Supplemental information: Efficacy of a novel shark bycatch mitigation device in a tuna longline fishery

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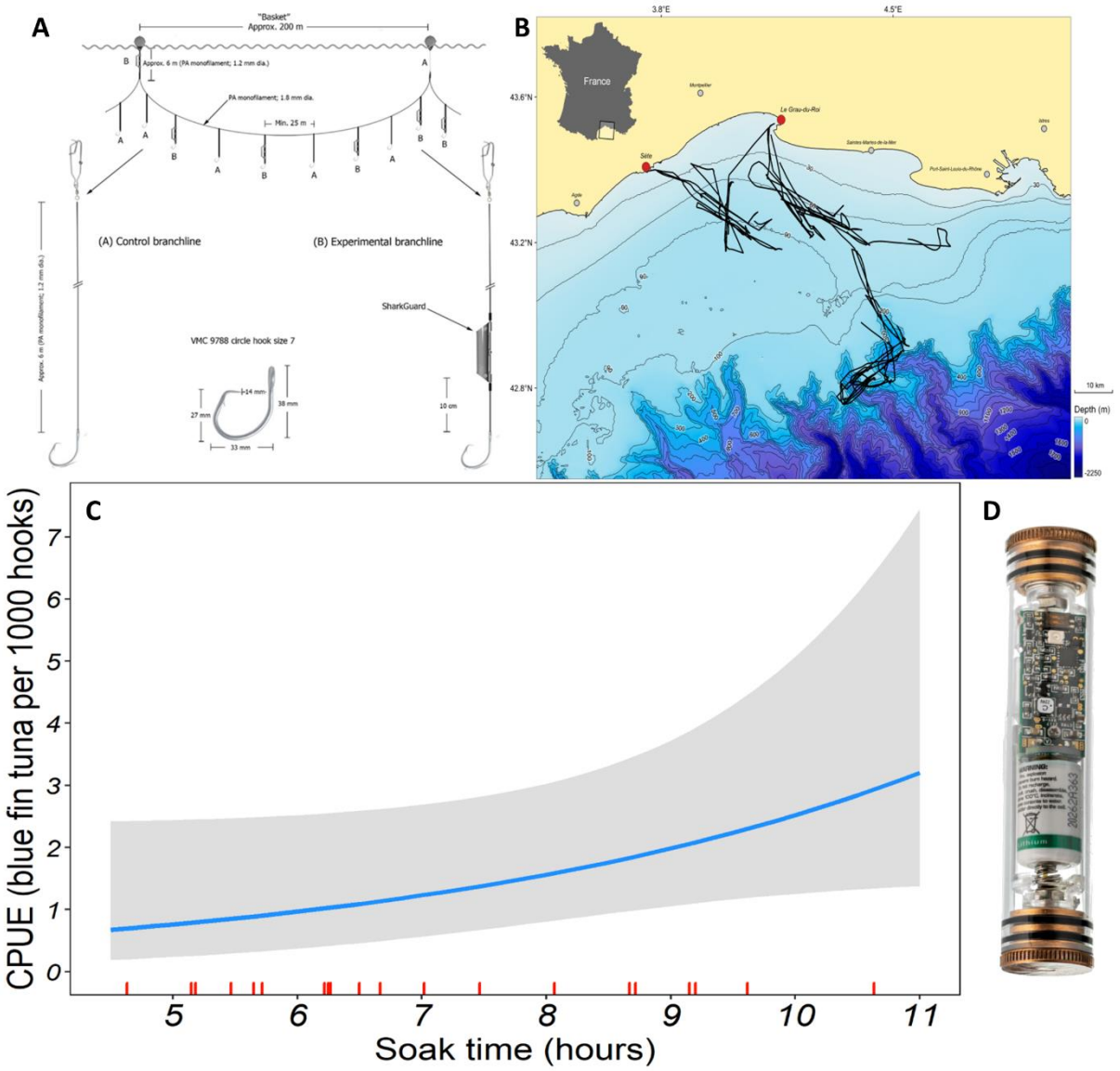

Figure S1. Experimental design and analyses of SharkGuard.

