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Evaluation of a long-term information tool reveals continued suitability for identifying bycatch hotspots but little effect on fisher location choice

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ABSTRACT

Bycatch represents a critical threat to many marine megafauna species. Dynamic ocean management (DOM) has been proposed as means to reduce bycatch interactions but currently, most DOMs provide information products only. These products delineate spatiotemporal areas of high bycatch of specific species with the goal of helping fishers engage in self-directed avoidance. However, the efficacy of information-based DOMs depends on fishers' use and their incentives to do so. We reviewed one of the longest and earliest DOM informational products, TurtleWatch, which is a U.S. government program to provide information to help Hawai'i shallow set pelagic longline fishers avoid North Pacific loggerhead sea turtle (*Caretta caretta*) interactions based on a specific sea surface temperature band. Though TurtleWatch continues to identify a zone of higher interactions, fishers have not been incentivized to use the product. Further, the rate of interactions has increased since TurtleWatch's deployment in 2005, and fishers continued to operate within and closer to the recommended avoidance area as interaction limits were approached. This indicates that the interaction limit, which was shared among all fishers, may have created a common pool resource that disincentivizes individual fishers to avoid hotspots of loggerhead bycatch. As the majority of DOM relies on similar informational products and incentives, our findings suggest strong and appropriate incentives are needed for DOM to reduce bycatch.

1. Introduction

Limiting detrimental fisheries bycatch interactions is a priority management concern for many marine species but especially those with protected status (Lewison et al., 2004, 2014; Savoca et al., 2020). Changes to fishing gear or bait can successfully reduce bycatch in some cases (Gilman, 2011; Swimmer et al., 2017, 2020; Poisson et al., 2022), but spatial or temporal closures may be desirable when these changes prove unsuccessful, insufficient, or too costly (O'Keefe et al., 2014). Still, the mobile nature of marine megafauna results in spatiotemporal dynamics that can stymy defining static management zones (Hazen et al., 2018). One proposed solution is to adopt dynamic zones that attempt to match the bycatch interaction distribution over time, an aspect of marine spatial planning termed dynamic ocean management (DOM) (Maxwell et al., 2015; Little et al., 2015; Hazen et al., 2018). Dynamic closures can be more efficient by reducing interaction rates with species of concern while maintaining target species catches (Pons et al., 2022).

Fisheries are complex socio-ecological systems in which the success of management measures depends on stakeholder behavior and their incentive structure (Ostrom et al., 1999; Lubchenco et al., 2016). Incentive structures can alter fishers' direct costs, access, or social capital. Appropriate incentives are essential for management to reduce bycatch, and have been applied across multiple governance approaches (Dunn et al., 2011; Lewison et al., 2015; Little et al., 2015). However, fishers who are well-incentivized to avoid undesired bycatch must still understand what fishing behaviors will help them do so. Informational products have been developed to provide some of this guidance by delineating areas of higher bycatch risk (Howell et al., 2008; Hazen et al., 2017, 2018). The intent is for fishers to use these products to select areas where bycatch rates are lower. Much of the current DOM research

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has focused on generating distributions (Siders et al., 2020; Hazen et al., 2021) or decision rules for defining closed areas (Welch et al., 2020; Smith et al., 2021). A remaining element in the utility of such DOM tools is whether or not fishers are incentivized to use them.

TurtleWatch (Howell et al., 2008) is one of the earliest and longest running informational product tools that is often described as an example of DOM. Via this tool, daily sea surface temperature (SST) maps delineate open-ocean areas between 17.5 and 18.5 °C, where the majority of north Pacific loggerhead sea turtle (*Caretta caretta*) interactions have taken place with Hawai'i-based shallow-set pelagic longline (SSLL) fishery. These maps are made publicly available so captains in the SSLL fishery can, if those so choose, voluntarily reduce the odds of a loggerhead sea turtle interaction. The strictly informational nature of the TurtleWatch product is, for now, the norm as most DOM products are for voluntary use and are not enforced as part of a regulatory system (Hazen et al., 2017, 2018). As TurtleWatch has been available from late 2006 to present, there is an opportunity to explore the effectiveness of informational products in avoiding bycatch.

For the majority of TurtleWatch's deployment, the SSLL fishery operated under a fleet-wide "hard cap", under which the fishery would close for the remainder of the calendar year if a specified number of annual loggerhead sea turtle interactions occurred with the fishery. The "hard cap" system was implemented as insurance against excessive loggerhead interactions while trialing new gear and bait combinations as well as effort limits to reduce interactions following a three-year closure (85 FR 57988, September 17, 2020). The level of interactions was set at the expected number of turtle interactions given the SSLL fisheries effort, which reduced the odds of exceeding the hard cap. This could be expected to result in fishers having little need of an informational product like TurtleWatch to avoid collectively reaching the hard cap limit.

