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Vessel monitoring systems (VMS) reveal an increase in fishing efficiency following regulatory changes in a demersal longline fishery

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ABSTRACT

A global expansion of satellite-based monitoring is making fisher behavioral responses to management actions increasingly observable. However, such data have been underutilized in evaluating the impacts of fishing on target and non-target fish stocks or the ramifications of management strategies on fishers. We demonstrate how vessel monitoring system (VMS) data can provide a suite of metrics (such as effort) for improving inputs to stock assessments, dynamic delineation of fishing grounds, and evaluation of regulatory or other (e.g., climatic) impacts on fisher performance. Using >1 million VMS records from the Gulf of Mexico grouper-tilefish demersal longline fishery, we first develop a generalized additive modeling approach that predicts fishing duration with $\sim$85% accuracy. We combine model predictions with logbook data to compare the fishery before and after implementation of a suite of regulatory changes (e.g., a shift to catch share management). We find a large-scale reduction in fleet size, accompanied by reduced fishing effort (duration * number of hooks), shorter trips, lower operational expenses, higher catch rates, and more earnings for those vessels that remained in the fishery. We discuss how the combination of VMS and associated metrics can be expanded for use in management strategy evaluation, parameterizing economic models of fisher behavior, improving fishery-dependent stock assessment indices, and deriving socioeconomic indicators in fisheries worldwide.

1. Introduction

Many factors drive the dynamics of commercial fisheries and substantial effort is expended on understanding and predicting fisher responses to such drivers. As fishing fleets react to changing environments, markets, and governance, the ability of scientists and managers to quantify their behavior becomes increasingly critical for understanding not only the dynamics of exploited stocks but the economic sustainability of the fisheries themselves (van Putten et al., 2012; Fulton et al., 2011).

Vessel monitoring systems (VMS) have improved our ability to monitor fishing vessel movements and to evaluate fishing fleet behavior (e.g., fishing location) and spatially-explicit economic decision-making (e.g., Watson and Haynie, 2018). VMS transmit vessel locations at regular intervals, and are required by dozens of national governments and regional fisheries management organizations. These systems facilitate monitoring of speeds, changes in bearing, locations, and other aspects of vessel behavior that can indicate when and where vessels are fishing.

VMS have been used to examine spatial fishing activities at higher temporal resolutions, leading to more precise estimates of effort (e.g., Mills et al., 2007; Peel and Good, 2011; Joo et al., 2013), validation of fisher-reported logbooks (e.g., Palmer and Wigley, 2009; Bastardie et al., 2010), delineation of fishing grounds (e.g., Stelzenmuller et al., 2008), assessment of benthic impacts from fishing (e.g., Lambert et al., 2011), and more. Some software packages now simplify and automate

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standard VMS analyses (Russo et al., 2014, or Hintzen et al., 2012), but specific case studies often still require customized modeling approaches. For example, Ducharme-Barth and Ahrens (2017) developed random forest algorithms with VMS data to assess changes in fishing effort as a result of closures associated with the Deepwater Horizon Oil Spill. O'Farrell et al. (2017) examined solutions for identifying fishing behavior when fishing events occurred over time intervals that were less than the VMS sampling frequency. Thus, while software can be used to automate some tasks, more general analytical approaches and metrics must be developed to address individual cases. As environments change and regulatory strategies shift, the ability to monitor impacts on fishers using VMS data will become increasingly important (Melnychuk et al., 2012; Clay et al., 2014).

Catch share systems are an example where managers may wish to quantify fisher responses to regulatory change. Catch shares seek to reduce the inefficiencies resulting from too many fishers competing for limited resources (Grafton, 1996) and evaluation of such systems can be enhanced through resolution of spatial dynamics in the fishery. With catch shares, individual fishers are allocated shares of the total catch, which enables them to seek fishing opportunities in locations that minimize costs and maximize expected revenue (e.g., Haynie and Layton, 2010; Birkenbach et al., 2017). VMS data provide the opportunity to monitor fishing locations and durations at the trip-, set-, or haul-levels. Through VMS-derived estimates of fishing duration, changes in the efficiency of fishing (e.g., catch or revenue per unit effort) can be quantified across time to monitor the effects of catch shares or other regulatory transitions.

