to identify such features. However, for these higher resolution analyses, the methods currently used to spatially represent pelagic longline fishing effort may significantly affect researcher's results. Here, we look at different methods to represent this fishing effort (i.e., points, centroids, polylines and polygons) at various resolutions (2 km to 5°) to better understand which method and spatial resolution are most appropriate. Our results validate the use of point features to represent fishing effort in previous low resolution studies of the Hawaiian pelagic longline fishery by showing that the set point method is suitable for studies with resolutions lower than 15 km. However, at higher resolutions (≤15 km) and in areas with more sparsely distributed fishing, aggregated effort values differed significantly between spatial representation methods. We demonstrate that the use of polygons to describe pelagic longline fishing effort is more representative and necessary for such high resolution analyses.

Keywords: Pelagic longline fisheries; Fishing effort; Minimum convex hull; Oceanography; Bycatch; Hawaii

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1. Introduction

Recent studies have highlighted the impact of various fisheries on endangered marine mega-vertebrates such as sea turtles, seabirds, and marine mammals. Due to the higher quality and availability of pelagic longline observer datasets as compared to other gear types (i.e., gillnet, traps, or trawls), these fisheries in particular have undergone more extensive scrutiny (Weimerskirch et al., 1997; Bjorndal et al., 1999; Bolten et al., 1996; Lewison et al., 2004; Nel et al., 2002). Bycatch of Pacific loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) turtles in pelagic longline gear may have played a role in the severe (80% and 95%, respectively) declines in the nesting populations of these species over the last 20–25 years (Spotila et al., 2000; Limpus and Limpus, 2003). Mortality due to interaction with longline gear is also a critical threat to albatrosses and other seabird species (Klaer and Polacheck, 1997; Brothers et al., 1999a,b; Gilman and Zollett, 2004; Tuck et al., 2001). The possible implication of fisheries in the decline of endangered populations of non-target species has led to a number of costly spatial and/or temporal fishery closures, as well as the enforcement of expensive gear alterations and the enactment of stringent management measures (Gilman et al., 2006). It is in the interest of both the fishing industry and the conservation community that we gain a better understanding of the context surrounding bycatch events to reduce the ongoing economic and biological losses (Curtis and Hicks, 2000).

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Analyses of pelagic longline fisheries have brought to light correlations between catch of target species and oceanographic variables such as sea surface temperature (Bigelow et al., 1999; Zagaglia et al., 2004; Santos et al., 2006), sea surface temperature fronts (Laurs et al., 1984; Power and May, 1991; Podesta et al., 1993; Seki et al., 2002), chlorophyll-*a* and sea surface height anomalies (Seki et al., 2002; Zagaglia et al., 2004), surface wind (Bigelow et al., 1999; Zagaglia et al., 2004), and salinity (Maury et al., 2001; Seki et al., 2002). This type of oceanographic analysis of longline fishing events may facilitate the identification of potential areas of high target fish catch as well as bycatch. The characterization and modeling of bycatch events using environmental covariates may serve to reduce bycatch of non-target species by temporally and spatially separating areas in which bycatch occurs from areas of high target species catch. Thus the development of methods to facilitate higher resolution oceanographic analyses of longline bycatch events is a prime commercial and conservation objective.

1.1. *The spatial representation of longline fishing effort*

The proper representation of the spatio-temporal distribution and magnitude of longline fishing effort (i.e., understanding exactly when, where, and how much effort is being applied) is an essential part of the oceanographic characterization of catch or bycatch rates. Point features, and to a much lesser extent polyline features, are the most common spatial representation of fishing effort. Numerous studies have either used the location where the longline gear begins to be set (the “set point”) to represent fishing effort or aggregate the effort to low resolution grid cells based on the set point location (He et al., 1997; Maury et al., 2001; Seki et al., 2002; Zagaglia et al., 2004). Others have used the central point (centroid) of non-specific set and haul locations (Bigelow et al., 1999), or the centroid of the beginning and end of the set (Riolo, 2006). Combinations of points used to form polylines (e.g., connecting the point at the beginning of the set with the point at the end of the haul) have also been used to designate fishing effort (Klaer and Polacheck, 1998; Brothers et al., 1999a; Santos et al., 2006). Relatively few fishing effort studies have explored the use of all four points commonly available for mapping longline fishing effort (i.e., the beginning and ending of the set and haul) to create polygons representing the potential area fished by a longline set.

