Received: 14 August 2019 | Accepted: 19 November 2019

DOI: 10.1111/1365-2664.13565

RESEARCH ARTICLE

Journal of Applied Ecology BRITISH ECOLOGICAL SOCIETY

Lost opportunity: Quantifying the dynamic economic impact of time-area fishery closures

James A. Smith[1,2] | **Desiree Tommasi**[1,2] | **Jonathan Sweeney**[1,2] | **Stephanie Brodie**[1,3] | **Heather Welch**[1,3] | **Elliott L. Hazen**[1,3] | **Barbara Muhling**[1,2] | **Steven M. Stohs**[2] | **Michael G. Jacox**[3,4]

[1]Institute of Marine Science, University of California Santa Cruz, Santa Cruz, CA, USA

[2]NOAA Southwest Fisheries Science Center, La Jolla, CA, USA

[3]NOAA Southwest Fisheries Science Center, Monterey, CA, USA

[4]NOAA Earth System Research Laboratory, Boulder, CO, USA

Correspondence
James A. Smith
Email: jsmith35@ucsc.edu

Funding information
NOAA Coastal and Ocean Climate Application COCA Program, Grant/Award Number: NA17OAR4310268

Handling Editor: Andre E. Punt

Abstract

1. Time-area closures are an important tool for reducing fisheries bycatch, but their effectiveness and economic impact can be influenced by the changes in species distributions. For fisheries targeting highly mobile species, the economic impact of a closure may by highly dynamic, depending on the current suitability of the closed area for the target species.
2. We present an analysis to quantify the fine-scale economic impact of time-area closures: the 'lost economic opportunity', which is the percentage of total potential profit for an entire fishing season that occurs within and during a time-area closure. Our analysis integrates a spatially explicit and environment-informed catch model with a utility model that quantifies fishing revenues and costs, and thus incorporates a dynamic target species distribution in the estimated economic impact of a closure. We demonstrate this approach by evaluating the economic impact of the Loggerhead Conservation Area (LCA) on California's drift gillnet swordfish *Xiphias gladius* fishery.
3. The lost economic opportunity due to the LCA time-area closure ranged from 0% to 6% per season, with variation due to port location and trip duration, as well as inter-annual changes in swordfish distribution. This increased by 40%–90% when a seasonally varying swordfish price was considered.
4. There was a clear signal in economic impact associated with a shift from warm to cool conditions in the California Current following the 1998 El Niño, with increased lost economic opportunity from 1999. This signal was due to higher swordfish catch inside the LCA during the cool phase, associated with increased water column mixing, and due to higher catches outside the LCA in the warmer phase, associated with increased sea-surface temperature.
5. *Synthesis and applications.* We found small economic impact from a fishery closure, but with meaningful inter-annual variation due to environmental change and the dynamic distribution of a target species. Our approach could be used to help determine the timing of closures, simulate impacts of proposed closures and, more generally, assess some economic consequences of climate-induced shifts in species' ranges.

Not all authors are U.S. Government employees.

KEYWORDS
bycatch, dynamic ocean management, fisheries management, fishery closure, spatial management, species distribution model, time-area closure, utility

1 | INTRODUCTION

Bycatch is the unintended catch of non-target species, and remains one of the greatest threats to sustainable fisheries worldwide (Lewison et al., 2014). Bycatch in fisheries for highly migratory species can result in huge economic loss, for example exceeding prescribed bycatch thresholds can result in the closure of entire fisheries (Pan & Li, 2015). Reducing bycatch is often a multi-pronged effort, focusing on changes to fishing gear and fishing practices, and implementation of spatial closures when more action is needed (Hall, Alverson, & Metuzals, 2000; O'Keefe, Cadrin, & Stokesbury, 2014). Spatial closures can be seasonal or temporary ('time-area' closures) and allow fishing when bycatch risk is low (Goodyear, 1999; Grantham, Petersen, & Possingham, 2008).

Time-area closures have been used to manage both target and non-target species, including protecting target species at juvenile life stages or during spawning (Dinmore, Duplisea, Rackham, Maxwell, & Jennings, 2003; Halliday, 1988). When used for bycatch management, a key challenge in the implementation of time-area closures is navigating the trade-off between bycatch reduction and economic opportunity. Closures that successfully navigate this trade-off are able to meet conservation goals through reducing interactions with bycatch species, while also limiting impacts on fishing opportunity and economic costs (Armsworth, Block, Eagle, & Roughgarden, 2010; Dunn, Boustany, & Halpin, 2011). Spatial management approaches remain tied largely to static boundaries (Hazen et al., 2018), so for highly migratory species with dynamic distributions, the effectiveness and impact of a closure might vary greatly through time depending on the habitat suitability of the area being closed, for both target and bycatch species (Hartog, Hobday, Matear, & Feng, 2011; O'Keefe et al., 2014). Thus, benefits and impacts of closures need to be evaluated over a range of oceanic conditions and species distributions. Yet, there are few spatially explicit analyses quantifying how the dynamic distribution of a target species influences the magnitude and variation of the economic impact of a time-area closure.

The design of time-area closures and evaluation of their biological and economic impacts can be informed by monitoring fisher revenues and costs after a closure is implemented (Hobday, Flint, Stone, & Gunn, 2009), but is also frequently aided by modelling and simulation. Approaches include the simulation of historical catch data (Hoos, Buckel, Boyd, Loeffler, & Lee, 2019), coupled population dynamic and fishing effort models (Armsworth et al., 2010; Chakravorty & Nemoto, 2000); systematic planning tools (Dwyer et al., 2019); and fully integrated ecosystem models incorporating population dynamics and the spatial distribution of target and bycatch species (Dichmont et al., 2013). Although most of these models are somewhat spatially explicit, few operate outside the temporal extent of the observed catch data, nor at the fine spatio-temporal scales at which highly migratory species interact with closures. In addition, fully integrated models (e.g Dichmont et al., 2013; Metcalfe et al., 2015), which can evaluate a range of impacts of spatial closures, are complex and difficult to parameterize. It is challenging to operate any of these models at the fine spatio-temporal scales required to resolve the ocean dynamics, species movement and fisher behaviour in dynamic pelagic systems.

Simpler models that include just catch rates and movement costs (Chakravorty & Nemoto, 2000; Powers & Abeare, 2009) are easier to parameterize and can measure the economic impact of time-area closures, but have so far considered only coarse spatial scales, and have not assessed the impacts of changes in species distribution. Adapting this approach to include an environmentally informed statistical model of catch can allow time-area closures to be evaluated in terms of changes in the distribution of highly migratory species, and enable detection of oceanography- and climate-driven signals in impact. An advantage of a 'species distribution' approach is the prediction of economic value ('utility') throughout the fishery domain, to quantify the changing economic opportunity available to a fleet under various closure scenarios (rather than model uncertain fleet responses). This approach also allows a more structured evaluation of closure impact based on port location and fishing trip characteristics, and improves synergy between closure evaluation and 'dynamic ocean management', which seeks to align scales of management to the scales of variability in the distributions of target and bycatch species (Lewison et al., 2015; Maxwell et al., 2015).

Our goal was to evaluate temporal variation in the economic impact of a fishing closure due to changes in the accessibility of profitable fishing grounds caused by environment-driven variation in the distribution of a target species. Our approach combines: (a) a statistical model of catch, to indicate habitat suitability and catchability of the target species, informed by a high-resolution ocean circulation model; and (b) a trip-dependent utility model, to quantify the value of this catch based on its accessibility to the fishery, informed by economic data including a cost-earnings survey. The economic impact of a closure was measured as 'lost economic opportunity': the percentage of potential profit attributable to swordfish catch that occurs within a time-area closure. We demonstrate this analysis using the drift gillnet swordfish *Xiphias gladius* fishery on the U.S. West Coast, and the event-triggered Loggerhead Conservation Area (LCA) in Southern California (Figure 1).

