Supplementary Material S4: Fishing Model and ABM

Our fishing model specified how many vessels to simulate, where they should fish, and what they caught each set. The 'where' was determined using an agent-based model (ABM), which simulated a fleet that could move in response to dynamic spatial closures. Closure scenarios were evaluated by comparing the performance in terms of trip-level catch, but also distance travelled during trips and the associated cost. We describe this fishing model in three sections: 1) port selection (where agents depart and return); 2) fishing effort (how many agents to simulate); and 3) fisher behavior (where agents choose to move and fish).

1) Simulated fishing ports

A tractable list of ports was required to act as departure and landing ports in the ABM. The 1990-2000 observer data recorded 32 ports used for starting or landing. Most were rarely used, and 18 ports (accounting for 97% of observed trips) were consolidated by proximity into 11 ports (**Table S4.1**). Seven of the most used ports were selected as departure ports, based on the departure information recorded in the observer data (95% of observed trips departed from these ports). See **Table S4.2** for the simulated fishing effort from each of these ports. All ports could be used in the simulation as landing ports.

Table S4.1. The 11 consolidated ports, ordered south to north, and their approximate locations used in this simulation. Ports 1-6 and 10 were used as departure ports. These are mapped in Fig. 5 of the main article.

	Combined Port	State	Lat	Lon
1	San Diego	CA	32.6828	-117.249
2	San Pedro, Los Angeles	CA	33.7257	-118.279
3	Ventura, Oxnard, Santa Barbara	CA	34.2445	-119.267
4	Morro Bay	CA	35.3689	-120.856
5	Moss Landing, Monterey, Santa Cruz	CA	36.8062	-121.788
6	San Francisco, Oakland	CA	37.7836	-122.393
7	Bodega Bay	CA	38.3307	-123.054
8	Fort Bragg	CA	39.4255	-123.804
9	Gunther, Eureka	CA	40.7511	-124.215
10	Crescent City	CA	41.7454	-124.183
11	Newport	OR	44.6229	-124.050

2) Fishing Effort

We calculated the number of sets to simulate each month, and thus how many vessels to send from each port, using DGN logbook data (sourced from PacFIN, https://pacfin.psmfc.org). This logbook data had poor spatial resolution, so we calculated monthly fishing effort in 2º latitude bins. Mean monthly fishing effort (number of sets), for the 1990-2000 period and in 2º latitude bins, was calculated by fitting a GAM to the logbook data. The data consisted of ~35,600 sets with recorded months and latitude bins. The GAM had the form:

$$E_{l,m} = s_{cc}(m){:}\, l + l$$

$E_{l,m}$ is mean effort (number of sets) in latitude bin l (9 levels: 30-32…46-48) and month m (integers, 1-12), and s_{cc} represents a cyclic cubic regression spline for month, which was fitted separately for each latitude bin. We used a Poisson family with log-link. This model explained most of the data (explained deviance = 88.6%), and the mean effort values from the fitted model are reported in **Table S4.2**.

Table S4.2. The mean monthly fishing effort (number of sets) in each 2º latitude bin, as fitted using a GAM to the 1990-2000 logbook data.

		Latitude Bin								
		30-32	**32-34**	**34-36**	**36-38**	**38-40**	**40-42**	**42-44**	**44-46**	**46-48**
Month	**1**	23.2	308.0	22.8	8.9	5.6	1.3	0.0	0.0	0.0
	7	8.4	111.5	62.8	3.9	0.2	0.0	0.0	0.1	1.1
	8	10.9	144.9	49.4	7.5	10.9	1.6	0.0	1.2	1.1
	9	16.2	215.3	127.0	71.2	50.1	17.8	3.9	3.5	0.8
	10	16.9	223.9	239.9	115.8	73.2	11.2	9.7	1.9	0.0
	11	27.3	363.2	106.7	68.5	54.1	3.9	0.5	0.0	0.0
	12	23.2	308.0	22.8	8.9	5.6	1.3	0.0	0.0	0.0

The mean monthly fishing effort calculated for each latitude bin ($E_{l,m}$, mean number of sets per month) was used to calculate a mean number of vessels (‘agents’) and fishing sets for each day of the simulation. The duration of each overnight set was fixed at the median value (12 h; see main article), which meant one vessel could do one set per day. We also fixed the duration of each fishing trip (5 sets per trip; the median value), and started every 5-set trip on the same day. Also, a new set of vessels departed from port on the same day the previous set returned to port, so that vessels were fishing every day of the simulation. These choices were done to create a tractable model, and simplified the calculation of fishing effort. For example, 208 sets were assigned in every January to vessels departing San Diego (**Table S4.3**), which resulted in 42 simulated trips (42 × 5 sets each = 210 sets).