The need to use a polygon to represent a pelagic longline set stems from the length of the gear and the potential for it to drift significantly while actively fishing. The spatial ambiguity inherent in representing 25–65 km of drifting pelagic longline gear as a single point is described by Podesta et al. (1993) and Bigelow et al. (1999) as a “radius of uncertainty.” The use of all reported points associated with the setting and hauling of the gear to create a polygon bounding the potential area fished encompasses most of this radius of uncertainty and more closely depicts the actual area fished than a single point or a polyline. When investigating the cumulative effect of multiple fishing sets, individual points or polylines may not accurately describe the density of fishing gear at any given location over time. Only by looking at the entire area affected by each longline set can we see the actual overlap between sets, and consequently understand the intensity of fishing effort in that area. Similarly, only through the use of all available spatial data can we get a clear portrayal of the full geographic extent of the fishery.

1.2. *Issues of scale and resolution in studying fishing effort and bycatch*

The scale and resolution of studies of the environment are often determined not by the system observed, but rather by the technological or logistic constraints imposed on the researcher (Levin, 1992). Historically, oceanographic characterizations of fisheries have been large-area studies (He et al., 1997; Bigelow et al., 1999; Maury et al., 2001; Xavier et al., 2004; Zagaglia et al., 2004) because many of the commercial fisheries target highly migratory species (i.e., tunas, swordfish, and shark) that tend to have large geographic ranges (Block et al., 2001; Palumbi, 2004). Thus studies have been on a large (regional or basin-wide) scale to encompass these large fisheries or the range of the species being investigated, and this has dictated the need to use lower resolutions. This type of analysis can identify factors that may influence a marine species’ range (e.g., minimum or maximum sea surface temperatures, salinity; Wiens, 1989; Maury et al., 2001; Santos et al., 2006). Possibly due to computational limitations, or the error inherent to commonly used methods of spatially representing fishing effort (e.g., point features), high-resolution oceanographic analyses of longline fisheries (<1°) appear to have been deemed infeasible in the past.

In this paper, we use correlation statistics and rank sum tests to compare the relative similarity of effort values calculated by using different methods of representing fishing effort in space at different resolutions. Our intention is to improve subsequent oceanographic analyses by developing a method that better approximates the true spatial nature of the fishing effort. We also analyze the effect of fishing density on the different effort representation schemes and make recommendations regarding which methods are appropriate based on the density of the fishing effort data and the desired resolution of the model.

2. Data and methods

2.1. *Fishing effort data*

To compare the different methods of spatially representing fishing effort, we used data from the U.S. National Marine Fisheries Service’s Hawaiian Longline Observer Program from 1999 to 2005 (Fig. 1). This dataset includes four locations for each longline fishing set: the beginning and end of the set, and the beginning and end of the haul. The data were filtered to remove any set that did not have all points recorded, and to eliminate any sets with clearly erroneous location information (i.e., those on land). Sets that did not have the necessary effort metrics used in our analysis (e.g., number of hooks and soak time) were also removed. After filtering, 18,048 sets remained and were used to conduct the analyses. The average number of hooks deployed per set was 1843 hooks (range = 60–3660), and the average soak time (the time from when the first hook is deployed until the last

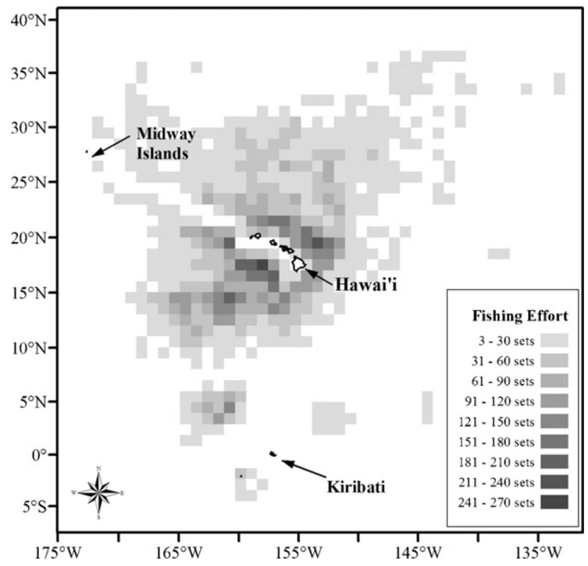

Fig. 1. Geographic distribution of fishing effort aggregated to 1° grid cells from the U.S. NMFS Hawaiian Longline Fishery Observer Dataset from 1999 to 2005. All cells containing less than three sets were removed according to NMFS confidentiality rules.