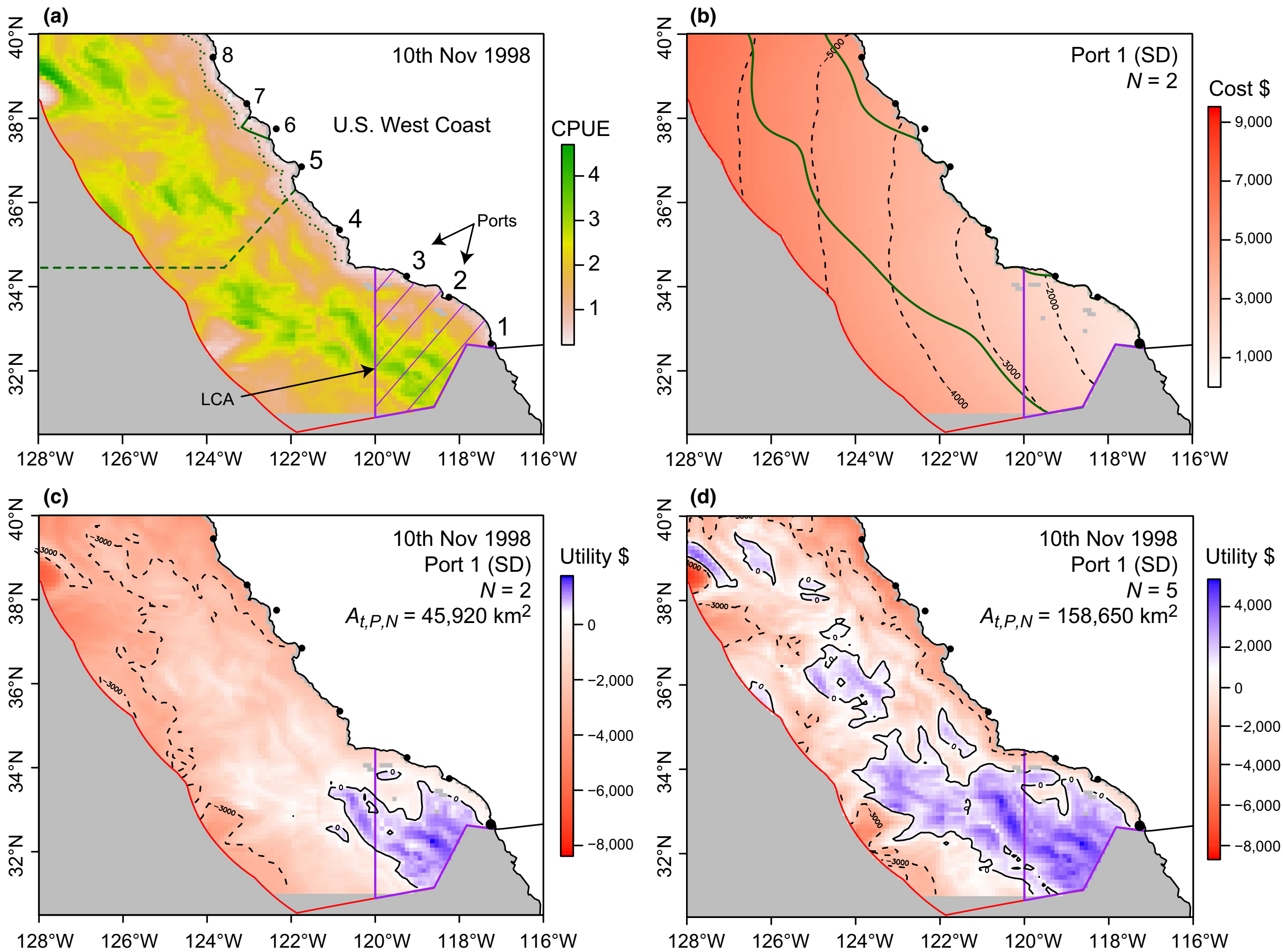

FIGURE 1 (a) Predicted drift gillnet swordfish fishery (DGN) catch-per-unit-effort (CPUE; mean number of swordfish per 12 hr set) for an example date (10 November 1998). Black dots are ports; all were potential landing ports and 1–5 were starting ports (see Appendix S4 for port names). The Loggerhead Conservation Area (LCA) is shown (purple hatched area), although it is not active on this date. Closures active on this date are the PLCA (dashed green), the 12 nmi closure (dotted green) and Point Reyes closure (full green). (b) Approximate total trip variable cost of a 2-set duration trip (*N* = 2) leaving San Diego; dashed lines are cost contours ($2,000–$6,000). Also shown is the 95% fishing effort contour from observer data (green line; see Appendix S5). (c, d) The estimated utility ($) given this CPUE and the variable cost of travel for a vessel leaving San Diego on a 2-set (c) or 5-set (d) duration (*N*) fishing trip. The total profitable area ($A_{t,P,N}$) is the blue area inside the full black contour line; the dashed black line illustrates −$3,000 utility. The DGN is not permitted outside the EEZ so only the EEZ area is shown

2 | MATERIALS AND METHODS

2.1 | General approach

Our analysis estimates lost economic opportunity to the California large mesh drift gillnet swordfish fishery (DGN), for each fishing season, assuming the LCA closure is enacted. To do this (Figure 1), we: (a) estimate potential mean swordfish catch each day, using a statistical model of catch informed by a data-assimilative configuration of the Regional Ocean Modeling System (ROMS) for the West Coast EEZ (Neveu et al., 2016); (b) calculate the daily economic value for each cell in this area using a utility model incorporating swordfish revenue and fishing costs; and (c) calculate the percentage of the total economic value (for each season) within the LCA, which we refer to as 'lost economic opportunity'. This approach is similar to measuring a closure's impact by analysing effort redistribution (Powers & Abeare, 2009), but quantifies the lost opportunity for profitable fishing across the entire area open to fishing, rather than modelling specific responses in effort distribution.

2.2 | The DGN and LCA

The DGN is a federally managed fishery operating in the territorial waters of the U.S. West Coast off California and Oregon. The DGN targets highly migratory species (HMS) and sharks, with significant catches of non-target species (Mason, Hazen, Bograd, Dewar, & Crowder, 2019). DGN vessels remain at sea for multiple days before landing their catch, deploying the usually 1.8 km long gillnet (as a 'set') typically at night and for a variable duration (frequently ~12 hr). The DGN fishery has a complex history (Holts & Sosa-Nishizaki, 1998; Urbisci, Stohs, & Piner, 2016). Briefly, the DGN started in the late 1970s, initially targeting thresher shark, but soon switched to target the more valuable swordfish. Over time, restrictions were imposed to reduce bycatch, including gear modifications (e.g. acoustic pingers) and time-area closures. There are currently 14 permanent or temporary closures (see Appendix S1), including two closures aimed at reducing bycatch of sea turtles (Urbisci et al., 2016). The National Marine Fisheries Service (NMFS) established an observer program in 1990 to monitor the DGN, which provides detailed location and catch information at the set-level for a portion of the vessels. The California coast is closed to the DGN out to 75 nmi from 1 May to 14 August (Appendix S1), thus a de-facto fishing season starts from 15 August. However, vessels can fish before this date, and high catch rates of swordfish can exist outside the 75 nmi closure from June–August (Urbisci et al., 2016).

Our study focuses on the LCA in Southern California, which is implemented early in the fishing season in El Niño declared years, to reduce bycatch of loggerhead sea turtles *Caretta caretta* that aggregate in this area during warm-water events. The LCA can be enacted by the NMFS for a duration of 1–3 months between 1 June to 31 August, when ocean temperatures in Southern California are warmer than normal (Welch et al., 2019). We consider this a periodic event-triggered time-area closure (Dunn et al., 2011); periodic because it has the same enactment window each season, and event-triggered because it depends on warmer than normal conditions. Its spatial extent is fixed. To date, the LCA has been enacted in August 2014, June–August 2015, June–August 2016 and June–August 2019.