In general, the "hard cap" system ensures the costs from a closure are shared among the fleet while the benefits from catching Swordfish (*Xiphius gladius*) are solely enjoyed by the individual fisher, a classic reciprocal externality (Holland, 2010). Fishers might be expected to not alter their fishing locations as the hard cap is approached based on the classic tragedy of commons understanding (Gordon, 1954; Scott, 1955; Hardin, 1968). Worse yet, a race to fish may be incentivized under a hard cap resulting in little avoidance of bycatch (Abbott and Wilen, 2009). The "hard cap" system also further disincentivizes individual fishers to proactively avoid loggerhead interactions using DOM informational products as the costs associated with voluntary avoidance (e.g., fuel, travel time) are experienced solely by the individual while the benefits, the fishery remaining open, are shared among all fishers. These binding, pooled, annual hard caps are a frequent regulatory strategy setting protected species bycatch limits in the U.S. (Abbott and Wilen, 2009; Holland, 2010). However, the SSLL fishery also shares some characteristics of systems in which individuals have been shown to behave in the best interest of the community rather than the individual (Olson, 1965; Ostrom, 1990), such as a limited number of participants (12–15 vessels per year) who live in relative proximity to the resource and may share social norms. The hard cap, coupled with social pressure among fishers (Gintis, 2000) may further incentivize individuals to consider the fishing community in their behaviors. In concert, there are reasons to think an informational product such as a TurtleWatch might be used, and reasons to think it might not be used.

We evaluated the TurtleWatch informational product in the three contexts: 1) the continued suitability of the dynamic 17.5–18.5 °C SST TurtleWatch band to demark an area of high loggerhead sea turtle interactions; 2) the historic efficacy of TurtleWatch to prevent loggerhead sea turtle interactions; and 3) the change in the apparent fishers' behavior since the launch of the TurtleWatch informational product. A fourth objective was to understand alternative incentives that may have influenced the use of TurtleWatch by fishers. Each of these objectives touches on an area of broad concern for the utility of DOM products. The first focuses on the definition and longevity of the product, the second on the efficacy of the product under the "hard cap" system, and the third and fourth on the viability of the product. All four represent key elements to understand if fishers have been appropriately incentivized to reduce bycatch and partake in DOM systems. In this case, we are concerned with extrinsic incentives resulting from the governance system motivating fishers to avoid bycatch and cannot speak to the fisher's intrinsic motivations. Together, these aspects of the use of TurtleWatch in SSLL fishery can apprise other protected species management systems considering using or currently using DOM.

2. Approach

2.1. Hawaii-based shallow-set pelagic longline fishery

The Hawai'i-based shallow-set pelagic longline fishery operates out of Honolulu, Hawai'i and several ports in California, U.S.A. and fishes approximately 175–130° W and 25–40° N primarily for Swordfish. The fishery uses a mainline and four to five branch lines between floats with 700–1000 hooks per set. The SSLL fishery operates in all months, but most of the effort occurs December–May. The loggerhead annual hard cap was 17 turtles from 2005 to 2012, with the exception of 2010 when the hard cap was 46 turtles, and 34 turtles from 2013 to 2018, before being dropped back to 17 turtles in 2019 (85 FR 57988, September 17, 2020).

2.2. TurtleWatch

A hard-cap-initiated fishery closure occurred in 2006 (71 FR 14824, March 24, 2006) and prompted the development of the TurtleWatch informational product, deployed on December 26, 2006. TurtleWatch consists of daily maps of SST highlighting a spatial band where interactions have historically been higher (Howell et al., 2008, 2015). The SSTs of the locations of loggerhead sea turtle interactions were compared to the average SST where satellite-tag equipped loggerhead sea turtles located (details below). This resulted in a 17.5–18.5 °C SST band within which roughly 50 % of loggerhead sea turtle interactions were occurred. As SST changes dynamically over the course of the year, the spatial bounds of the band also change dynamically. No additional shutdowns occurred as a result of loggerhead sea turtle interactions since TurtleWatch's deployment in 2006, until 2018 when a court order settlement agreement (TIRN vs. NMFS, 9th Circuit 2017) closed the fishery and lowered the hard cap limit back to 17 turtles (83 FR 49495, October 1, 2018). Subsequently, the interactions reached the 17 turtle hard cap limit on March 19, 2019 and closed for the remaining calendar year (84 FR 11654, March 28, 2019). Since September 17, 2020, the hard cap for loggerhead sea turtles has been replaced by individual trip and vessel limits (50 CFR 665.813).

2.3. Fishery-dependent data

Fisheries-dependent data from the SSLL targeting swordfish were gathered by the National Oceanographic and Atmospheric Administration (NOAA) Fisheries' Pacific Islands Regional Observer Program (PIROP) and provided for 2005–2019 (Pacific Islands Regional Office, 2021), the period when only fleet-wide turtle hard caps were in place. During fishing trips, observers record information about catch by species, the location of fishing effort, and the rigging of fishing gear (Allen and Gough, 2007) and coverage has been 100 % since 2004. PIROP data provides the start and end coordinates where the longline was set and hauled and these four coordinates were converted into a polygon for each set using the *sf* package (Pebesma, 2018) in *R* (R Core Team, 2020), and the centroid of the resulting polygon was used as the interaction location. The total number of loggerhead sea turtle interactions per set was calculated from the PIROP records and, for each set, we calculated the number of swordfish per set, the soak time of the set as the difference in the begin of set and the end of the haul, and the area of the set. We used these data to calculate the catch per unit effort (CPUE) of swordfish, defining effort as the number of hooks per set per time-area swept, where time-area swept was the soak time in hours per square kilometer.