hook is retrieved) was 19 h (range = 1–131 h). We incorporated both of these effort metrics by using hook-hours (e.g., the number of hooks set × the number of hours the gear fished) as our unit of comparison. The average number of hook-hours per set for the Hawaii pelagic longline fishery during this period was 34,957 (range = 85–209,510 hook-hours). The average distance between the initial set point and the end haul point was 12.09 km (range = 0–198 km). Although sets within the Hawaiian pelagic longline fishery may be separated and characterized as tuna sets and swordfish sets (He et al., 1997), the differences between the methods used to target these species (i.e., depth of set, number of hooks, time of set, number of light-sticks) are irrelevant to this study and thus both types of fishing were considered together.

2.2. Methods to spatially represent fishing effort

We examined five methods for spatially representing longline fishing effort (set point, polyline, polyline centroid, polygon, and polygon centroid; Fig. 2) using ArcGIS 9.2 (ESRI, 2005). Set points were taken directly from the coordinates in the observer data for the beginning of the setting of the longline gear. Polylines were generated by using the begin set and end haul points as either end of the line segment. The centroids (central point) of these polylines were created through the XTools extension for ArcGIS 9.x (DataEast, 2006). Polygons were created using the minimum convex hull (MCH) of the four points reported for the beginning and ending of the set and haul. Hawth's Tools extension for ArcGIS 9.x (Beyer, 2004) was used to create the MCHs, as well as the vector lattice of square cells for each resolution examined: 5° or ∼555 km × ∼555 km (308,025 km^2), 1° or ∼111 km × ∼111 km (12,321 km^2), 30 km (900 km^2), 15 km (225 km^2), 9 km (81 km^2), 4 km (16 km^2), and 2 km (4 km^2). These cell resolutions were chosen because they were either used in previous longline fisheries studies or generally corresponded to the resolutions of various commonly used oceanographic datasets.

Fishing effort was measured in hook-hours and allocated to point, polyline and polygon features using different techniques. For methods using points (the set point, the polyline and polygon centroid methods), effort was distributed by assigning all hook-hours from a particular set to the individual point representing the longline set. As polylines and polygons could potentially span numerous grid cells, we calculated effort for the individual cells by measuring the length or area of the part of the set that fell within the grid cell, and then divided it by the total length or area of the whole longline set. This ratio was then multiplied by the number of hooks-hours in the set. Total effort for each grid cell was summed using each method of representing fishing effort at each of the seven resolutions.

2.3. The effect of scale and spatial representation method on aggregate effort

This study was divided into two parts. The first analysis ensured a statistically robust sample size at lower resolutions (i.e., 1° and 5°) by maintaining the same number of grid cells across all resolutions ($n = 30$). In this "constant N" analysis, polygons were created for all sets. Grid cells that did not intersect any fishing effort were eliminated for each of the seven resolutions. Of the remaining grid cells, 30 were randomly selected

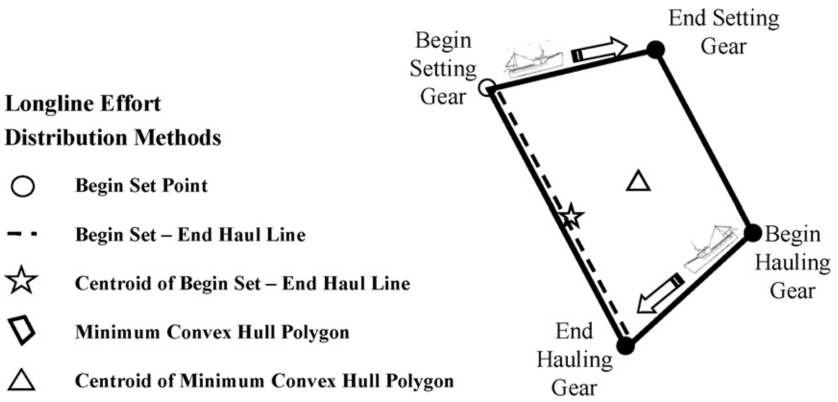

Fig. 2. Five methods to spatially represent pelagic longline fishing effort: set points, polylines, polyline centroids, polygons and polygon centroids.