2.3 | Catch models

Statistical catch models were fit to the DGN observer data to model the distribution of swordfish catch-per-unit-effort (CPUE, number of swordfish per set) as a function of environmental and spatial variables. To acknowledge and evaluate model uncertainty we created two catch models: a generalized additive mixed model (GAMM) and a boosted regression tree (BRT). The models were fitted to catch data from 1990 to 2000, because this was when the DGN was widely distributed (before the large Pacific Leatherback Conservation Area, PLCA, was implemented in 2001; Urbisci et al., 2016). This historical period provided a total of 5,585 DGN sets for the catch models, after removal of observations with missing environmental or trip information.

The general form of the GAMM was (in script notation):

$$\begin{aligned}\text{CPUE} \sim\; & s(\text{SST}) + s(\text{SST}_{sd}) + s(\text{ILD}) + s(\text{SSH}) + s(\text{EKE}) \\ & + s(Z_{sd}) + s(\text{FTLE}) + s(\text{Distance}) + s(\text{Duration}) + (1|\text{Vessel}),\end{aligned}$$

where CPUE is the number of swordfish per set, SST is sea-surface temperature (°C) at each set, SST_{sd} is the spatial standard deviation of SST (calculated over a 0.7° square), ILD is isothermal layer depth (m), SSH is sea-surface height (m), EKE is eddy kinetic energy (m^2/s^2), Z_{sd} is the standard deviation of bathymetry depth (calculated over a 0.3° square; Brodie et al., 2018), FTLE is finite-time Lyapunov exponent (day^{-1}, a Lagrangian coherent structure), Distance is distance to coast (km), Duration is the soak time (hr) of each set (recorded by the observer) and Vessel is a vessel identifier (included as a random effect); '*s*' indicates a thin plate regression spline. See Appendix S2 for more information on these covariates.

The general form of the BRT was the same as the GAMM, except with the addition of the Latitude of each set (recorded by the observer), and without the Vessel random effect:

$$\begin{aligned}\text{CPUE} \sim\; & \text{SST} + \text{SST}_{sd} + \text{ILD} + \text{SSH} + \text{EKE} + Z_{sd} \\ & + \text{FTLE} + \text{Distance} + \text{Latitude} + \text{Duration}.\end{aligned}$$

These covariates represent common variables used to represent dynamic ocean habitat, and SST, ILD and FTLE are known drivers of swordfish distribution (Brodie et al., 2018; Scales et al., 2018). Latitude was added to the BRT as it greatly increased the explained information, but was excluded from the GAMM to ensure one model was influenced predominantly by dynamic habitat variables. Daily dynamic environmental variables were taken from the data-assimilative ROMS configured for the California Current system (Neveu et al., 2016). This ocean model has a 0.1° (~10 km) horizontal resolution, and the values of the dynamic environmental covariates at each set were taken from the ROMS grid cell in which the set occurred (Brodie et al., 2018).

Catch-per-unit-effort was modelled with a negative binomial family in the GAMM, and with a Poisson family in the BRT (36% of sets caught zero swordfish). Evaluation of residuals and overdispersion in the GAMM showed the negative binomial was appropriate. This family was not available for the BRT, but an evaluation of the model prediction from the BRT showed a sensible distribution of catch rates. Mean percent deviance explained and root-mean-square error (RMSE) from cross-validation was used to evaluate model performance. The BRT was fitted using the DISMO (Hijmans, Phillips, Leathwick, & Elith, 2017) and GBM (Greenwell, Boehmke, Cunningham, & GBM, 2019) packages in R v3.6.0 (R Core Team, 2019). The GAMM was fitted using the MGCV package (Wood, 2017). Cross-validation was assisted by the DISMO package. See Appendix S3 for more information on model specification and cross-validation, and for model results.

2.4 | Predicted CPUE

The catch models were used to predict mean swordfish CPUE for the West Coast EEZ for the duration of the fishing season and the duration of the simulation (1991–2009). Predictions used dynamic environmental data from ROMS and were made at the spatial resolution of the ocean model (0.1°). Set Duration was fixed at 12 hr for the prediction, which is the mode and median duration for observed DGN sets; predicted catch is thus the potential mean swordfish catch per 12 hr set. In our analysis, the fishing season begins on 1 July and ends on 31 January the following year (see Section 2.6).

2.5 | Trip-dependent utility

A utility model was used to estimate the spatial distribution of economic value for the DGN. In general terms, utility of a location was defined as its potential profit, that is the revenue from swordfish catch less the fuel and crew costs to fish that location. Utility depends not only on the distance to a location (and thus port location), but also on the planned duration of a fishing trip (more distant locations have higher utility for longer trips). Thus, we calculate each location's 'trip-dependent utility', which estimates the utility of a location if it was fished on a trip of specified duration and start location, and we calculate this daily based on each day's predicted swordfish CPUE.

The utility model had the form:

$$U_{c,t,P,N} = \mathrm{CPUE}_{c,t} N\,\mathrm{Pr} - \left(C_{\mathrm{km}} D_{\mathrm{trip}_{c,P,N}} + C_h H_{c,P,N} \right)$$

$$C_{\mathrm{km}} = \frac{C_f}{D_{\mathrm{day}}}$$

$$C_h = \frac{C_v}{24}$$

$$D_{\mathrm{trip}_{c,P,N}} = D_{c,P} + \min\left\{ D_{c,P1} \dots D_{c,Pn} \right\} + D_{\mathrm{set}}\,(N-1)$$

$$H_{c,P,N} = NH_{\mathrm{set}} + (N-1)\,(24 - H_{\mathrm{set}}) + \frac{D_{c,P} + \min\left\{ D_{c,P1} \dots D_{c,Pn} \right\}}{S}$$

$U_{c,t,P,N}$ ($US) is the approximate utility (i.e. profit = revenue − costs) of cell c on day t, if it were fished by a vessel leaving start port P on a trip of duration N, where N is the number of overnight 12 hr sets. $\mathrm{CPUE}_{c,t}$ is the mean swordfish CPUE (number per 12 hr set) predicted by the catch models, and Pr is the ex-vessel price ($) per swordfish. Variable costs are split into two components: C_{km} is the distance component (fuel and oil, $/km) and is multiplied by the total trip distance from port P (D_{trip}, km); and C_h is the time component (crew and food, $/hr), and is multiplied by total trip duration (H, h). C_{km} was calculated from a daily cost (C_f, $/day) divided by the mean distance travelled per day on a multi-day trip (D_{day}, km); C_{h} was also calculated from a daily cost (C_v, $/day). $D_{\mathrm{trip}\,c,P,N}$ is calculated as the sum of: $D_{c,P}$ the distance between start port P and cell c, min($D_{c,P1}$... $D_{c,Pn}$) the minimum return distance from cell c and n potential landing ports (assumes vessels land at the nearest port), and the product of the estimated mean daily distance travelled between sets (D_{set}) and total number of travel steps between sets in a trip (N − 1). $H_{c,P,D}$ is calculated as the time taken to travel to and from cell c, given transit speed (S, km/hr), plus the time taken to complete N sets, given set duration H_{set} (hr), plus the duration between sets (N − 1)(24 − H_{set}).

The metrics of utility used in this analysis were:

$$A_{t,P,N} = \sum_{c=1}^{m} A_c$$

$$O_{t,P,N} = \sum_{c=1}^{m} U_{c,t}$$

$$LO_Y = 100\,\frac{\sum_{t=1}^{y_L} O_{t_L,P,N}}{\sum_{t=1}^{y} O_{t,P,N}}$$

$A_{t,P,N}$ is the total area (km^2) on day t that can be fished for profit (i.e. the revenue from swordfish landings exceeds the cost to catch them), by a vessel leaving port P for a trip of duration N. This is calculated by summing the area A_c for all m cells with positive utility (i.e. $U_{c,t,P,N} > 0$). $O_{t,P,N}$ is the total economic opportunity ($), calculated as the sum of the utility for the m cells with positive utility ($U_{c,t,P,N} > 0$). Only accessible cells (i.e. those inside the EEZ and not inside an active closure on day t) were summed. LO_Y is the lost economic opportunity (representing an opportunity cost) for fishing season Y, calculated as the percentage of economic opportunity for the entire season (the sum of $O_{t,P,N}$ over y days in season Y) that occurred within and during the LCA (the sum of $O_{t_L,P,N}$ over y_L days in Y; see Figure 2). $O_{t_L,P,N}$ ($) is the economic opportunity that occurs inside and during the LCA. In our simulation, y = 215 days (1 July to 31 January) and y_L = 62 days (1 July to 31 August). An increase in LO_Y represents a decline in opportunity for profitable trips throughout that season, given a fleet capable of dynamically distributed effort.