Effort occurring in each latitude bin (**Table S4.2**) was assigned by proportion to each of the consolidated ports (**Table S4.4**), based on proximity and so that the proportional use of departure ports was similar to that recorded in the observer data. This was then used to determine how many sets to simulate leaving each port, to achieve the modelled mean monthly fishing effort (**Table S.4.3**). This was successful, although simulated effort was slightly lower than observed for Crescent City, and slightly higher than observed for Morro Bay. We note, however, that the port-level coverage of the observer program is not necessarily in proportion to fishing effort. The final component of fishing effort was to assign trips to start dates within each month. This was done randomly, to acknowledge variation in fisher behavior. Because a set of fishing trips were programmed to depart and return together, there was a pre-determined set of departure dates for each month. A custom algorithm assigned the specified number of trips for a given month to these start dates randomly. For example, if there were six departure dates within an August (1991-08-05, 1991-08-10, …, 1991-08-30), and there were to be 20 trips simulated from San Diego in August (**Table S4.3**), the algorithm would distribute these 20 sets randomly across the six departure dates, while avoiding extreme inequality among departure dates.

Table S4.3. The monthly effort at the seven consolidated departure ports. 'Logbook Sets' is the mean monthly effort (**Table S4.2**) assigned to each of the simulated ports. 'Sim Trips' is the number of 5-set trips simulated each month, and 'Sim Sets' is the number of simulated trips each month. Only the months during the simulated fishing season (Jul-Jan) are shown. The observed mean number of sets per fishing season was 2977, and our MSE simulated 3000.

		Month						
		1	**7**	**8**	**9**	**10**	**11**	**12**
San Diego	Logbook Sets	208.0	80.8	101.7	156.5	173.5	253.2	208.0
	Sim Trips	42	16	20	31	35	51	42
	Sim Sets	210	80	100	155	175	255	210
San Pedro Los Angeles	Logbook Sets	58.9	24.1	29.6	46.7	54.0	73.4	58.9
	Sim Trips	12	5	6	9	11	15	12
	Sim Sets	60	25	30	45	55	75	60
Ventura Oxnard Santa Barbara	Logbook Sets	22.7	10.9	12.6	21.4	27.7	30.8	22.7
	Sim Trips	5	2	3	4	6	6	5
	Sim Sets	25	10	15	20	30	30	25
Morro Bay	Logbook Sets	58.5	48.5	47.2	102.9	165.1	114.7	58.5
	Sim Trips	12	10	9	21	33	23	12
	Sim Sets	60	50	45	105	165	115	60
Moss Landing Monterey Santa Cruz	Logbook Sets	13.3	21.6	20.6	90.4	156.7	82.7	13.3
	Sim Trips	3	4	4	18	31	17	3
	Sim Sets	15	20	20	90	155	85	15
San Francisco Oakland	Logbook Sets	5.3	0.9	8.0	47.2	66.8	44.6	5.3
	Sim Trips	1	0	2	9	13	9	1
	Sim Sets	5	0	10	45	65	45	5
Crescent City	Logbook Sets	3.2	1.3	7.8	40.7	48.7	24.9	3.2
	Sim Trips	1	0	2	8	10	5	1
	Sim Sets	5	0	10	40	50	25	5

Table S4.4. The assignment, by proportion, of fishing effort in each latitude bin to the seven departure ports. Ports are ordered as in **Table S4.3**.

		Latitude Bin								
		30-32	**32-34**	**34-36**	**36-38**	**38-40**	**40-42**	**42-44**	**44-46**	**46-48**
Port	**SD**	0.9	0.6	0.1	0	0	0	0	0	0
	SP-LA	0.1	0.18	0.05	0	0	0	0	0	0
	V-Ox-SB	0	0.07	0.05	0	0	0	0	0	0
	MB	0	0.15	0.5	0.1	0	0	0	0	0
	ML-M-SC	0	0	0.3	0.7	0.05	0	0	0	0
	SF-O	0	0	0	0.2	0.55	0.3	0	0	0
	CC	0	0	0	0	0.4	0.7	1	1	1

3) Fisher Behavior

We used an ABM to simulate vessels ('agents') leaving port, fishing and moving in response to closures, and returning to port to land their catch. The ABM determines the next location a fisher will choose to fish, depending on their current location, and vessel and trip characteristics (expected days remaining in trip, travel speed, etc). As stated above, we fixed the simulated duration of every fishing trip (at 5 overnight sets) in order to simplify the decision process, so that fishers only needed to decide where to fish next (and not whether to end a trip early). Our ABM operated in two stages: 1) utility was calculated for all cells in the domain; 2) a cell was selected from the available, accessible, and detectable cells, given some uncertainty (acknowledging that fishers detect utility imperfectly). 'Cell' refers to the spatial resolution of our simulation, with each cell 0.1° degree square.