at each resolution. The polygons of all filtered longline sets intersecting these 30 cells were selected and hook-hours were calculated for each set. Fishing effort was then ascribed to individual grid cells using the five effort representation methods, and total effort for each grid cell was summed for each representation method at each resolution. Using Statistica software (StatSoft, 2003), a Spearman's rank sum correlation statistic (Lehmann and D'Abrera, 1998), was then used to compare summed effort values between each point and polyline method and the polygon method. Effort values were further analyzed using the Friedman's test, a non-parametric repeated measures analysis of variance (ANOVA; Friedman, 1937). When the Friedman test showed significant differences among effort values ($\alpha = 0.05$), the post hoc Dunn's test (Dunn, 1964) was used to see which pairs were significantly different ($\alpha = 0.05$). All Friedman and Dunn's tests were performed using GraphPad's Prism 5.0 (GraphPad Software, 2007).

In the constant N analysis, the 30 grid cells used at each resolution were randomly chosen from all grid cells that intersected fishing effort, as represented by the polygon method. Because the polygon method represented a broader definition of where fishing effort for a given set could have taken place than the point or polyline methods, the grid cells selected may not have contained any fishing effort as represented using the other methods. In other words, each grid cell picked was guaranteed to have >0 fishing effort when using the polygon method, but using any of the other four methods for representing fishing effort might result in zero effort. A high number of zero values for effort aggregated by the non-polygon methods were common, which artificially inflated correlation coefficients in comparisons between the non-polygon methods. Thus, the constant N analysis was limited to comparing the correlation between the polygon method and all other methods.

To better understand the relationship among all methods, a second, 'constant set', analysis was performed in which 500 sets were intersected with grid cells at each resolution. This analysis offered a means to compare correlation coefficients among effort values calculated using any method of spatially representing fishing effort, as all effort was accounted for regardless of representation method. This constant set analysis was repeated at three levels of fishing density (i.e., 'high', 'medium', and 'low') to investigate the effect of fishing density on correlation among effort calculation methods. The total area of the polygons in each density level was also summed and divided by the total extent covered by the individual sets to calculate the area fished ratio, or use index: total area of polygons/total area of extent. Areas with high density of fishing effort had 1.06×10^{-3} sets/km^2 (a ~2.32 area fished ratio) while areas with medium density had 2.76×10^{-3} sets/km^2 (a ~0.766 area fished ratio.) The low density (4.60×10^{-5} sets/km^2; ~0.011 area fished ratio) fishing dataset was created by taking a random selection (using Hawth's Tools; Beyer, 2004) of 500 out of all sets within the observer dataset. For each of these density levels, grid cells at all scales (5°, 1°, 30 km, 15 km, 9 km, 4 km and 2 km) were intersected with the same 500 sets and effort distributed using the methods described in the first analysis. As in the constant N analysis, Spearman, Friedman, and Dunn's tests were performed at each resolution to compare effort values calculated using the different methods.

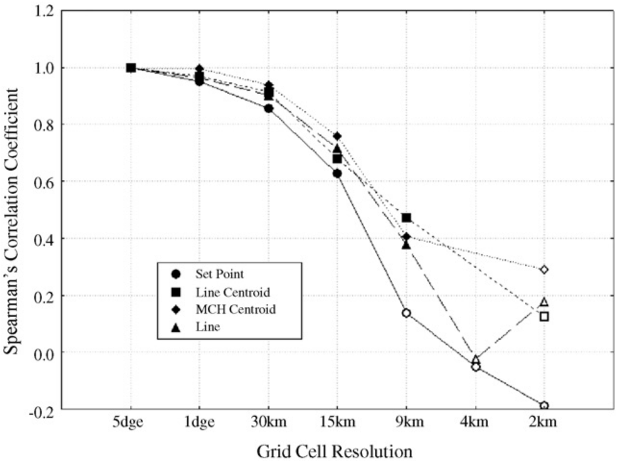

Fig. 3. Constant 'N' analysis results: Spearman's rank correlation coefficients (ρ) for all point and polyline methods compared to the polygon method. Solid symbols indicate significant correlation ($P < 0.05$) while hollow symbols indicate no significant correlation ($P > 0.05$) was found between that method and the polygon method.