Swordfish price Pr was estimated using landings data recorded by the Pacific Fisheries Information Network (PacFIN), and we tested two price scenarios: a fixed mean price and a seasonally variable price (Table 1). Swordfish price typically varies throughout the fishing season (Appendix S5), and this will influence the estimates of lost economic opportunity. However, the fixed mean price scenario is useful for evaluating economic impact independent of assumed trends of fishing effort and supply-demand (and thus price). C_f and C_v were estimated from a cost-earnings survey of the DGN (years 2009–2010; NMFS unpublished data), which reported annual variable costs. These annual variable costs were converted to daily costs, by dividing annual costs by the mean number of days fished per year (also reported in the survey). The mean step distance between sets (D_{set}) was calculated using the observer data as the straight line distance between consecutive sets (median D_{set} = 35 km). Sources and values for the utility parameters are summarized in Table 1. Potential landing ports were identified from the recorded ports in the observer data. Nearby ports were grouped into 11 consolidated ports (Appendix S4).

2.6 | The simulation

Mean swordfish CPUE, utility, total and LCA profitable areas, and total economic opportunity were calculated for each day in 19 fishing seasons (1991–2009) for a range of trip durations (N = 2–6) and start ports (P). Trip duration of DGN vessels shows considerable variation, but ~70% of trips in the observer data had durations N = 2–6, with median and mode N = 5. Five start ports were selected from the set of consolidated ports (P = 1–5, Appendix S4) to cover a spectrum of impacts from the LCA. These were the southernmost ports: San Diego, San Pedro/Los Angeles, Ventura/

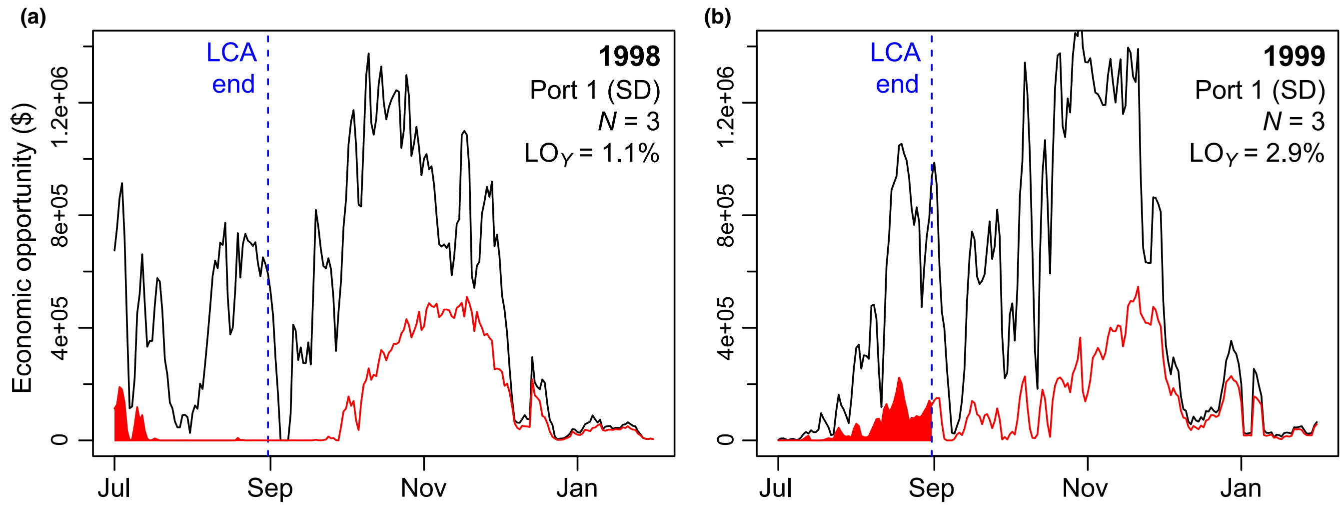

FIGURE 2 The economic opportunity for a drift gillnet swordfish fishery (DGN) vessel leaving San Diego on a 3-set duration (N = 3) trip, for every day of two fishing seasons, 1998 (a) and 1999 (b). The black line is the total economic opportunity (the sum of utility in all profitable cells) and the red line is the economic opportunity within the spatial domain of the Loggerhead Conservation Area (LCA). The blue-dotted line indicates the end of the LCA period (31 August). Lost economic opportunity (LO_Y) for each season is the economic value occurring inside and during the LCA (the filled red area) as a percentage of the total economic value for the season (the area under the entire black line). The impact is almost three times greater in 1999 (2.9%) than in 1998 (1.1%)

TABLE 1 Parameters used in the utility function. Pr is the fixed price value; see Appendix S5 for the variable price model

Parameter	Units	Value	Source
CPUE	Number of swordfish per 12 hr set	Model prediction	Fitted to observer data
N	Number of 12 hr sets per trip	Varied in simulation (2–6)	Observer data: 70% of trips consist of 2–6 sets
Pr	$US per swordfish	525	PacFIN ($3.50 per pound)
C_f	$US/day	160	Cost-earnings survey
D_{set}	km	35	Observer data
D_{day}	km	70	Observer data
C_{km}	$US/km	$160/day ÷ 70 km/day = 2.3	Calculated
C_v	$US/day	534	Cost-earnings survey
C_h	$US/hr	$534/day ÷ 24 hr = 22.3	Calculated
H_{set}	hr	12	Median and mode set length from the observer data
S	km/hr	15	Pers. Comm.

Oxnard/Santa Barbara, Morro Bay and Moss Landing/Monterey/Santa Cruz, and ~80% of observed trips departed and landed at these ports. Given that the potential fishing area can be quite large, we calculated lost economic opportunity for the entire EEZ, and for only the area likely to be fished (inside the 95% effort contour, Figure 1b). This meant that our simulation calculated lost economic opportunity for eight scenarios (every combination of): GAMM or BRT, fixed or variable swordfish price, and EEZ or 95% effort contour.

The 1991–2009 period was selected because the *FTLE* variable was not available for CPUE prediction outside these years. The simulated fishing season began on 1 July and ended on 31 January the following year (these dates encompass 99% of observed trips in the 1990–2000 period). The LCA can be enacted from 1 June, but due to negligible DGN fishing effort in June, our simulation started on 1 July. The LCA was implemented each fishing season, to measure the lost economic opportunity if it was enacted. All other time-area closures impacting the DGN were implemented on the dates they occur (Appendix S1). Some closures overlapped with the LCA (e.g. the 75 nmi and LCA) and lost opportunity considered only the area inside the LCA not inside any other closure. Closures were implemented every year, not just the years they were actually implemented (e.g. the PLCA was not enacted until 2001), to identify the impact of the LCA holding other regulations constant. In Appendix S5 we present a comparison of economic impact with and without non-LCA spatial closures. Our simulation was done using R, relying on the packages 'RASTER' (Hijmans, 2019) and 'MAPTOOLS' (Bivand & Lewin-Koh, 2019).

2.7 | Simulation caveats

It is important to note the caveats of this approach and simulation. For example, using a utility model to create the economic opportunity metric assumes that location decisions by individual fishers are based on profit maximization (van Putten et al., 2012), and that vessels are flexible in their location decisions. By modelling catch statistically and without population dynamics, we assumed that the swordfish population was stable and stock depletion does not occur within the EEZ. Our analysis also assumes that catch at a location for the first day of trip can represent the remaining days. These caveats and others are discussed in Appendix S6.

3 | RESULTS

The estimated lost economic opportunity due to the LCA was small, with a loss of 1%–3% opportunity per season (the mean of all combinations of trip duration and port location; Figure 3; Table 2).