2.4. Loggerhead sea turtle telemetry

Data from SSLL bycaught and captive-reared turtles were used to represent fishery-independent locations of loggerhead sea turtles. Turtles were outfitted with satellite transmitters attached to the dorsal carapace using the procedures outlined in Balazs et al. (1996) and equipped with a variety of Telonics and Wildlife Computers Argos-linked satellite transmitters transmitting locations according to the tag's set duty cycle. Positions were screened using the methods described in Kobayashi et al. (2008) with only the highest quality position data kept in the final data.

2.5. Sea surface temperature

Daily sea surface temperature (SST) was extracted from the Coral Reef Watch global daily sea surface temperature oceanographic product (CoralTemp) (Maturi et al., 2017) hosted on the NOAA OceanWatch ERDDAP server using the *rerddap* package (Chamberlain, 2021). Daily SST values were extracted using each SSLL fishery set polygon and the individual satellite telemetry location estimates. For each sampled day, the position of the 17.5–18.5 °C TurtleWatch band was calculated, and the distance to the band edge was calculated for each fishing set on that day. Additionally, the percent of the set and haul transects of each set that overlapped with TurtleWatch band were calculated.

2.6. Analysis

2.6.1. Objective 1: does TurtleWatch still cover a high proportion of the loggerhead sea turtle interactions?

We first assessed whether the original TurtleWatch product, the 17.5–18.5 °C band, was still valid as an area where the majority of loggerhead sea turtle interactions occur. We compared the distribution of SST for the PIROP observed sets, for sets with loggerhead sea turtle interactions, for telemetry sea turtle locations, and for telemetry locations in the minimum convex hull of the SSLL fishery operation. The minimum convex hull for the SSLL fishery was determined in each quarter using all fishing locations within a quarter across years (2005–2019). For the fishery locations, we further explored the relationship between log-transformed swordfish CPUE and SST by quarter. For each quarter, we calculated the proportion of total number of sets and loggerhead sea turtle interactions in the 17.5–18.5 °C band.

2.6.2. Objective 2: has TurtleWatch prevented loggerhead sea turtle interactions?

To evaluate if implementing TurtleWatch has changed the number of loggerhead sea turtle interactions, we fit a series of generalized linear models (GLMs) to the number of interactions per the number of hooks per hour of soak time, per the numbers of hooks per time-area swept, and per swordfish caught. We used the years since TurtleWatch was implementation and loggerhead sea turtle population size as covariates and accounted for temporal autocorrelation through autocorrelated errors (specifics can be found in Supplemental Information 1). We fit all models in STAN (STAN Development Team, 2020b) with the *rstan* package (STAN Development Team, 2020a) and assumed weakly informative priors. We assessed the effect size and significance of these covariates at an $\alpha = 0.1$ using the 90 % credible interval of each parameter.

2.6.3. Objective 3: has fisher behavior changed as a result of TurtleWatch?

We assessed changes in fishing location choice two different ways. We first modeled the distance to the TurtleWatch band as a function of the proportion of loggerhead sea turtle hard cap reached on a given day of a given year. We used a hurdle model (or delta-style) (Maunder and Punt, 2004) structure to separate the binary component and positive components and autocorrelated errors to account for temporal autocorrelation. The binary component modeled the odds of the average set occurring in the TurtleWatch band (resulting in a zero distance) while the positive component modeled the distance to the band if the average set occurred outside of the band on a given day. We used as covariates the proportion of the hard cap filled to account for location changes as the hard cap was approached and sea surface temperature to account for the seasonal dynamics in the fisheries' average fishing location (specifics available in Supplemental Information 1).

The second behavioral assessment modeled the average overlap of sets with the TurtleWatch band on a given day as a function of the proportion hard cap filled. This allowed us to assess if fishers were avoiding the TurtleWatch band as a fishery shutdown became more likely. We assumed the same hurdle model structure as the distance to the band model but modified to model the average overlap of sets on a given day using the Beta proportion distribution (specifics available in Supplemental Information 1).

2.6.4. Objective 4: what is influencing fisher behavior?

We were interested in exploring alternative extrinsic incentives to fishers that resulted in them fishing in the TurtleWatch band even as risk of a shutdown increased from loggerhead sea turtle interactions. We evaluated two possible factors. The first was that compression of the TurtleWatch band, associated with the compression of the North Pacific Transition Zone (Polovina et al., 2006), would concentrate loggerhead sea turtles and fishers in a smaller area leading to increased interactions. To evaluate this scenario, we estimated the width of the TurtleWatch band for every day SSLL fishing occurred from 2005 to 2019. On the 17.5 and 18.5 °C temperature isoclines, we systematically placed 100 pairs of points, one on each isocline, and calculated band width as the mean of the measured distance between each pair. We then modeled the rate of loggerhead sea turtle interactions per day as a function of the mean TurtleWatch band width for each year. We modeled the interaction rate as a function of the width following Eqs. (1)–(3) in the Supplemental Information without the additional fixed effect for loggerhead population size and implemented the model the same way in STAN. This allowed us to assess how the rate of interactions was influenced by the TurtleWatch band width.