3. Results

In the constant N analysis, positive correlations ($\rho > 0.85$, $P < 0.05$) between values calculated using all point or polyline methods and the polygon method were exhibited at large scales (>15 km; Fig. 3). At 15 km, correlation values between the polygon method and all other methods showed a significant decrease: fishing effort values calculated from all methods were still positively correlated, but correlation values declined considerably ($\rho = 0.63$–0.76, $P < 0.05$; Fig. 3). Below 15 km, no significant correlation was found between the set point method and the polygon method while correlation coefficients diminished between the polygon method and all other methods ($\rho < 0.47$, $P < 0.05$; Fig. 3). At 4 km and 2 km, no significant correlation was found between fishing effort values calculated using the polygon method and any other method of representing fishing effort.

Effort values for all methods were not significantly different at the 5° resolution in the initial 30 random grid cell analysis (Friedman test, $Q = 1.35$, $P = 0.85$). However, the Friedman test showed that effort values were significantly different using different methods at 1° ($Q = 13.13$, $P = 0.01$), 30 km ($Q = 13.14$, $P = 0.01$), 15 km ($Q = 21.63$, $P = 0.0002$), 9 km ($Q = 25.00$, $P < 0.0001$), 4 km ($Q = 84.92$, $P < 0.0001$), and 2 km ($Q = 62.51$, $P < 0.0001$). The Dunn's test showed significant differences between effort values calculated using the set point and polygon methods ($P < 0.05$) for resolutions at 30 km and higher (e.g., 15 km, 9 km, 4 km and 2 km; Table 1). Line centroid and polygon methods showed a significant difference in effort values for the 1°, 15 km, 4 km, and 2 km resolutions ($P < 0.05$), while values calculated using the line and polygon methods only showed significant differences for 4 km and 2 km resolutions ($P < 0.001$; Table 1).

Table 1
Summary of Dunn's test *P*-value from the 30 randomly selected grid cells for each representation method vs. the MCH method

	Resolution						
	5°	1°	30 km	15 km	9 km	4 km	2 km
Set point vs. polygon			*	**	**	***	***
Line centroid vs. polygon		*		**		***	***
Polygon centroid vs. polygon					**	***	***
Line vs. polygon						***	***

Blank values were not significant ($P > 0.05$); asterisks show significant differences (*$P = 0.01$–0.05, **$P = 0.001$–0.01, ***$P < 0.001$).

The 500 set density analysis revealed significant differences in effort values among methods depending on both the resolution and the density of sets in the area analyzed. High density fishing areas exhibited stronger correlation among all methods than in medium or low density fishing areas (Fig. 4). Similarly, correlation coefficients were stronger among every method in medium density fishing areas than in low density fishing areas (Fig. 4).

Effort values calculated using different spatial representation methods in the second analysis were not significantly different at the 5° or 1° resolutions in high, medium or low fishing densities (Friedman test, $P > 0.05$). However, the Friedman test showed that effort values were significantly different using different methods at 30 km and higher resolutions for high and low density fishing, and 15 km and higher for medium density fishing activity (Friedman test, $P < 0.0001$). The Dunn's test showed significant differences between the set point and polygon ($P < 0.001$) for resolutions at 30 km and higher resolutions in high and low density fishing areas, and 15 km and higher in medium density fishing activity (Table 2). Significant differences in all densities of fishing were found at 15 km and higher between: polyline centroid and polygon, polygon centroid and polygon, and polyline and polygon (Dunn's test, $P < 0.001$) methods (Table 2). At 4 km and 2 km resolutions, all pairs calculated significantly different values (Dunn's test, $P < 0.001$) except: set point and polyline centroid, set point and polygon centroid, and polyline centroid and polygon centroid (Table 2).