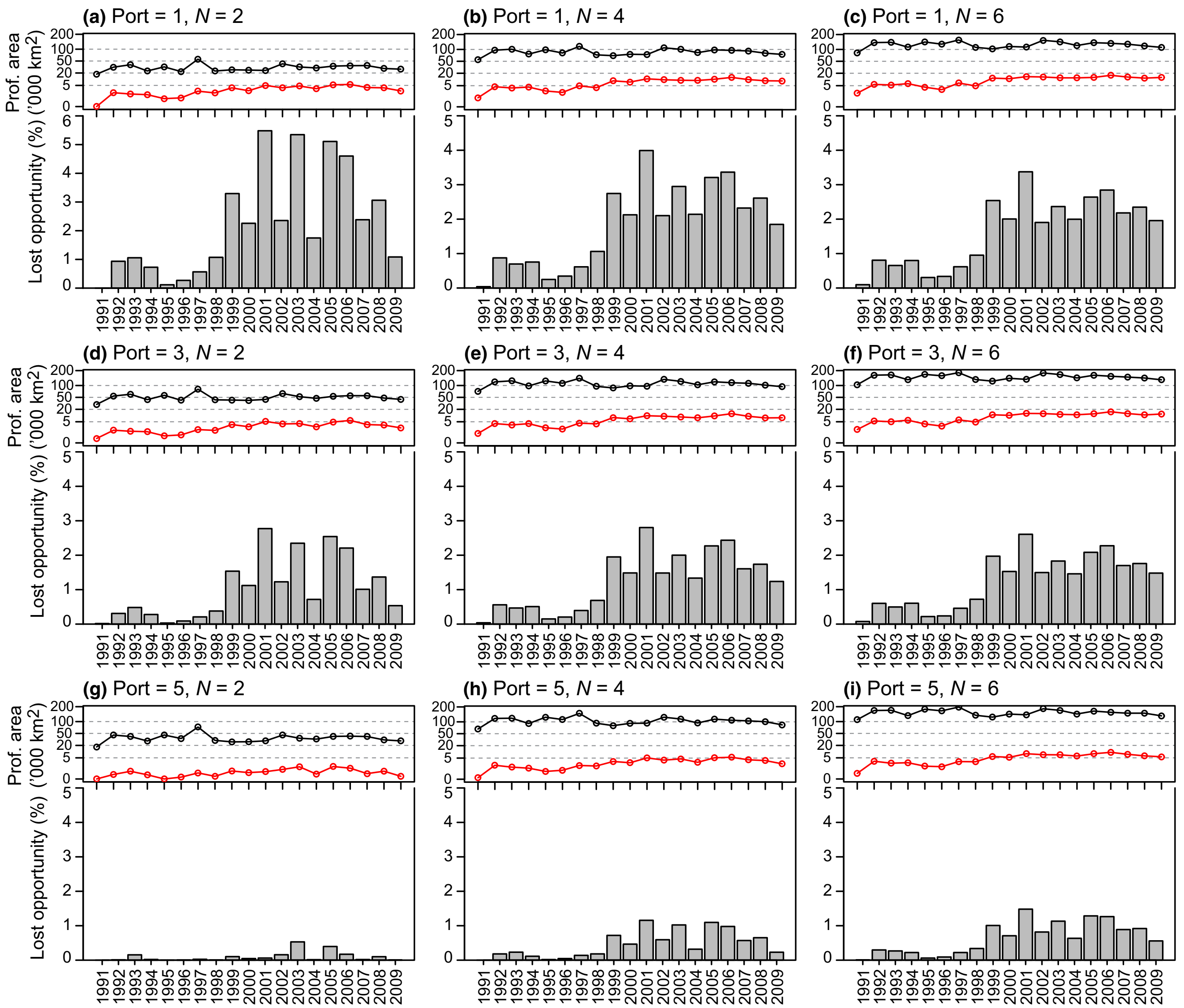

FIGURE 3 The percentage of total economic opportunity enclosed by the Loggerhead Conservation Area (LCA; %, grey bars) for each fishing season (1991–2009) and for a combination of starting ports (P = 1, 3, 5) and trip durations (N = 2, 4, 6). Also shown is the total profitable area ('000s km^2, black line) and the profitable area inside and during the LCA (red line). The profitable area axis has been rescaled (cube-root) to better compare the two areas. The maximum impact is greatest for vessels leaving port 1 (San Diego) on a 2-set trip (a); although they have access to a smaller total profitable area (black line) a larger proportion of this can be inside the LCA (red line). The CPUE used in this result is that from the generalized additive mixed model (GAMM) (Appendix S3), using a fixed swordfish price, and accounts for all 14 closures (Appendix S1)

Vessels leaving San Diego were the most impacted due to their proximity to the LCA, with lost opportunity given a fixed price ranging from 0% to 6% (Figure 3a–c). Lost opportunity increased by 50%–90% given a variable swordfish price (Table 2; Figure S5.4), because price was historically higher during the timing of the LCA (Figure S5.3). Restricting the assessed area to only the area likely to be fished increased lost opportunity by 30%–40% (Table 2; Figure S5.1). The LCA contained low predicted economic value compared to other areas of the EEZ until around October (Figure 2; Figure S7.1), indicating that if the LCA were enacted later in the year its impact would be greater. Longer trips generally had access to a larger profitable fishing area (Figure 3), but this had small effect on lost economic opportunity because longer trips could also access greater profit from the LCA.

TABLE 2 Mean (±*SD*) lost economic opportunity (% per season) due to the Loggerhead Conservation Area (LCA), for each of the four scenarios analysed for both the generalized additive mixed model (GAMM) and boosted regression tree (BRT) swordfish catch models: within the entire EEZ or within the 95% effort contour ('Eff-95'), and with a fixed or varying swordfish price. The mean is that of 2- to 6-day fishing trips (*N* = 2–6) leaving ports 1–5. EEZ and fixed price is the scenario illustrated in Figures 2–4

	Lost economic opportunity (%)	
Scenario	GAMM	BRT
EEZ and fixed price	1.11 (1.02)	1.28 (1.18)
EEZ and varying price	2.11 (1.65)	1.83 (1.42)
Eff–95 and fixed price	1.50 (1.31)	1.68 (1.47)
Eff–95 and varying price	2.98 (2.14)	2.61 (1.84)

The magnitude of lost economic opportunity was consistent between the two catch models (GAMM and BRT; Appendix S3) although they varied in the estimated impact for some fishing seasons (Figure 4; Appendix S5). Comparison with a previous analysis of the LCA (Welch et al., 2019) showed that the closure would be enacted in years with lower economic impact (Figure 4). Both the GAMM and BRT catch models, and all tested scenarios, revealed generally lower economic impact in 1991–1998 and higher impact in 1999–2009 (Figures 3 and 4; Figures S5.1 and S5.4). This likely represents a climate regime change, leading to a deeper isothermal layer depth (ILD) in 1999–2009, especially in the August-October period for the LCA (Figure 5a). This increase in ILD increased potential catch of swordfish in the LCA (Figure 5b). In contrast, variation in ILD occurring outside the LCA was in a range of values not associated with the change in swordfish catch (Figure 5c).

4 | DISCUSSION

4.1 | Lost economic opportunity and its variation

Our modelling framework allowed for quantification of the lost economic opportunity induced by a time-area closure, while accounting for environmentally driven changes in the distribution of a target species. For this DGN fishery case study, the potential for lost economic opportunity due to the LCA was on average only 1%–3% per season, showing that the majority of opportunity for catching swordfish lies outside the spatial and temporal domain of this closure.