The second factor we evaluated was fishers seeking to maintain an expected catch rate. If catch rate is a strong motivator of fisher location choice, the expectation is that effort will distribute spatially so that no area has a catch rate higher than any other (i.e., an ideal free distribution). In general, areas with greater availability of the target species will have a greater fishing effort. If catch rate is level across the thermal gradient (a surrogate for longitude and productivity), then catch rate is likely a strong motivator driving fishers' decisions. To investigate if this catch rate leveling is occurring in the SSLL fishery, we tabulated the distribution of swordfish CPUE in each quarter and across the year by shifting 0.5 °C SST bins (e.g., 17–18 °C, 17.5–18.5 °C).

3. Results

3.1. Summary of loggerhead sea turtle interactions

A total of 192 loggerhead sea turtle interactions with the SSLL fishery occurred from 2005 through the hard cap triggered fishery closure in 2019. Of these, 165 interactions have occurred since the deployment of TurtleWatch in late 2006. Across all years, by quarter, there were 143, 17, 5, and 27 loggerhead sea turtle interactions. In the first quarter, interactions decreased from 54 in January, to 49 in February, to 37 in March while all but one interaction in the second quarter occurred in April. Similarly, all but 5 interactions occurred in December in the fourth quarter. December through April is the main period of loggerhead sea turtle interactions for the SSLL fishery.

3.2. Summary of loggerhead sea turtle telemetry

From 1997 to 2015, a total of 380 satellite-linked transmitters were deployed for a mean of 323 days. The majority of the tags (93.4 %) were deployed west of 180° with only 25 turtles tagged east of 180°W in the fishery operational area. Captive rearing programs from nesting beaches in Japan released the majority of tagged turtles, with release dates mainly occurring in the spring-fall. There is ongoing research to increase the number of observations from larger turtles captured and released within the operational area of the fishery. While there is no direct comparison between the at-sea behavior between wild and captive-reared loggerheads, there are some suggestions that behavior in sea turtles is similar between the two types (Nichols et al., 2000). Six of the turtles did not have a size recorded at capture but, of the remaining 374, 30 % were sizes typically caught in the SSLL fishery (i.e., greater than 40 cm standard carapace length) (Martin et al., 2020). Locations of class G, 1, 2, 3 were used for positions resulting in a reduction of the initial 206,729 locations down to 107,681, a ten-fold increase from Howell et al. (2008). Coverage had a minor seasonal trend with lower number of observations in the spring and summer months. In the observations, 51 % of the locations were west of 180° and 47 % occurred in the operating area of the SSLL fishery (Supplemental Fig. 1).

3.3. Objective 1: does the TurtleWatch product still predict potential interactions?

We found that the original TurtleWatch product, 17.5–18.5 °C SST, still overlapped with the SSTs of loggerhead sea turtle interaction locations in the first and fourth quarters (Fig. 1). In the first quarter, most of the interactions had SSTs between 16.9 and 17.5 °C showing that current TurtleWatch band covers a wider range of SST than may be necessary while most telemetry locations occurring in waters colder than 17.5 °C (Fig. 1). In the second and third quarters, the distribution of SST for the telemetry and fishery locations shifted to warmer waters with minimal overlap with TurtleWatch in the interactions in the second quarter and none in the third. Loggerhead sea turtle interactions in the second quarter were approximately 4 °C colder than the set locations resulting in the greatest disparity between these two subsets across all quarters. In the fourth quarter, the distribution of SST for the telemetry and fishery locations all strongly overlapped with the 17.5–18.5 °C band and was the most similar over all quarters (Fig. 1).