Stage 1: Calculating Utility

From a vessel's current cell, we calculate every other cell's 'trip-dependent utility' (Smith *et al.* 2020). This is the utility of a cell if it was fished on a trip of specified duration and start location, given the predicted swordfish CPUE. Trip-dependent utility is calculated on each day of a fishing trip (not just the first day), and is calculated based on the number of expected remaining days in the trip; i.e. a fisher with 2 days remaining in a 5-day trip will measure utility based on the expected revenue from the catch in the two remaining days only. Utility is calculated according to:

$$U_{c,t,z,N} = CPUE_{c,t}NPr - \left(C_{km}D_{trip_{c,z,N}} + C_h H_{c,z,N}\right)$$

$$D_{trip_{c,z,N}} = D_{c,z} + \min\{D_{c,P1} \dots D_{c,Pn}\} + D_{set}(N-1)$$

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

$$N = \min\{N_r, N_{max}\}$$

$U_{c,t,z,N}$ ($US) is the expected trip-dependent utility of cell c on day t, given current cell z and the expected remaining trip duration N (number of overnight 12 h sets). $CPUE_{c,t}$ is the mean swordfish catch (number per 12 h set) for day t, predicted by the catch model. This is replaced by $CPUE_{c,lw}$ if t is the first day of a trip (i.e. the vessel is at port), which is the mean $CPUE_{c,t}$ from the previous week (lw = last week); this acknowledges that fishers may use recent conditions to determine the start location of a new trip. Pr is mean ex-vessel price ($) per swordfish. Variable costs are split into two components: C_{km} is the distance component (fuel and oil, $ km^{-1}), and is multiplied by the expected remaining trip distance (D_{trip}, km); and C_h is the time component (crew and food, $ h^{-1}), and is multiplied by expected remaining trip duration (H, h). C_{km} was calculated from a reported daily cost ($160 d^{-1}; from a cost-earnings survey, see Smith et al. 2020) divided by the mean distance travelled per day on a multi-day trip (70 km; from the observer data). C_h was also calculated from a daily cost ($534 d^{-1}; cost-earnings survey) divided by 24 h. $D_{trip_{c,z,N}}$ (km) is the expected remaining trip distance, and is calculated as the sum of: $D_{c,z}$ the distance between current cell z and cell c, min($D_{c,P1} \dots D_{c,Pn}$) 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 expected remaining sets in a trip ($N-1$). $H_{c,z,N}$ (h) is the expected remaining trip duration, and is calculated as the time taken to travel to cell c and to nearest landing port, given transit speed (S, km h^{-1}), plus the time taken to complete N remaining sets, given set duration H_{set} (h), plus the duration between sets $(N-1)(24-H_{set})$. N is calculated as the minimum of the actual sets remaining in a trip N_r (i.e. the trip being simulated) and the maximum number of days a fisher will use for location decisions N_{max} (i.e. their cautiousness when determining trip-level utility). Parameter N allows us to distinguish between a trip's simulated duration, and the trip duration a fisher is willing to plan on. For example, a simulated trip might be 5 sets long, but the simulated fisher can choose to approach this trip cautiously, and make decisions based on 3 sets. This means that for the first two days of the trip the cautious fisher may select locations closer to shore than a fisher planning on 5 sets.

We used the parameter N to help match the offshore movements and step distances of simulated fishers to observed fisher behaviour. However, the simulated fishers would still sometimes fish farther offshore than observed fishers, so an additional weighting was used to reduce the probability of fishing far offshore, while leaving the inshore area unweighted. This was achieved by weighting utility by the probability of fishing beyond a distance threshold:

$$U_{c,t,z,N} \leftarrow U_{c,t,z,N} \times f(Dist)$$

Where $f(Dist)$ is a custom function based on a single coast-wide Weibull distribution fitted to distances fished from shore ($Dist$, km) in the observer data (**Fig. S4.1**). This weighting only affected location decisions beyond the distance threshold (100 km) out to the EEZ, which was 50% of observed trips in the 1990-2000 period.