There was, however, meaningful variation in lost economic opportunity among fishing seasons. It was challenging to identify the

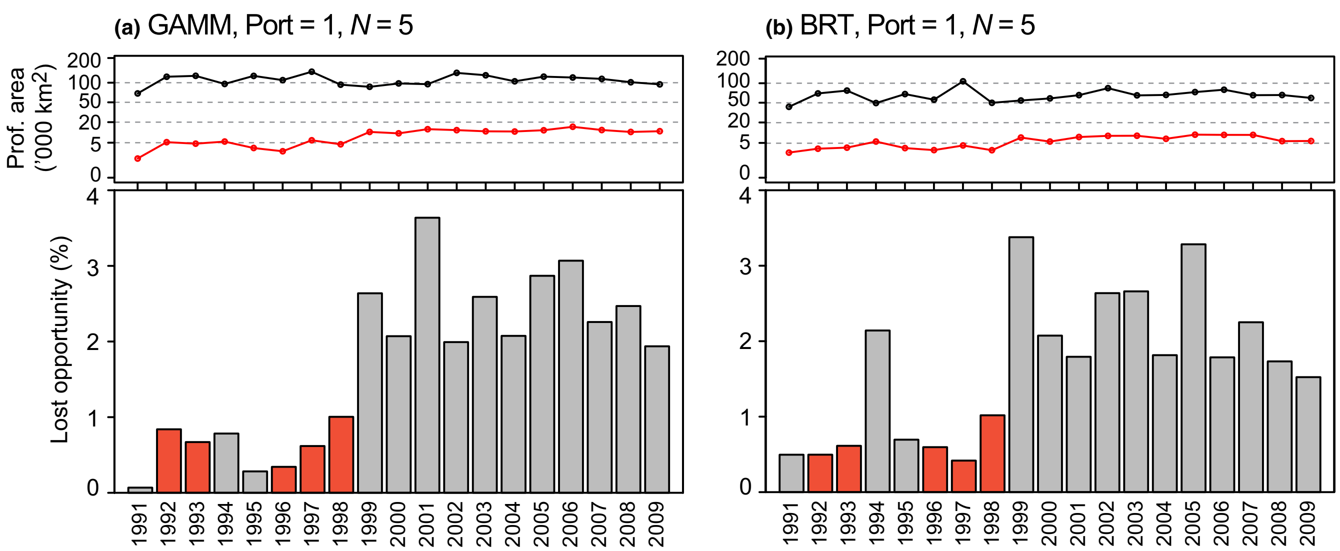

FIGURE 4 Comparison of lost economic opportunity (%, grey bars) calculated using the generalized additive mixed model (GAMM) (a) and boosted regression tree (BRT) (b) catch models. This is for a vessel leaving port 1 (San Diego) on a 5-set trip. Also shown is the total profitable area ('000s km^2, black line) and the profitable area inside and during the Loggerhead Conservation Area (LCA; red line). Shown are five 'El Niño' years in which the LCA would have been enacted (red bars) based on the 6-month SST-anomaly indicator of Welch et al. (2019)

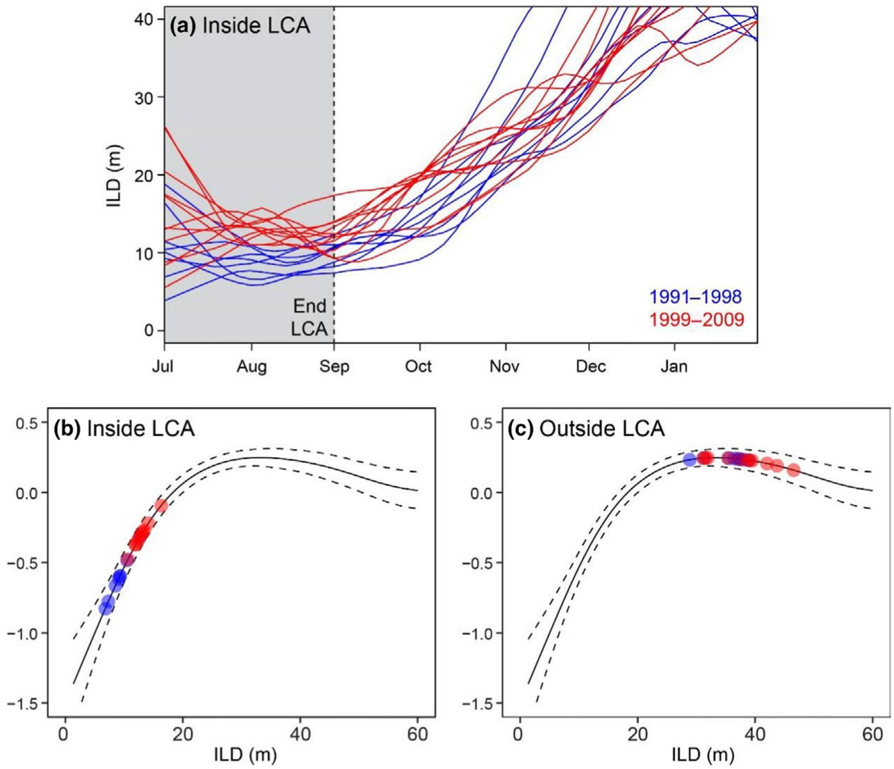

FIGURE 5 (a) The mean daily isothermal layer depth (ILD, m) inside the Loggerhead Conservation Area (LCA; loess smoothed) throughout each fishing season (blue: 1991–1998, red: 1999–2009). The period in which the LCA can be enacted is shaded grey. (b, c) The mean ILD inside and during the LCA (b) or outside the LCA (c) for each season (dots, blue: 1991–1998, red: 1999–2009) plotted on the generalized additive mixed model smoother for ILD in the swordfish catch model (Appendix S3). This illustrates the increased catch-per-unit-effort inside the LCA due to higher ILD in the later period (b)

cause of this variation, because our lost opportunity metric is the result of a multivariate process influencing the catch rates inside and outside the LCA, and is sensitive to fine-scale changes in economic value. An increase in lost opportunity can be caused by either a relative increase in value of the fishable area inside the LCA, or a relative decrease in the value of fishing area outside the LCA. Although both processes contributed, it was predominantly change in value inside the LCA driving inter-annual differences (compare the relative stability of total profitable area vs. LCA area in Figure 3). Although both the GAMM and BRT fitted similar environmental responses, the GAMM's smoothed responses may have reduced the prediction of hot spots in swordfish catch. For example, in 1994 the LCA had much greater simulated economic impact when using the BRT (Figure 4b), which was due to increased catch in an ephemeral oceanographic front (and strong FTLE values) identified by the BRT but not the GAMM (Appendix S7).

A signal in lost economic opportunity shared by the GAMM and BRT models was the lower economic impact of the LCA in 1991–1998, and higher impact in 1999–2009. This shift coincided with a Northeast Pacific climate regime change, in which the California Current switched from a warm to a cool state, with strengthened winds off the California coast (Peterson & Schwing, 2003). Along with this change in the ocean temperature and wind forcing a deeper isothermal layer depth (ILD) in 1999–2009 during the timing of the LCA occurred, which caused increased potential catch of swordfish inside the closure. The deeper surface layer associated with ILD may provide a thermal or oxygen refuge for swordfish (Brodie et al., 2018), increasing their occurrence or abundance. Another contributor to the shift in lost economic opportunity was warmer SST during 1991–1998 which increased the potential swordfish catch outside the LCA, thus reducing the closure's impact.

4.2 | Realized impact

The potential economic impact of the LCA on the DGN was expected to be reasonably small, because the closure covers only part of the fishable area, and is enacted early in the season when there is less fishing effort (~90% of observed fishing trips occurred after the LCA period). Our analysis does not incorporate fishing effort, only the potential for profitable fishing if fishing occurred, which leads to this discussion of the 'realized impact' of lost economic opportunity. Our analysis is a fundamentally different approach to measuring a management strategy's impact by simulating the reaction of fishers (e.g. Dinmore et al., 2003; Little et al., 2004). There can be considerable uncertainty in fleet behaviour, and rather than model specific agents our approach measures the *opportunity* on which agents can act.