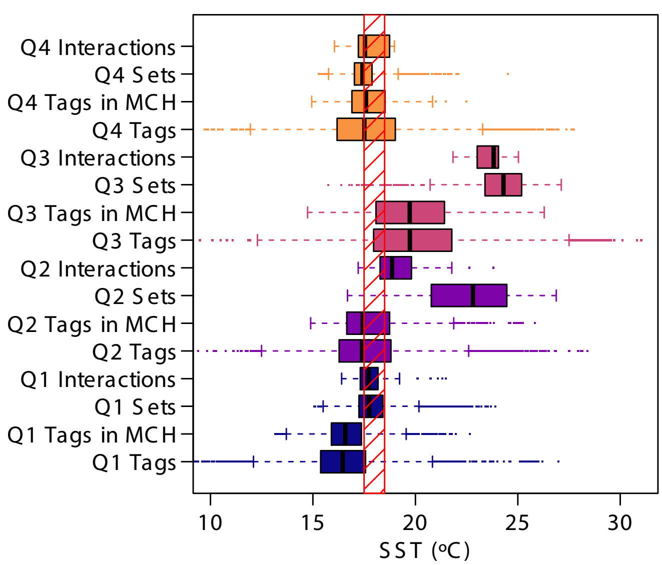

Fig. 1. Boxplots of the sea surface temperature (SST) by quarter aggregated from the years 2005–2019 for the loggerhead sea turtle telemetry locations (tags), the telemetry locations in the minimum convex hull of the Hawai'i shallow-set pelagic longline fishing effort (tags in MCH), the Hawai'i shallow-set pelagic longline fishing sets (sets), and the Hawai'i shallow-set longline pelagic interactions with loggerhead sea turtle (interactions). For each, the interquartile range is given by the box, one-and-a-half times the interquartile range by the whiskers, and data beyond the whiskers as dots. The 17.5–18.5 °C TurtleWatch band is shown in the red hash. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Across all quarters, swordfish CPUE was concentrated between 1 and 100 swordfish per hook per time-area swept (h, km^2) (Fig. 2). In the first quarter, fishing operations spanned the band and the majority of loggerhead sea turtle interactions occurred within the TurtleWatch band or in cooler waters. Interactions with multiple turtles tended to occur within the band (Fig. 2A). In the second and third quarters, only 4 % and 3 % of the sets, respectively, occurred in the band; most sets were in far warmer waters (Fig. 2B and C). In the fourth quarter, the fleet fished predominantly colder waters or in the band (Fig. 2D). A third of interactions in the second and fourth quarters came from within the band, but in the second quarter the remainder came from SSTs warmer than the band, while interactions in the fourth quarter came from SSTs within 1 °C of the band. Only the first and fourth quarters had more than one interaction per set. These multi-turtle interactions made up a greater proportion of the sets with interactions in the fourth quarter.

3.4. Objective 2: has TurtleWatch prevented loggerhead sea turtle interactions?

All three GLMs of loggerhead sea turtle interactions per hooks hour^{-1}, per hooks hour^{-1} area^{-1}, and per swordfish had significant negative intercepts (α) and significant positive slopes for time since the TurtleWatch implementation (β_{TW}), indicating the interaction rate increased after the implementation of TurtleWatch (Table 1). All of the models had insignificant negative slopes for loggerhead sea turtle population trend (β_P) and insignificant positive temporal autocorrelation (ϕ) (Table 1). These results suggest that the implementation of TurtleWatch has not decreased loggerhead sea turtle interactions even when accounting for population trend and autocorrelation (though these were not significant).

3.5. Objective 3: has fisher behavior changed as a result of TurtleWatch?

Most effects for the distance to the TurtleWatch band and the degree to which a set polygon overlapped the TurtleWatch band were significant. The probability of a set occurring in the TurtleWatch band was higher for the overlap model (~50 %) than the distance model (~10 %), though this difference is due to the averaging by day (Supplemental Fig. 2A). Similarly, the temporal autocorrelation was higher in the overlap model than the distance model (Supplemental Fig. 2B). Sets were predicted to be approximately 7.5 km from the band and have an odds-ratio of 2 (Supplemental Fig. 2D) when none of the loggerhead sea turtle hard cap is filled and the set SST is at its minimum, 15.07 °C. The band model predicted the distance to insignificantly decrease as the hard cap was filled (Supplemental Fig. 2E), but significantly increase as SST increased (Supplemental Fig. 2F). The inverse was true for the overlap model with a significant positive increase in TurtleWatch band overlap as the hard cap was filled (Supplemental Fig. 2E), but an insignificant decrease in overlap as SST increased (Supplemental Fig. 2F). For both models, this indicated that fishers fished closer to and overlapping more with the TurtleWatch band as the hard cap was filled. At the mean SST, this equates to a 142 % increase in the median odds for the overlap model when the hard cap is filled. Thus, there is no evidence that the TurtleWatch band discouraged fishing in the high-interaction zone, at least given the incentives the governance approach imposed.