4. Discussion

4.1. Fishing effort representation method selection

The most common method used to spatially represent fishing effort in assessments of pelagic longline fisheries has been the allocation of all effort from a particular set to a single point feature (usually the location reported as the beginning of the set; He et al., 1997; Seki et al., 2002; Zagaglia et al., 2004). The strong correlation exhibited at low resolutions (>15 km) among effort values calculated using all methods in both analyses suggests that the method used to spatially represent fishing effort will have little to no effect on spatial analyses of fishing effort at these resolutions. This validates the use of point methods for low (>15 km) resolution analyses in this fishery or in the study of other pelagic longline datasets temporally aggregated to similar levels of data density (2.76×10^{-3} sets/km^2, ~0.766 area fished ratio). Compared to all of the methods considered in this study, the use of the beginning of the set point is easy to collect from fishermen (Dietrich et al., 2007), the most straightforward since information can be taken directly from the observer database, and does not require additional geoprocessing as do the other effort representation methods discussed here. Thus, for the sake of efficiency and to limit compounding error by using multiple location points, we recommend the use of point representation methods for such low-resolution studies (>15 km).

There are also particular occasions when the allocation of all fishing effort to a point or polyline feature is warranted regardless of the resolution of the analysis. Specifically, analyses of bycaught species that are likely to be uniquely caught during the setting or hauling of fishing gear (e.g., plunge diving seabirds that become hooked or entangled as the baited hooks are being set) would be more interested in specific times during the fishing set and not the overall area fished. Under such circumstances, the fishing event being characterized should be depicted by points or polylines.

Although methods other than the use of the set point are not common in analyses of pelagic longline fishing, they have been used in trawl fisheries to map complete trawl towlines (Bellman

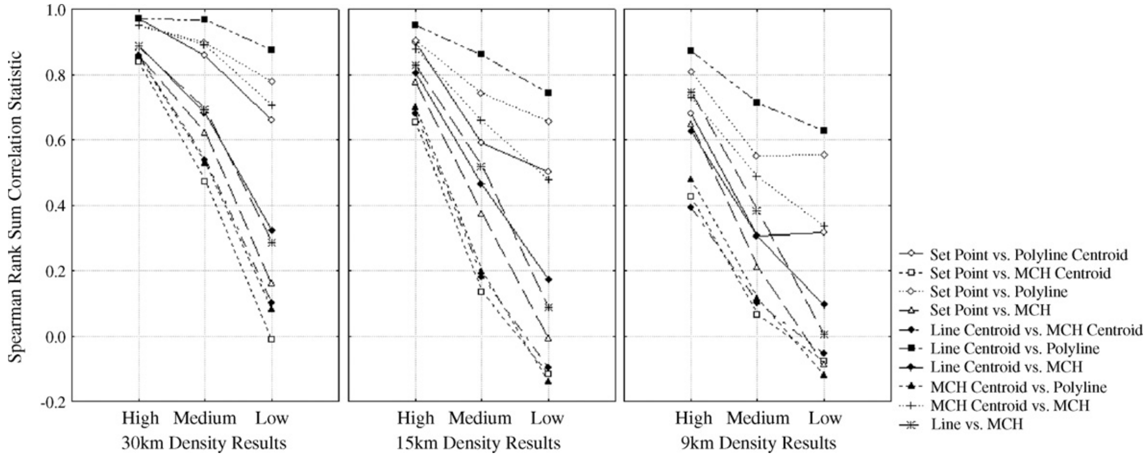

Fig. 4. Constant set analysis results: Spearman's rank correlation coefficients (ρ) for all methods at high medium and low fishing densities and 30 km, 15 km and 9 km resolutions.

Table 2
Summary of Dunn's test P-value for each pair of distribution methods for three density types at seven different resolutions