In reality, a loss of economic opportunity may manifest in a range of impacts on individual vessels and the fleet. We found the LCA had a generally small impact on economic opportunity, but this differed among ports and trip durations. Impact for short trips was sometimes the greatest, but the profitable area for these short trips was relatively small (Figure 3). For this impact on short trips to be realized, this area would need to be discoverable by fishers and fished, which will be less likely if the conditions are ephemeral or the area is infrequently fished. The realized impact of the LCA would also depend on fisher behaviour. For example, the LCA may have a greater realized impact on fishers who are area specialists (i.e. fish in specific areas) than fishers who are movement specialists (Branch et al., 2006). A small loss in economic opportunity may have a negligible impact on landings, for example a loss of 5% economic opportunity might mean that vessels travel farther and experience reduced profit during enactment of the LCA, or simply postpone one planned trip until the LCA ends, and the total swordfish landings for the season could be unaffected. Thus, we consider our lost economic opportunity metric as an economic indicator of the severity of changes to effort or fisher behaviour that will occur due to a closure's enactment.

4.3 | Climate and management implications

We assumed the LCA was implemented each year to demonstrate our approach, but the LCA is enacted only occasionally in El Niño declared years when waters off the Southern California coast are warmer than average (Welch et al., 2019). Our analysis suggests that the LCA would have been triggered in years with lower potential impact on the fishery (Figure 4). Welch et al. (2019) also found that the LCA enacted using an SST indicator had a comparatively low opportunity cost, based on proportion of time the closure was enacted. Our study adds the dimension of economic value to the closure period, to estimate *economic opportunity cost*, and confirms that the LCA has even lower opportunity costs than expected, given that it likely occurs in relatively warm years with increased relative fishing opportunity outside the LCA. Given increasing ocean temperatures the LCA may be enacted more frequently in the future; and our lost economic opportunity metric would be a useful management indicator to identify whether the LCA's economic impact remains acceptably low. If changes to the temporal or spatial dimensions of the LCA were ever proposed, our metric would also be a useful impact assessment tool to help evaluate alternatives. There are other bycatch concerns for the DGN fishery in addition to loggerhead turtles, and spatially dynamic tools are being developed to help manage bycatch risk (EcoCast; Hazen et al., 2018). Our lost economic opportunity metric is well suited to evaluating the potential impact of different risk thresholds used by such dynamic tools to identify unacceptably high bycatch risk.

We do not consider bycatch rates of loggerhead turtles in our analysis, as this consideration is inherent in the LCA's spatial dimensions and timing. Ultimately, the effectiveness of management strategies, including time-area closures, should be evaluated across multiple management objectives (Pascoe, Plagányi, & Dichmont, 2016), and the number of interactions with loggerhead turtles would be the other key component for a complete evaluation of the LCA. This could be done alongside our analysis by, for example, measuring the proportion of summed probability of presence of loggerhead turtles protected by the LCA each fishing season (although there is currently insufficient data to do this accurately).

Lost economic opportunity should not be used by itself for tactical spatial management decisions, such as the design and redesign of time-area closures (which would benefit from a fully integrated approach, such as management strategy evaluation). However, it does provide an ecological-economic metric that could: (a) be used in pre-closure discussions and modelling to explore closure options, including being a performance metric in management strategy evaluation; (b) contribute to decisions on the timing of event-triggered time-area closures; and (c) inform strategic decisions such as a closure's suitability or sustainability, by identifying ports and fishing strategies most affected by a closure. Time-area closures triggered by an environmental signal represent the benefits of managing static closures dynamically, but it remains prudent to evaluate the economic aspect of such triggers, so that the closure meets bycatch mitigation objectives while minimizing the economic burden for fishers (Dunn et al., 2011). Our approach linking pelagic habitats and economic opportunity can help monitor time-area closures against these goals in a dynamic and changing ocean ecosystem.

ACKNOWLEDGEMENTS

This research was funded by a NOAA Coastal and Ocean Climate Application COCA Program grant (NA17OAR4310268).

AUTHORS' CONTRIBUTIONS

All the authors conceived and designed the study; J.A.S., D.T., S.B. and J.S. analysed the data; and J.A.S., D.T., J.S. and B.M. led the writing of the manuscript. All the authors contributed critically to drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

The fisheries-dependent data from the DGN observer program were collected by the NOAA National Marine Fisheries Service, and are confidential U.S. government data. The raw data cannot be made public, under the Magnuson–Stevens Fishery Conservation and Management Reauthorization Act of 2006, section 402 (b), 16 U.S.C. 1881a. To request access to data from the West Coast Region Observer Program, please contact Charles Villafana (Charles.Villafana@noaa.gov). Predicted daily swordfish catch rasters and the model code to calculate lost economic opportunity are available via archive on Zenodo https://doi.org/10.5281/zenodo.3549038 (Smith, 2019).

ORCID

James A. Smith https://orcid.org/0000-0002-0496-3221
Heather Welch https://orcid.org/0000-0002-5464-1140

REFERENCES

Armsworth, P. R., Block, B. A., Eagle, J., & Roughgarden, J. E. (2010). The economic efficiency of a time–area closure to protect spawning bluefin tuna. *Journal of Applied Ecology*, *47*, 36–46. https://doi.org/10.1111/j.1365-2664.2009.01738.x

Bivand, R., & Lewin-Koh, N. (2019). *maptools: Tools for handling spatial objects*. R package version 0.9-5. https://CRAN.R-project.org/package=maptools

Branch, T. A., Hilborn, R., Haynie, A. C., Fay, G., Flynn, L., Griffiths, J., … Young, M. (2006). Fleet dynamics and fishermen behavior: Lessons for fisheries managers. *Canadian Journal of Fisheries and Aquatic Sciences*, *63*, 1647–1668. https://doi.org/10.1139/f06-072

Brodie, S., Jacox, M. G., Bograd, S. J., Welch, H., Dewar, H., Scales, K. L., … Hazen, E. L. (2018). Integrating dynamic subsurface habitat metrics into species distribution models. *Frontiers in Marine Science*, *5*, https://doi.org/10.3389/fmars.2018.00219

Chakravorty, U., & Nemoto, K. (2000). Modeling the effects of area closure and tax policies: A spatial-temporal model of the Hawaii longline fishery. *Marine Resource Economics*, *15*, 179–204. https://doi.org/10.1086/mre.15.3.42629301

Dichmont, C. M., Ellis, N., Bustamante, R. H., Deng, R., Tickell, S., Pascual, R., … Griffiths, S. (2013). Evaluating marine spatial closures with conflicting fisheries and conservation objectives. *Journal of Applied Ecology*, *50*, 1060–1070.

Dinmore, T. A., Duplisea, D. E., Rackham, B. D., Maxwell, D. L., & Jennings, S. (2003). Impact of a large-scale area closure on patterns of fishing disturbance and the consequences for benthic communities. *ICES Journal of Marine Science*, *60*, 371–380. https://doi.org/10.1016/S1054-3139(03)00010-9

Dunn, D. C., Boustany, A. M., & Halpin, P. N. (2011). Spatio-temporal management of fisheries to reduce by-catch and increase fishing selectivity. *Fish and Fisheries*, *12*, 110–119. https://doi.org/10.1111/j.1467-2979.2010.00388.x

Dwyer, R. G., Campbell, H. A., Pillans, R. D., Watts, M. E., Lyon, B. J., Guru, S. M., … Franklin, C. E. (2019). Using individual-based movement information to identify spatial conservation priorities for mobile species. *Conservation Biology*, *33*, 4126–4137. https://doi.org/10.1111/cobi.13328

Goodyear, C. P. (1999). An analysis of the possible utility of time-area closures to minimize billfish bycatch by U.S. pelagic longlines. *Fishery Bulletin*, *97*, 243–255.

Grantham, H. S., Petersen, S. L., & Possingham, H. P. (2008). Reducing bycatch in the South African pelagic longline fishery: The utility of different approaches to fisheries closures. *Endangered Species Research*, *5*, 291–299. https://doi.org/10.3354/esr00159

Greenwell, B., Boehmke, B., Cunningham, J., & GBM Developers. (2019). *gbm: Generalized boosted regression models*. R package version 2.1.5. https://CRAN.R-project.org/package=gbm

Hall, M. A., Alverson, D. L., & Metuzals, K. I. (2000). By-catch: Problems and solutions. *Marine Pollution Bulletin*, *41*, 204–219. https://doi.org/10.1016/S0025-326X(00)00111-9

Halliday, R. (1988). Use of seasonal spawning area closures in the management of haddock fisheries in the Northwest Atlantic. *NAFO Scientific Council Studies*, *12*, 27–36.