Stage 2: Cell Selection

The following steps define our framework for determining selection of the next cell to be fished. If the previous location was the final set in the pre-determined trip duration (i.e. there are no remaining sets; $N_r = 0$), then the vessel returned to the nearest port and the trip is complete. In general, to select the next fishing cell, the ABM: 1) excludes from selection all cells inside closures; 2) then excludes all cells that cannot be reached in a specified travel time, with fishers preferring closer cells when a previous day's catch was good; 3) then randomly selects a cell from the non-excluded cells with highest utility using an 'accuracy' term, prioritizing well-connected cells and cells not occupied by another vessel; 4) then moves the vessel to the selected cell and computes a catch. These steps are defined in more detail in **Table S4.5**, and illustrated in **Fig. S4.2**. The random selection using 'accuracy' acknowledges that fishers will detect utility imperfectly. This is instead of adding an error term to utility (Rose *et al.* 2015). We prefer using this area-based approach, as it allows uncertainty to be expressed in meaningful units; e.g. a fisher will be able to select the most profitable ~6000 km^2 (m = 60) from the surrounding environment. Area-based accuracy can also represent variation in the ability of fishers to interpret oceanographic features, and in which different features fishers might select.

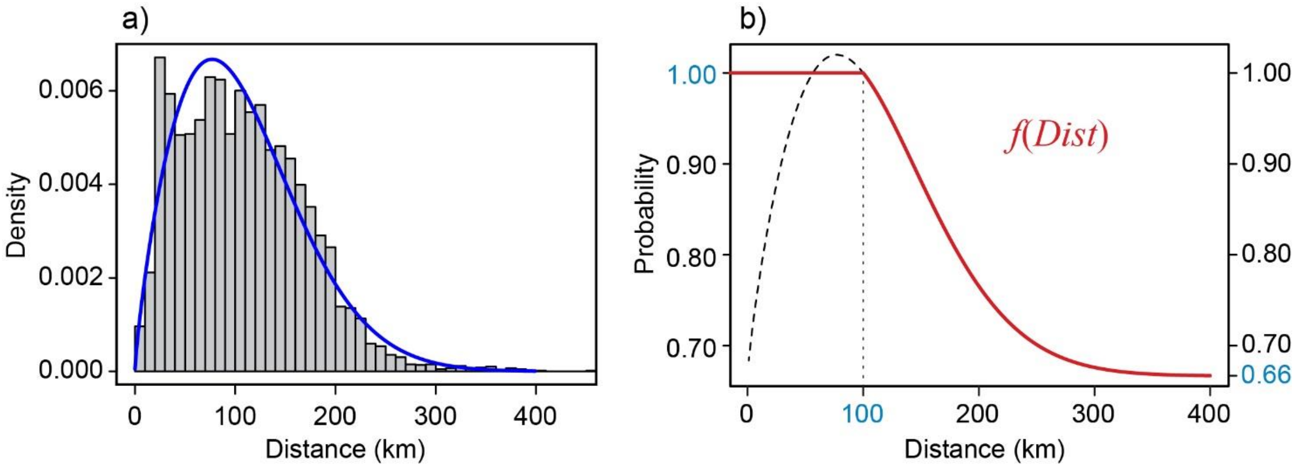

Fig. S4.1. a) A histogram (grey bars) of observed fishing sets (1990-2000 period) according to distance from shore (km), and the fitted Weibull distribution (blue line). This was fitted using the 'MASS' package in R, with fitted scale and shape parameters 120.67 and 1.801 respectively. b) The Weibull-based function used to weight utility (*f*(*Dist*); red line). Only locations > 100 km offshore (our distance threshold; dotted line) were weighted using the fitted Weibull distribution, which was rescaled to give an appropriate probability of offshore fishing, *additional to the implied distance costs of the utility function*. The rescaling meant that fishing far offshore (at the EEZ, ~400 km) was two-thirds (*f*(*Dist*) = 0.66) as likely as inshore fishing (*f*(*Dist*) = 1), assuming equal utility. The distance threshold and rescaling were tuned so that the offshore distribution of modelled and observed sets matched as closely as possible (Supp. Material S5, **Fig. S5.3**).

Table S4.5. The specific steps for cell selection in the ABM. Parameters are also defined in Table S4.7.