(A) Schematic diagram of longline set-up deployed in fishing trials. Eight branchlines between a set of floats terminating in baited circle hooks were attached to a mainline. These consisted of alternating

control branchlines, and branchlines fitted with a SharkGuard device. (B) Trajectories of fishing vessels (solid black lines) during sea trials testing SharkGuard. Cities (grey circles), ports of fishing operation (red circles), and bathymetric depth (continuous blue palette) displayed. (C) Mean number of individual bluefin tuna caught per 1000 hooks for increasing soak time (time of hauling end – time of deployment start). Predicted mean estimates (solid blue line), and standard error (se; grey shading) from GLMM presented for range of soak times observed during at-sea fishing trials (red dashes). (D) Close up image of a SharkGuard device.

Model	Response	Fixed effects		β	SE	χ^2	*p*
Negative Binomial	***Number of individuals caught***	*Intercept*		-5.631	0.305		
		Treatment					
			SharkGuard	0.000	0.000		
			Control	1.266	0.303		
		Species					
			Pelagic ray	0.000	0.000		
			Blue shark	-2.087	0.520		
			Bluefin tuna	-1.593	0.445		
		Soak time		0.003	0.002	3.127	0.077
		Treatment x Species				**10.585**	**0.005**
			SharkGuard x Pelagic ray	0.000	0.000		
			Control x Pelagic ray	1.266	0.303		
			SharkGuard x Blue shark	-2.087	0.520		
			Control x Blue shark	1.498	0.605		
			SharkGuard x Bluefin tuna	-1.593	0.445		
			Control x Bluefin tuna	-0.722	0.583		
Poisson	***Number of individual blue sharks caught***	*Intercept*		-5.548	0.738		
		Treatment				**62.194**	**<0.001**
			Control	0.000	0.000		
			SharkGuard	-2.443	0.426		
		Soak time		0.001	0.002	0.428	0.513
Poisson	***Number of individual pelagic rays caught***	*Intercept*		-6.345	1.481		
		Treatment				**87.606**	**<0.001**
			Control	0.000	0.000		
			SharkGuard	-1.248	0.146		
		Soak time		0.003	0.003	0.946	0.331
Poisson	***Number of individual blue fin tuna caught***	*Intercept*		-8.379	1.202		
		Treatment				1.817	0.178
			Control	0.000	0.000		
			SharkGuard	-0.528	0.399		
		Soak time		**0.004**	**0.002**	**3.968**	**0.046**

Table S1. Summary results of generalised linear mixed models (GLMMs). Output from model of interaction between treatment and species, and species-specific effects models. Significant terms highlighted in bold.

Supplemental Experimental Procedures

SharkGuard

SharkGuard devices were positioned 10 cm above the eye of the hook, crimped directly to the branchline to prevent any movement (**Figure S1**). Two vessels fished using the same gear configuration, with two trained onboard fisheries observers who collected data on the number of hooks per treatment, set and haul GPS locations, start and end of set and haul times, and species caught on each hook. Only bluefin tuna were landed during the trials, with all other bycaught individuals released. SharkGuard creates a powerful, short-range, 3D pulsed electric field designed to overstimulate the electroreceptors possessed by sharks with the intent of reducing the frequency of individuals approaching or interacting with hooks. SharkGuard automatically switches on/off when entering/exiting seawater and emits an electrical pulse (30 V, lasting 1.5 milliseconds every 2 seconds [0.5 Hz]) powered by a single, 3.6 V Lithium thionyl chloride battery. The battery lasts 65 hours (in water), with an indicator light (red LED) signalling when the battery has <15% capacity remaining (>1 full set). SharkGuard electronics are encased in a 100 mm x 20 mm cylindrical tube and are easily removed from its bespoke polycarbonate housing, which is permanently attached to the branchlines above each hook, facilitating efficient battery changes (**Figure S1**). SharkGuard is depth rated to 1000 m and weighs 46 g in seawater (inclusive of housing). SharkGuard functionality was tested (using Picoscope 7 software; picotech.com, and a bespoke cradle) prior to first deployment by the Fisheries Observers, and after each battery change. Where SharkGuard hooks caught shark species, the device was removed (for function tests ashore) and replaced with a new device