Hartog, J. R., Hobday, A. J., Matear, R., & Feng, M. (2011). Habitat overlap between southern bluefin tuna and yellowfin tuna in the east coast longline fishery – Implications for present and future spatial management. *Deep Sea Research Part II: Topical Studies in Oceanography*, *58*, 746–752. https://doi.org/10.1016/j.dsr2.2010.06.005

Hazen, E. L., Scales, K. L., Maxwell, S. M., Briscoe, D. K., Welch, H., Bograd, S. J., … Lewison, R. L. (2018). A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. *Science Advances*, *4*, eaar3001. https://doi.org/10.1126/sciadv.aar3001

Hijmans, R. J. (2019). *raster: Geographic data analysis and modeling*. R package version 2.8-19. Retrieved from https://CRAN.R-project.org/package=raster

Hijmans, R. J., Phillips, S., Leathwick, J., & Elith, J. (2017). *Dismo: Species distribution modeling*. R package version 1.1-4. Retrieved from https://CRAN.R-project.org/package=dismo

Hobday, A. J., Flint, N., Stone, T., & Gunn, J. S. (2009). Electronic tagging data supporting flexible spatial management in an Australian longline fishery. In J. L. Nielsen, H. Arrizabalaga, N. Fragoso, A. Hobday, M. Lutcavage, & J. Sibert (Eds.), *Tagging and tracking of marine animals with electronic devices* (pp. 381–403). Dordrecht, the Netherlands: Springer.

Holts, D., & Sosa-Nishizaki, O. (1998). *Swordfish*, Xiphias gladius, *fisheries of the Eastern North Pacific Ocean. Biology and fisheries of Swordfish*, Xiphias gladius. NOAA Technical Report NMFS 142, pp. 65–76. U.S. Department of Commerce, Seattle, Washington.

Hoos, L. A., Buckel, J. A., Boyd, J. B., Loeffler, M. S., & Lee, L. M. (2019). Fisheries management in the face of uncertainty: Designing time-area closures that are effective under multiple spatial patterns of fishing effort displacement in an estuarine gill net fishery. *PLoS ONE*, *14*, e0211103. https://doi.org/10.1371/journal.pone.0211103

Lewison, R. L., Crowder, L. B., Wallace, B. P., Moore, J. E., Cox, T., Zydelis, R., … Safina, C. (2014). Global patterns of marine mammal, seabird, and sea turtle bycatch reveal taxa-specific and cumulative megafauna hotspots. *Proceedings of the National Academy of Sciences of the United States of America*, *111*, 5271–5276. https://doi.org/10.1073/pnas.1318960111

Lewison, R., Hobday, A. J., Maxwell, S., Hazen, E., Hartog, J. R., Dunn, D. C., … Crowder, L. B. (2015). Dynamic ocean management: Identifying the critical ingredients of dynamic approaches to ocean resource management. *BioScience*, *65*, 486–498. https://doi.org/10.1093/biosci/biv018

Little, L. R., Kuikka, S., Punt, A. E., Pantus, F., Davies, C. R., & Mapstone, B. D. (2004). Information flow among fishing vessels modelled using a Bayesian network. *Environmental Modelling & Software*, *19*, 27–34. https://doi.org/10.1016/S1364-8152(03)00100-2

Mason, J. G., Hazen, E. L., Bograd, S. J., Dewar, H., & Crowder, L. B. (2019). Community-level effects of spatial management in the California drift gillnet Fishery. *Fisheries Research*, *214*, 175–182. https://doi.org/10.1016/j.fishres.2019.02.010

Maxwell, S. M., Hazen, E. L., Lewison, R. L., Dunn, D. C., Bailey, H., Bograd, S. J., … Crowder, L. B. (2015). Dynamic ocean management: Defining and conceptualizing real-time management of the ocean. *Marine Policy*, *58*, 42–50. https://doi.org/10.1016/j.marpol.2015.03.014

Metcalfe, K., Vaz, S., Engelhard, G. H., Villanueva, M. C., Smith, R. J., & Mackinson, S. (2015). Evaluating conservation and fisheries management strategies by linking spatial prioritization software and ecosystem and fisheries modelling tools. *Journal of Applied Ecology*, *52*, 665–674. https://doi.org/10.1111/1365-2664.12404

Neveu, E., Moore, A. M., Edwards, C. A., Fiechter, J., Drake, P., Crawford, W. J., … Nuss, E. (2016). An historical analysis of the California Current circulation using ROMS 4D-Var: System configuration and diagnostics. *Ocean Modelling*, *99*, 133–151. https://doi.org/10.1016/j.ocemod.2015.11.012

O'Keefe, C. E., Cadrin, S. X., & Stokesbury, K. D. E. (2014). Evaluating effectiveness of time/area closures, quotas/caps, and fleet communications to reduce fisheries bycatch. *ICES Journal of Marine Science*, *71*, 1286–1297. https://doi.org/10.1093/icesjms/fst063

Pan, M., & Li, S. (2015). Evaluation of fishing opportunities under sea turtle interaction limits—A decision support model for Hawaii-based longline swordfish, *Xiphias gladius*, fishery management. *Marine Fisheries Review*, *77*, 31–38. https://doi.org/10.7755/MFR.77.3.3

Pascoe, S. D., Plagányi, É. E., & Dichmont, C. M. (2016). Modelling multiple management objectives in fisheries: Australian experiences. *ICES Journal of Marine Science*, *74*, 464–474. https://doi.org/10.1093/icesjms/fsw051

Peterson, W. T., & Schwing, F. B. (2003). A new climate regime in Northeast Pacific ecosystems. *Geophysical Research Letters*, *30*. https://doi.org/10.1029/2003GL017528

Powers, J. E., & Abeare, S. M. (2009). Fishing effort redistribution in response to area closures. *Fisheries Research*, *99*, 216–225. https://doi.org/10.1016/j.fishres.2009.06.011

R Core Team. (2019). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.

Scales, K. L., Hazen, E. L., Jacox, M. G., Castruccio, F., Maxwell, S. M., Lewison, R. L., & Bograd, S. J. (2018). Fisheries bycatch risk to marine megafauna is intensified in Lagrangian coherent structures. *Proceedings of the National Academy of Sciences of the United States of America*, *115*, 7362–7367. https://doi.org/10.1073/pnas.1801270115

Smith, J. A. (2019). LostOpportunity: Example data and code (version v1.0). *Zenodo*, https://doi.org/10.5281/zenodo.3549038

Urbisci, L. C., Stohs, S. M., & Piner, K. R. (2016). From sunrise to sunset in the California Drift Gillnet Fishery: An examination of the effects of time and area closures on the catch and catch rates of pelagic species. *Marine Fisheries Review*, *78*, 1–11. https://doi.org/10.7755/MFR.78.3-4.1

van Putten, I. E., Kulmala, S., Thébaud, O., Dowling, N., Hamon, K. G., Hutton, T., & Pascoe, S. (2012). Theories and behavioural drivers underlying fleet dynamics models. *Fish and Fisheries*, *13*, 216–235. https://doi.org/10.1111/j.1467-2979.2011.00430.x

Welch, H., Hazen, E. L., Briscoe, D. K., Bograd, S. J., Jacox, M. G., Eguchi, T., ... Bailey, H. (2019). Environmental indicators to reduce loggerhead turtle bycatch offshore of Southern California. *Ecological Indicators*, *98*, 657–664. https://doi.org/10.1016/j.ecolind.2018.11.001

Wood, S. N. (2017). *Generalized additive models: An introduction with R* (2nd ed.). Boca Raton, FL: Chapman and Hall/CRC Press.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Smith JA, Tommasi D, Sweeney J, et al. Lost opportunity: Quantifying the dynamic economic impact of time-area fishery closures. *J Appl Ecol*. 2020;00:1–12. https://doi.org/10.1111/1365-2664.13565