If $N_r = 0$,

1. Move to nearest port; trip is complete

If $N_r > 0$,

1. Exclude cells within any closure, including simulated static/dynamic turtle closures
2. Exclude cells beyond the maximum step distance ($D_{step} = S \times h$)[a]
   - 2a. If at port, h = 12-24 h[b]
   - 2b. If not at port, h = 10 h (if $Catch_{t-1} = 0$)[c]
     - h = 6 h (if $Catch_{t-1}$ = 1-2)
     - h = 2 h (if $Catch_{t-1} \geq 3$)
3. From non-excluded cells, randomly select next cell from m cells with highest utility[d]
   - 3a. If at port, m = 200
   - 3b. If not at port, m = 60
   - 3c. Prioritize connected areas ($Clump > 5$)[e] and not same or shared cell[f]
4. Move to next cell, and record a catch

[a] Agents prioritize cells within these maximum step distances (*h* values), but if none exist they will move up to 18-24 h for next cell (rather than return to port) and will record a catch if a valid cell exists; a ‘travelled too far’ event is recorded. If no valid cells exist within the extended 18-24 h travel (e.g. when a port is far inside a closed area), the vessel will stay at (or return to) port and record no fishing; a ‘no valid fishing’ event is recorded.

[b] Maximum step distances from port (the initial transit) are port-specific, and were reduced from 24 h for two ports based on observer data (**Table S4.6**).

[c] Agents prioritize closer cells when previous days swordfish catch ($Catch_{t-1}$) was high, according to three tiers (no catch, 1-2 swordfish per set, ≥ 3 swordfish per set).

[d] Random selection using *m* represents fisher ‘accuracy’ when detecting utility, with less accuracy when at port (m = 200) than when already fishing (m = 60).

[e] Agents prioritize connected cells (we assume larger areas of high-quality cells are easier to find and are more attractive) but agents will select a cell below the *Clump* threshold if necessary and record a catch; a ‘below clump threshold’ event is recorded.

[f] Agents prioritize new cells for next fishing set, and cells unoccupied by another vessel, but will remain in place or share a cell if no other valid cells exist, and will record a catch; a ‘shared location’ event is recorded.