The demersal longline fishery for reef fishes in the Gulf of Mexico is one fishery with VMS that has undergone a dramatic regulatory transition, providing an opportunity for quantifying the associated changes in fishing behavior (e.g., location and duration) and economic performance (e.g., catch, cost, and revenue). This fishery primarily targets gag grouper (*Mycteroperca microlepis*) and red grouper (*Epinephelus morio*) as well as tilefishes (*Caulolatilus* spp.) and a complex of other deep- and shallow-water groupers (Farmer et al., 2016; Supplementary material Appendix Table A.1), with 2015 ex-vessel revenue of $28 million (NMFS, 2016). In 2010, an individual fishing quota (IFQ), or catch shares, system was implemented to avoid continuation of "… higher than necessary levels of capital investment, increased operating costs, increased likelihood of shortened-seasons, reduced safety at-sea, wide fluctuations in grouper supply, and depressed ex-vessel prices; leading to deteriorating working conditions and lower profitability for participants." (Amendment 29; Gulf of Mexico Fishery Management Council, 2008). The changes associated with the catch share transition came a year after sea turtle bycatch regulations were introduced, consisting of time-varying, area-specific depth restrictions and a reduction in the maximum number of hooks. The fleet was further impacted by a longline endorsement program that restricted fishing to vessels that had sustained average annual catches greater than 40 000 pounds from 1999 to 2007 (Amendment 31; Gulf of Mexico Fishery Management Council, 2010).

Our study makes several contributions to the literature on quantifying fisher behaviors (e.g., unobserved spatial fishing patterns) and exploring fisher responses to regulatory changes. First, we use VMS data to build a probabilistic model for estimating unobserved fishing duration (for our purposes, duration is longline set, soak, and retrieve time). Second, we combine the results from our VMS-based model with logbook data to derive fishing activity and performance metrics like trip distance, effort (fishing duration * number of hooks), catch per unit effort, and revenue per unit effort. Finally, we test the hypothesis that regulatory changes increased fishing efficiency (i.e., increased revenue for less effort) in the Gulf of Mexico demersal longline fishery for reef fishes. Although we demonstrate our method by asking questions of fisher responses to regulatory changes, we stress that the approach could also be used to investigate fishing responses to a broad range of disturbances, including climatic regime shifts, catastrophic events (e.g., oil spills), or fishery collapse.

2. Data and methods

We integrated three data sources (observer, VMS, and logbook data) into our modeling approach. Observer data were used to train and validate models of VMS data for estimating fishing effort, as described below. VMS data were then merged with logbook data to derive and evaluate a suite of behavioral, performance and economic metrics to understand the impacts of regulatory changes. All analyses were performed using R Statistical Software Version 3.3.2 (R Core Team, 2016).

2.1. Data

An observer program was established in 2006 for all vessels federally permitted to target reef fish using demersal longlines in the Gulf of Mexico (Scott-Denton et al., 2011). The number of vessels in this program changed dramatically during our study period (discussed below). Trips in this fishery average ~10 days and on-board observers are assigned to vessels in the fleet to record operational and catch information (e.g., information on gear, set, catch and trip characteristics). In our case, 183 bottom longline trips (~4% of trips) were observed on 62 vessels from 2007 to 2012 for which we also had VMS and logbook data.

Since 1993, commercial vessels that were federally permitted in the Gulf of Mexico also had logbook reporting requirements. Logbook requirements have evolved since then and, for many years, longline soak times or other metrics of fishing duration were not consistently collected. Thus, no estimates of fishing duration other than trip days were available from logbooks for the pre- and post-regulatory transition (unless trip duration was considered as a proxy for fishing effort).

VMS programs have required the transmission of hourly vessel location information since 2007 (Amendment 18A; Gulf of Mexico Fishery Management Council, 2005). We used VMS-based vessel locations and time-stamps to calculate the distance between VMS records (using the Haversine formula [Sinnot, 1984; Charles et al., 2014]), vessel speed, and distance from port.

Speed calculations were based on the average time and distance travelled between records at times t and t-1 and times t + 1 and t. Records with speeds over either of these time periods exceeding 20 knots were considered erroneous and were excluded.

2.2. Model-estimation of fishing duration from VMS data

VMS data for individual trips were combined with observer data and modeled to estimate fishing duration (see Supplementary material Appendix A for details on identification of trips from VMS data). When observers were present (~4% of trips during our study period), they reported the start and end times for each longline set, which allowed us to train models that predicted fishing duration based on VMS data. Observers reported an average of 27 (± 13.1) sets per trip with an average duration of 4.2 h per set, so that the average set had 4–5 VMS records, depending on when a VMS ping occurred relative to observed start and stop times of fishing (see O'Farrell et al., 2017 for a discussion of VMS transmissions vs. fishing event duration). If a VMS record occurred between observer-reported set start and end times, we considered the VMS record to represent a fishing event. We fit logistic generalized additive models (GAMs; Hastie and Tibshirani, 1990; Wood, 2006) with a logit link to observed VMS records to estimate the probability that fishing occurred (p(fishing)) based on a suite of covariates (Table 1) that described fishing activities:

$$\text{logit}(p(\text{fishing})) = s_1(\text{Covariate}_1) + s_2(\text{Covariate}_2,\text{Covariate}_3) + \ldots + s_j(\text{Covariate}_k), \quad (1)$$

where $s_i(\cdot)$ represents an individual smoothing function for each