Fishing density	Distribution methods compared	Resolution						
		5°	1°	30 km	15 km	9 km	4 km	2 km
High density	Set point vs. polyline centroid							
	Set point vs. polygon centroid							
	Set point vs. polyline					*	***	***
	Set point vs. polygon			***	***	***	***	***
	Polyline centroid vs. polygon centroid							
	Polyline centroid vs. polyline						***	***
	Polyline centroid vs. polygon			**	***	***	***	***
	Polygon centroid vs. polyline						***	***
	Polygon centroid vs. polygon			*	***	***	***	***
	Polyline vs. polygon			*	***	***	***	***
Medium density	Set point vs. polyline centroid							
	Set point vs. polygon centroid							
	Set point vs. polyline					***	***	***
	Set point vs. polygon				***	***	***	***
	Polyline centroid vs. polygon centroid							
	Polyline centroid vs. polyline				*	***	***	***
	Polyline centroid vs. polygon				***	***	***	***
	Polygon centroid vs. polyline					***	***	***
	Polygon centroid vs. polygon				***	***	***	***
	Polyline vs. polygon				***	***	***	***
Low density	Set point vs. polyline centroid							
	Set point vs. polygon centroid							
	Set point vs. polyline				***	***	***	***
	Set point vs. polygon			***	***	***	***	***
	Polyline centroid vs. polygon centroid							
	Polyline centroid vs. polyline				***	***	***	***
	Polyline centroid vs. polygon			***	***	***	***	***
	Polygon centroid vs. polyline			*	***	***	***	***
	Polygon centroid vs. polygon			***	***	***	***	***
	Polyline vs. polygon			***	***	***	***	***

Blank values were not significant ($P > 0.05$); asterisks show significant differences (*$P = 0.01$–0.05, **$P = 0.001$–0.01, ***$P < 0.001$).

et al., 2005), determine the location of fishing using the midpoint of the haul (Stelzenmüller et al., 2005), and to estimate catch or bycatch using the trawl area swept (Kaiser, 1996; Freese et al., 1999; Fritz and Brown, 2005; Piet et al., 2007). By utilizing multiple fishing points, these studies were able to estimate the area fished and give a more complete representation of gear interactions within the environment (Freese et al., 1999; Ragnarsson and Steingrımsson, 2003; Piet et al., 2007). For longline fishing effort, the polygon method considered in the current study is similar to the method used to determine the area swept in the trawl fisheries, and better represents the potential area where a pelagic longline fished than a single point (begin set point or centroid) or a polyline. Therefore, the strength of the correlation between values calculated using the polygon method and any other method can be viewed as the degree to which those methods are appropriate proxies for the best estimate of the actual area fished.

Compared to previous methods used to map pelagic longline fishing effort, the polygon method not only most closely describes the maximum potential area fished for a set, but can also integrate the temporal nature of the fishing activity. For the observed longline sets within the Hawaii Pelagic Longline Fishery Observer dataset (1999–2005) the average soak time of gear was approximately 19 h (range = 1–131 h; $n = 21{,}389$). Point features (e.g., those used by the begin set or centroid methods) are quick snapshots of fishing activity and do not account for what happens to the gear over time. Alternatively, polyline and polygon features describe a route or area that the gear may have traveled through during the period it was fishing. Understanding the effective area fished, or the area of 100% probability of capture (Hovgård and Lassen, 2000), is essential to accurately characterize catch and bycatch events. At high resolutions, the ascription of effort to the location of the gear at one single point in time leads to the overestimation of catch and bycatch at that particular location and exaggerates the importance of the location in any analysis.

Our results indicate that high-resolution studies ($\leq$15 km) are influenced by the method used to spatially represent fishing effort. The weak to non-existent correlation among effort values resulting from different spatial allocation methods at resolutions less than or equal to 15 km, and the significant differences found by the Friedman and Dunn's test, establish that point representation methods likely mischaracterize the true magnitude of fishing effort at any particular location and are not appropriate for such high-resolution studies. At resolutions of 15 km or higher, the polygon method is required to improve estimates of the location of pelagic longline effort, and oceanographic characterizations of rates based on fishing effort (i.e., target catch rates and bycatch rates).

The resolution we found to be the limit at which the representation method affects the results of fishing effort analyses (15 km) may have been dependent upon the scale at which the observed Hawaiian pelagic longline fishery operates. Observer data from 1999 to 2005 showed that the average polygon created by using the MCH of the beginning/end set and beginning/end haul points was 224 km^2 ($n = 18{,}048$), which is comparable to the area of the resolution at which methods for mapping longline fishery effort diverged (15 km × 15 km grid cell; 225 km^2). Fisheries functioning on larger or smaller scales may have larger or smaller threshold resolution, respectively. Thus the potential area fished should be considered when selecting a resolution for future analyses.