Study design and data collection

It was necessary to alternate control and SharkGuard hooks on the same longline to prevent hook treatments fishing at different depths, whilst also accounting for patchy distribution of environmental conditions and pelagic predators in pelagic marine ecosystems. Vessels in this fishery would ordinarily deploy branchlines every 16-20 m, but for the purposes of these sea trials, branchlines were spaced

25 m apart, with the crew deploying these using a timed alarm for a set vessel speed. This spacing was required to ensure hooks were at a distance where there was no contamination effect of SharkGuard on control hooks. This effect was tested using three-dimensional finite element analysis (FEA) software (Quickfield Professional, version 6.4; quickfield.com). SharkGuard, complete with its field-generating electrodes and polycarbonate housing for line attachment was accurately modelled within the Quickfield simulation environment, centrally located within a uniformly conductive body of 40 m x 40 m x 40 m (representing the surrounding seawater). The three-dimensional electric field strength was subsequently calculated for all points within the body of water. The minimum hook spacing was deduced from the outputs of the simulated model where the electric field strength from the SharkGuard device at mid-distance between two alternating hooks (one SharkGuard, one control) was below the median electrical stimulus threshold (for initiation of orientation) for pelagic stingray[S1]. No electrical stimulus threshold data were available for blue sharks (or other pelagic sharks). A branchline spacing of 25 m was used to ensure the control and SharkGuard hooks were independent of each other (i.e., at 12.5 m, the modelled field strength of SharkGuard was below the median stimulus threshold of the pelagic ray). To ensure treatments were deployed alternately, one vessel pre-attached branchlines to the mainline and stored in separate bins ensuring that when set one treatment followed another at the correct spacing distance. The other vessel used longline snaps with treatments in separate bins to be "snapped" on during deployment in an alternating fashion at correct spacing.

Data processing

A unique trip ID was created combining information on the vessel ID and the sequential number of trips carried out by that vessel. Soak time was classified as the time difference between the start of hook deployment and the end of hook retrieval to encompass the entire time when hooks were in the water (i.e., time within which an animal could be caught).

Statistical analysis

To test the efficacy of SharkGuard as a mitigation device, we first needed to establish if there were differences in hook treatments across species. To achieve this, we modelled the response of number of all individuals caught (all species combined) using a negative binomial generalised linear mixed model (GLMM) due to overdispersion. We tested the interaction between treatment (control / SharkGuard) and species (blue shark / pelagic stingray / bluefin tuna), as well as including an individual fixed effect of soak time (time of hauling end – time of deployment start). The model also included an offset term of the log of fishing effort (number of hooks) to model the rate of catch per unit effort (CPUE) standardised to individuals per 1000 hooks, and a random effect of set nested within trip to account for effect of vessel, survey design, and observation effect where multiple sets were deployed within a single trip. Then, to investigate species-specific effects, we fitted separate models for each species of interest: (1) blue shark, (2) pelagic stingray, and (3) bluefin tuna. These models included the response variable of number of species-specific individuals caught using poisson GLMMs and included the same variables as the interaction model, but all fixed effects fitted as individual variables. All models were fitted using the *glmmTMB* package[S2] in R v4.0.2[S3]. In each analysis, to assess the significance of each fixed effect we compared the likelihood ratio of the maximal model to that of the model without the fixed effect. To avoid problems associated with stepwise model reduction we did not remove non-significant main effects [S4, S5].

Diagnostic checks of model residuals were conducted inspecting dispersion using a nonparametric dispersion test of residuals fitted vs. simulated residuals via the *testDispersion* function in the DHARMa package[S6], and uniformity via visually inspecting QQ plots of model residuals via the *testUniformity* function in the *DHARMa* package[S6].

Supplemental References

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