3.6. Objective 4: what may influence fisher behavior?

We explored two alternative extrinsic incentives that may motivate

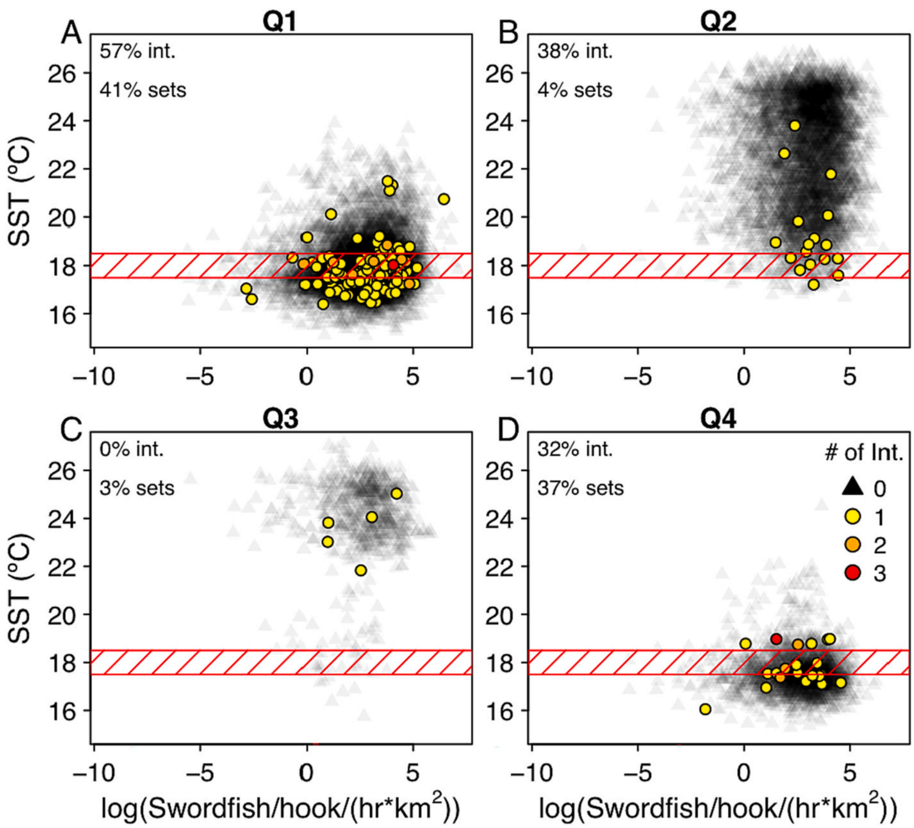

Fig. 2. Sea surface temperature (SST) as a function of swordfish CPUE (log(swordfish/hook/(h * km^2))) for every Hawai'i shallow-set pelagic longline fishery set without a loggerhead sea turtle interaction (black triangles) or with an interaction (colored dots; warmer colors indicate more turtles per set) for the first (A), second (B), third (C), and fourth (D) quarters aggregated from the years 2005–2019. The 17.5–18.5 °C TurtleWatch band is shown in the red hash. In the upper left of each plot is the percent of interactions occurring in the band (% int.) and the percent of fishery sets occurring in the band (% sets) for that quarter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Median and 90 % credible intervals (in parentheses) effect sizes for the intercept (α), slope of years since TurtleWatch implementation (β_t), slope of loggerhead sea turtle population size (β_P), temporal autocorrelation coefficient (ϕ), and standard deviation (σ) for each of the three different models using loggerhead sea turtle interactions per hooks per hour (hk h^{-1}), per hooks per area-hour (hk h^{-1}a^{-1}), and per Swordfish.

θ	Per hk h^{-1}	PER hk h^{-1}a^{-1}	Per swordfish
α	−0.94 (−1.67 to −0.25)	−0.92 (−1.64 to −0.21)	−1 (−1.66 to −0.31)
β_{TW}	0.15 (0.06–0.25)	0.15 (0.06–0.25)	0.16 (0.07–0.25)
β_P	−0.34 (−0.73–0.09)	−0.31 (−0.7–0.13)	−0.31 (−0.66–0.09)
ϕ	0.37 (−0.07–0.75)	0.49 (0.03–0.88)	0.32 (−0.14–0.71)
σ	0.7 (0.51–1.05)	0.67 (0.48–1)	0.67 (0.49–1.02)

fishers to choose locations that could result in increasing odds of shutting down the fishery. In terms of habitat compression driving fisher's location choice, we observed an insignificant but negative relationship between the loggerhead sea turtle interactions per day and TurtleWatch band width (Fig. 3). This means habitat compression of the North Pacific Transition Zone seems to have some influence on fisher's location choice, assuming that the band is a reasonable representation of a region more densely occupied by loggerhead sea turtles. However, the influence of habitat compression is highly variable across years and within years and unlikely to be the major motivator of location choice. Two years, 2012 and 2017, departed from this relationship and instead showed a low number of interactions across a very narrow TurtleWatch band and, unlike the other time series models, there was no temporal autocorrelation in the time series (Fig. 3).

In terms of catch rate driving fisher's location choice, we observed a nearly identical mean CPUE for every 0.5 °C SST bin for all quarters (Supplemental Fig. 3). Fisher behavior was such that swordfish CPUE was relatively level across SST bins and across quarters despite large changes in fishing locations and SST regimes within and across years (Supplemental Fig. 1). This remarkable catch rate leveling indicates (i) the highly unlikely possibility that swordfish are equally available across a range of conditions and locations;, (ii) the far more likely possibility that the fleet, as a whole, operates as if it has good knowledge of where swordfish can be caught under different temperatures, or (iii) the fleet engages in effort sorting such that effort is expended by certain vessels only when suitable catch rates can be obtained. It is most likely a combination of fleet-wide expertise and effort sorting in the SSLL fishery as fishers can retool their gear to target tuna and join the Hawai'i deep-set pelagic fishery.