4.2. Polyline methods and the importance of haulback direction

Although it may be evident that the polygon method most closely represents the potential area of pelagic longline fishing, other alternatives can potentially be used as a proxy when working at high resolutions. If fishing effort data were limited to only the begin set and end haul point locations, the use of a polyline or polyline centroid might be sufficient for studying relative fishing effort. These methods should result in effort values that are correlated to values calculated using the polygon method if the polyline between the begin set and end haul point crosses the centroid of the polygon created by all four set and haul points. Whether or not the polyline does this is entirely determined by the haulback direction (i.e., the direction the mainline is hauled based on which end is retrieved first, the end set first or the end set last).

Our results did not show a very strong correlation between values resulting from the polygon and either polyline or polyline centroid methods. The weak correlation between these methods may be due to our assumption that hauls generally began from the mainline end that was first set in the water. This led us to use the begin set and end haul points to create a polyline which we believed would bisect the polygon. Contrary to our assumption, fishermen in the Hawaiian pelagic longline fishery generally begin the haul at the end of the mainline that was set last. If the end of the mainline set last is hauled first, the begin set and end haul points we used as the basis of the polyline and polyline centroid methods would result in an unrealistic representation of fishing effort along one side of the potentially fished area. If the general haulback direction was known and accounted for, we believe that a much stronger correlation between the polyline and polygon methods would have resulted. Future analyses that use polylines must consider haulback direction to create proper polylines that cross through the center of the potential area fished.

4.3. The role of fishing density in the selection of methods to distribute fishing effort

The density of fishing sets needs to be considered when choosing an appropriate method of spatially representing pelagic longline fishing effort because changes in fishing density can have a significant impact on how strongly correlated effort values are at different resolutions. Within the Hawaiian pelagic longline fishery's regional extent in the Pacific Ocean (about 1.80×10^7 km^2) there were areas of high and low fishing density, while the average density most closely resembled the medium density levels examined in the 500 set analysis. The density of longline fishing is not only spatially heterogeneous within this particular fishery but also varies between this fishery and pelagic longline fisheries in other geographic locations. Our analyses showed that for resolutions less than or equal to 30 km, methods for mapping fishing effort in areas of low fishing density (4.60×10^{-5} sets/km^2; ~0.011 area fished ratio) within the extent of the Hawaii pelagic longline observer data led to set point and polygon values that were poorly or not significantly correlated ($\rho < 0.16$). Therefore, analyses of similarly sparsely distributed fisheries must take into account the effects of the method used to distribute fishing effort at lower resolutions than otherwise would be necessary (i.e., <1°). Since methods were still highly correlated ($\rho > 0.64$) in areas of high density fishing (1.06×10^{-3} sets/km^2, ~2.32 area fished ratio) for resolutions at 9 km and above, application of any method for mapping fishing effort in comparably high density fisheries at such resolutions is likely suitable.

4.4. Future considerations and applicability of methods

Further improvements in describing the area fished can be made in the quality and types of data collected. Standardized methods for currently collected data (observed or from vessel logbook) and a set minimum level of precision (Dietrich et al., 2007) can facilitate error estimates in target catch and bycatch analyses. Other variables that could be collected to improve spatial estimates of fishing effort and target catch or bycatch analyses include the haulback direction (considered critical to research needs by observer data users; Dietrich et al., 2007), the speed of setting and hauling, typical gear shape (curvature) and gear drift from geostrophic currents. However, since most of these variables are not a high priority and therefore not commonly collected within observer programs, evaluations of alternative uses of frequently collected data (like those used in this analysis) are more critical.

Methods used in this study are easily repeatable and transferable to address the proper representation of fishing effort in other pelagic longline fisheries as well as other types of fisheries. Methods for geoprocessing and storing effort data can be implemented using a geographic information system. The creation of points, centroids, polylines, or polygons from latitude and longitude points in any dataset can be automated within a framework such as the ArcGIS Modelbuilder (ArcGIS; ESRI 2005), and organized within a recognized data model schema as time duration points, polylines, or polygons (Wright et al., 2007). The applicability of these results to other fisheries is likely to be highly dependent on the relative difference in fishing density and, possibly, the scale of the gear used. Through the use of methods defined in our study, fishing effort is more accurately represented and higher resolution analyses that offer a better picture of the factors driving local heterogeneity in the fishing effort, catch and bycatch should be possible. This, in turn, may facilitate more efficient fishing, the prediction of bycatch hotspots, and help reduce the economic and ecological impact associated with bycatch.

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