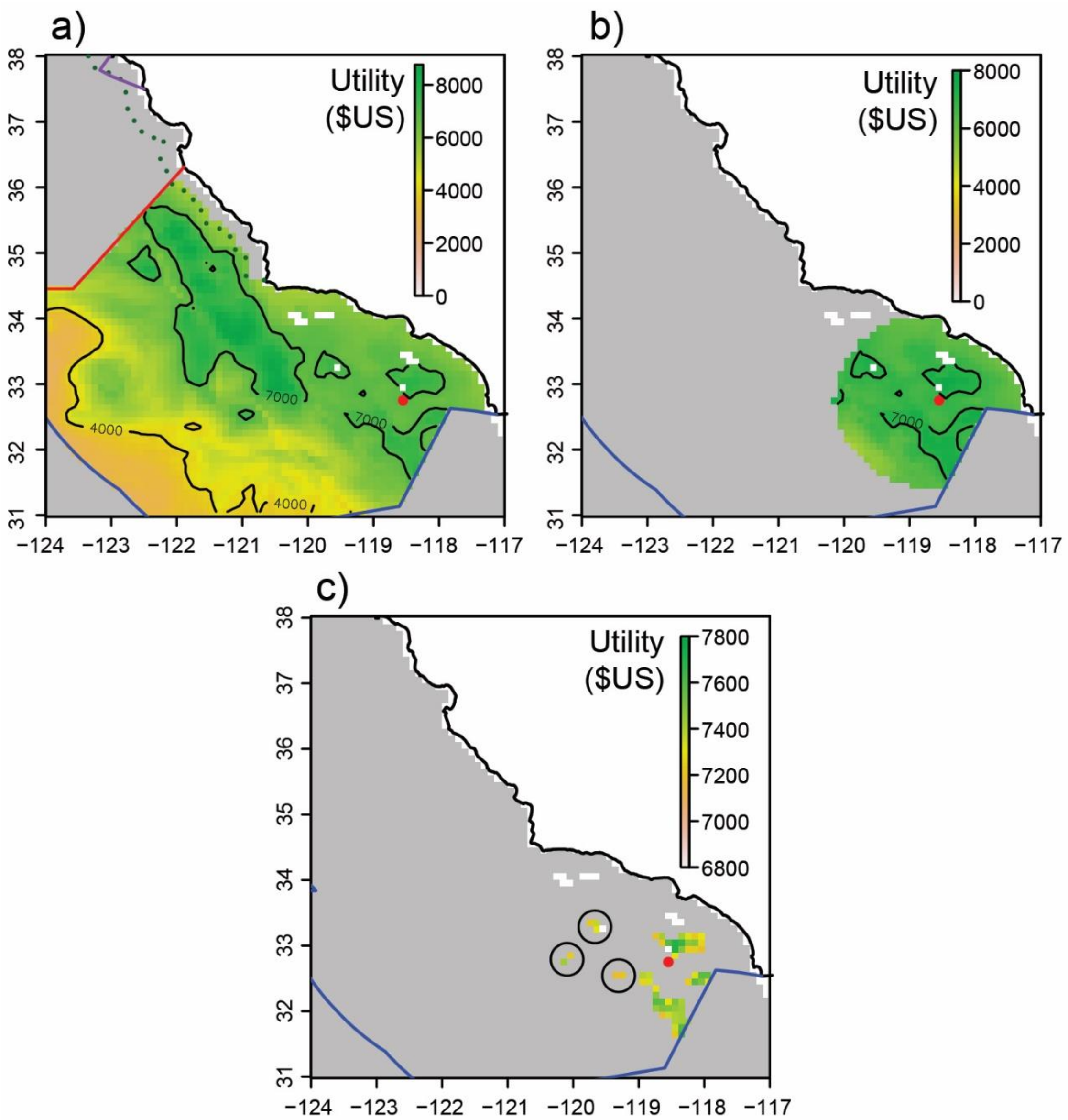

Fig. S4.2. Example of location decisions in the ABM. A vessel has just fished a location in Southern California (red dot), and must decide where to fish next (for 2nd set in a planned 5-set trip). a) On this example date (13th October 1996), three closures are active in the plotted area: the PLCA (red line), the Port Reyes closure (purple line), and the 12 nm closure (green dotted line); the color scale is the trip-dependent utility from that location (with $4000 and $7000 contour lines). b) The vessel can access cells within the maximum step distance (here, h = 10 h); the color scale is utility (with $7000 contour line). c) The vessel randomly selects one cell from the accessible cells with a specified accuracy (m = 60 cells with highest utility); any of these m cells (all other cells grey) are equally likely to be selected, except for cells in clumps smaller than 5 connected cells (circled) which are only selected if there are no better-connected cells.

Table S4.6. The initial maximum travel times vessels are willing to search within to find their initial fishing location (*h*, from port). If a valid cell is not found within these travel times/distances (distance = speed × time), the vessel does not leave port. Travel times were reduced from 24 h at two ports, to better match the 90% percentile of initial step distances observed from those ports. Ports are ordered as in **Table S4.3**.

Port	**Maximum travel time from port (h)**
SD	12
SP-LA	24
V-Ox-SB	18
MB	24
ML-M-SC	24
SF-O	24
CC	24

Table S4.7. Summary of parameters and their values. Also see Smith et al. (2020) for discussion of values and sources.

Parameter	**Symbol**	**Value**	**Units**	**Source**
Set duration	H_{set}	12	h	Median & mode duration from observer data
Price per swordfish	*Pr*	525	$US	PacFIN ($3.50 per pound)
Expected travel between sets	D_{set}	35	km	Observer data
Variable travel costs	C_{km}	2.3	$US km^{-1}	Calculated using cost-earnings survey
Variable hourly costs	C_h	22.25	$US h^{-1}	Calculated using cost-earnings survey
Sets remaining in trip	*Nr*	max = 5	sets	Observer data
Expected max trip duration	N_{max}	3	days	Inferred
Vessel maximum travel speed	*S*	15	km h^{-1}	Pers. Comm.
Maximum travel time, at port	*h*	12-24	h	Observer data
Maximum travel time, not at port; previous catch = 0	*h*	10	h	Observer data
Maximum travel time, not at port; previous catch = 1-2	*h*	6	h	Inferred
Maximum travel time, not at port; previous catch > 2	*h*	2	h	Inferred
Clumped cells threshold	*Clump*	5	cells	Inferred
Fisher accuracy, at port	*m*	200	cells	Inferred
Fisher accuracy, not at port	*m*	60	cells	Inferred

References

Rose, K.A., Fiechter, J., Curchitser, E.N., Hedstrom, K., Bernal, M., Creekmore, S., Haynie, A., Ito, S.-i., Lluch-Cota, S., and Megrey, B.A. (2015) Demonstration of a fully-coupled end-to-end model for small pelagic fish using sardine and anchovy in the California Current. *Progress in Oceanography* **138**, 348-380.

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