4. Discussion

We evaluated the suitability, efficacy, and behavioral impacts of providing the TurtleWatch informational product for the SSLL for swordfish. We found that the information provided by TurtleWatch does not appear to have reduced loggerhead sea turtle interactions nor altered fisher behavior in the SSLL fishery, as evidenced by no apparent change in the setting locations of the fishers relative to the TurtleWatch band. Thus, it appears that the hard cap regulatory structure did not motivate voluntary avoidance and use of TurtleWatch. However, we can unequivocally conclude in the first and fourth quarters the 17.5–18.5 °C TurtleWatch sea surface temperature band overlaps with the SST of 30 % to 60 % of loggerhead interactions with the fishery. We can also confirm, as do Howell et al. (2008), that in the second and third quarters of the year the TurtleWatch band does not overlap with the SST of the few loggerhead sea turtle interactions that occurred. Nonetheless, the TurtleWatch product is effective for delineating the habitat characteristics where most loggerhead interactions occur and during the period when the majority occur.

The importance of socioeconomic incentives for inducing desired individual fisher and fleet-wide behavior is well-established (Hanna, 1998; Hilborn, 2004; Hilborn et al., 2005; Grafton et al., 2006), particularly for limiting bycatch (Gilman et al., 2008; Miller and

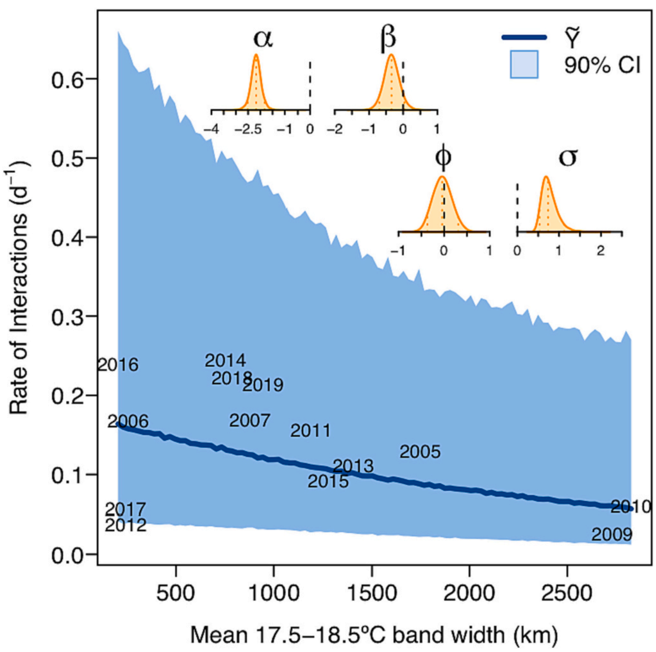

Fig. 3. The rate of loggerhead sea turtle interactions with the Hawai'i shallow-set pelagic longline fishery per day by year as a function of the mean width of the 17.5–18.5 °C sea surface temperature band (TurtleWatch band) in kilometers. The solid blue line is the median prediction, and the shaded blue region is the 90 % credible interval of predictions from a log-normal linear model of the interaction rate as a function of the band width. Posteriors of the intercept (α), slope (β), autocorrelation (ϕ), and the standard deviation (σ) are shown in orange with dashed orange vertical lines indicating the 5, 50, and 95 % quantiles and the black dashed line indicating zero. Posteriors overlapping zero are considered insignificant. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Deacon, 2017; Lent and Squires, 2017). The economic theory of utility suggests that individual operators will select fishing sites in the high-interaction band as long as these locations provide the greatest utility among alternatives (McFadden, 1986) and provided fishers are rational (Holland, 2008). Further, it has been shown that some information sharing programs do reduce bycatch, but only when incentives are such that individual fishers in fact want to or need to do so (Gilman et al., 2006). Taken in this context, our results that fishers concentrating in the TurtleWatch band, especially as the hard cap was approached, represent their highest-utility choice. This could be the result of several different dynamics affecting individual or fleet behavior.

The first dynamic is operational compression. The SSLL fishery is seasonal, occurring mostly from December through April, and the drive to maximize catch in this window may reduce the incentivization to avoid protected species because any given interaction is rare. A second dynamic is that with an increasing turtle population, a rare and variable interaction rate, and a fixed hard cap, a traditional tragedy-of-the-commons incentive structure may have been established (Crowder and Murawski, 1998; Holland, 2010; Bisack and Das, 2015). Here, the full benefits of catching a swordfish accrue to the individual vessel whereas the costs of reaching the cap are shared across the entire fleet, i.e., reciprocal externalities, and likely incentivize a race to fish (Abbott and Wilen, 2009). A third dynamic is that perhaps the costs of the fleet hitting the hard cap are not substantial enough to warrant avoidance behavior. Fishers in the SSLL fishery can retool and fish in Hawai'i deep-set pelagic longline fishery targeting bigeye tuna (*Thunnus obesus*) at some cost if the SSLL fishery is shut down (Pan, 2014). A fourth dynamic is that the hard cap limit was originally set at the expected number of interactions given the SSLL effort and, with the exception of 2006 and 2019, has prevented naturally exceeding this cap (84 FR 11654, March 28, 2019). These alternatives have previously been recognized as factors contributing to non-compliance with bycatch rules in other fisheries (Bisack and Das, 2015). Finally, other potential drivers exist that were not explored here, such as broader market competitive forces that may incentivize interaction-risky behavior (Panagopoulou et al., 2017). These could be driven by market value of Swordfish or encroachment of international fisheries with SSLL fishing grounds that might alter catch rates. Lastly, the regulations for reducing loggerhead bycatch occur simultaneously with other protected species regulations, such as those for leatherbacks sea turtles (*Dermochelys coriacea*) and false killer whales (*Pseudorca crassidens*), that could provide stronger incentives for avoidance than loggerhead regulations. Any combination of these dynamics may be occurring and while the result is the same for loggerhead sea turtle interactions, the differing underlying motivation of the fishers would almost certainly have implications for the efficacy of alternative incentive and broader management or governance approaches (O'Keefe et al., 2014; Segerson, 2022).

The recent regulatory change to individual trip limits (50 CFR 665.813) may change the individual vessels' perception of the cost of loggerhead sea turtle interactions. This change moves from a fleet-wide cap of 17 loggerhead sea turtles (as of 2019) to an individual vessel trip limit of 5, at which point the vessel must immediately stop fishing, return to port, and may not resume shallow-setting until it meets certain requirements. These new regulations were intended to shift the incentives from fleet to individuals as well as reduce any inequities that result from an individual vessel disproportionately contributing to the fleet-wide hard cap. Gilman et al. (2007) reported a long-tailed distribution of the interactions of loggerheads per vessel from 1994 to 2006 from 68 vessels with half the fleet interacting with less than 3 turtles and a maximum of 23. In our dataset from 2005 to 2019, we observe the same long-tail distribution as Gilman et al. (2007) with 240 different permitted vessel numbers with a maximum of 38 turtles but, departing from Gilman et al. (2007), with 90 % of those interacting with less than 3 turtles. The new individual trip-limits might deter the race to fish (Abbott and Wilen, 2009) and also would seemingly affect only the individual vessels' perception of the cost of loggerhead sea turtle interactions and might cause some fishers to use the TurtleWatch informational product. This new incentive structure should provide an interesting comparison to the hard cap incentivization under the same DOM informational product once a sufficient time series is developed.

Previous explanations for the increasing interactions have focused on the change in the loggerhead sea turtle population. Martin et al. (2020) estimated an increasing north Pacific loggerhead sea turtle population and hypothesized this could be driving the increased in interactions with the SSLL fishery. While our analyses suggest that this is currently not the case, a growing population would likely produce more frequent interactions. The increase in interactions may be the result of above-average year classes moving into the area of fishery operations as the population grows, a dynamic that would be difficult to directly relate to nesting beach trends (Martin et al., 2020). A growing population may also result in the spatial expansion of areas of high interactions reducing the utility of the TurtleWatch product. The chlorophyll-a front that motivated Howell et al. (2008) to develop TurtleWatch fluctuates year-to-year, and changes in the gradient strength could result in changes to the fishing fleet and turtles' distributional overlap. The increase in turtle interactions in years where the TurtleWatch band is compressed creates an additional level of complication for the fishery which is further complicated by the compression of large-scale oceanographic features due to effects of climate changes (Stramma et al., 2012; Mislan et al., 2017; Santora et al., 2020). The North Pacific subtropical convergence zone may be one of these areas. If the TurtleWatch band continues to demark a productive area for swordfish, band compression may result in a further increase in interaction rates over time making the TurtleWatch information more relevant to fisher's decision-making.

Informational products, such as TurtleWatch, are intended to help fishers engage in self-directed DOM with the aim of reducing interactions with specific bycatch species. Our evaluation of TurtleWatch clearly demonstrates that a suitable informational product does not necessarily translate to an effective DOM tool. The lack of avoidance of high interaction areas suggests that the historic incentive structure (i.e., common pool interaction limits) did not sufficiently incentivize an individual fisher to seek out areas with a lower chance of interaction. This results from the range of socio-ecological factors fishers consider in their decision-making with protected species bycatch comprising some fraction. While much of DOM research has focused on generating avoidance areas, it is prudent to strongly evaluate whether fishers are appropriately incentivized to use the information to avoid bycatch especially in self-directed DOM structures. With multiple protected species regulations to consider in many pelagic fisheries, the individual species incentive structures are likely to interact in unexpected ways and result in inefficiencies to the fishery and to the populations' conservation.

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CRediT authorship contribution statement

Zachary Siders: Conceptualization, Formal Analysis, Writing, Resources, Funding acquisition **Robert Ahrens:** Conceptualization, Data Curation, Formal Analysis, Writing **Summer Martin:** Resources, Writing **Edward Camp:** Conceptualization, Writing **Alexander Gaos:** Investigation, Data Curation, Writing **John Wang:** Resources, Writing **Jamie Marchetti:** Resources, Writing **Todd Jones:** Conceptualization, Resources, Writing.

Declaration of competing interest

The authors have no conflict of interests to declare.

Data availability

The Hawai'i shallow-set pelagic longline fishing information used herein is confidential, protected information and cannot be disseminated.

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Appendix A. Supplementary data

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