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Marine and Freshwater Research

Supplementary Material

Multifaceted effects of bycatch mitigation measures on target or non-target species for pelagic longline fisheries and consideration for bycatch management

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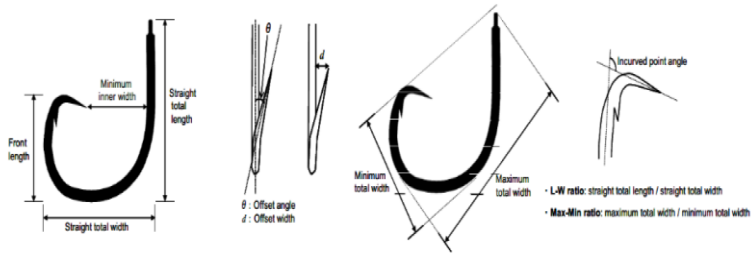
Table S1. Detailed measurements of hooks used in the experiment and a figure explaining measurement points of hooks (copied from Yokota *et al*. 2006).



Manufacture	**Komatsu Keisaku**	**Hisamatsu Tankichi**	**Doitomi**	**Komatsu Keisaku**	**Komatsu Keisaku**	**Komatsu Keisaku**	**Komatsu Keisaku**	**Komatsu Keisaku**	**Komatsu Keisaku**	**Komatsu Keisaku**	**Pacific Fishing Tackle MFG, Co.**
Hook name	tuna hook	Uruwa hook BKN	tuna circle hook SS-170	modified circle hook	modified circle hook	modified circle hook	cirlce hook type Koshina	cirlce hook type North America	cirlce hook type North America	modified circle hook	circle hook
Standardised size	4.0 sun	3.8 sun	#4	4.0 sun	4.5 sun	4.8 sun	4.5 sun	4.3 sun	5.2 sun	5.2 sun	18/0
material	stainless steel	hard steel	stainless steel	stainless steel	stainless steel	stainless steel	stainless steel	hard steel	hard steel	stainless steel	stainless steel
Hook eye	yes, with ring	yes, with ring	yes, with ring	yes, with ring	yes, with ring	yes, with ring	yes, with ring	yes, with ring	yes, with ring	yes, with ring	yes, with ring
Shank thickness (mm)	5.3	4	4.1	5.3	5.2	N/A	4.9	5.3	5.7	5.3	5.1
Straight total length (mm)	63	56	58	60	63	N/A	62	57	74	76	68
Straight total width (mm)	38	44	49	47	49	N/A	56	45	56	54	59
Minimum total width (mm)	38	36	39	41	45	N/A	51	41	52	48	51
Maximum total width (mm)	63	64	69	68	71	N/A	76	63	81	85	80
Front length (mm)	41	33	38	35	44	N/A	47	39	49	47	45
Minimum inner width (mm)	27	20	15	24	25	N/A	26	20	27	26	27
L/W ratio	1.7	1.3	1.2	1.3	1.3	N/A	1.1	1.3	1.3	1.4	1.2
Max.–min. ratio	1.7	1.8	1.8	1.7	1.6	N/A	1.5	1.5	1.6	1.8	1.6
Incurved point angle		80	70	90	70	N/A	70	65	75	80	80
Offset angle	$5 \leq \theta < 10°$	$\theta = \sim 0°$	$\theta = \sim 0°$	$\theta = \sim 10°$	$5 \leq \theta < 10°$	$\theta < 10°$	$\theta = \sim 10°$	$5 \leq \theta < 10°$	$10 \leq \theta < 15°$	$\theta = \sim 5°$	$10 \leq \theta < 15°$
Offset width (mm)	0.9	~0	~0	1.8	2.6	N/A	2.1	1.5	3.7	1	5.4
Weight (g)	19.9	12.2	15	19.7	21.6	N/A	21.4	19.4	30.3	25.5	23.2

Table S2. Estimates of the posterior distribution of the proportion of hooking location by hook when squid bait is used (median) and lower and upper limits of Bayesian credible interval (95% highest density interval, HDI) are shown in parentheses.

Species	Hook type		
	Tuna	Small-C	Large-C
Hooking location: external			
Blue shark	0.020 (0.015–0.027)	0.008 (0.005–0.012)	0.005 (0.001–0.014)
Loggerhead turtle	0.025 (0.006–0.066)	0.079 (0.037–0.143)	0.031 (0.001–0.154)
Longnose lancetfish	0.049 (0.020–0.092)	0.031 (0.011–0.067)	0.074 (0.018–0.185)
Shortfin mako	0.102 (0.041–0.199)	0.107 (0.052–0.185)	0.136 (0.021–0.381)
Striped marlin	0.083 (0.026–0.186)	0.068 (0.016–0.173)	0.048 (0.002–0.235)
Swordfish	0.075 (0.030–0.148)	0.109 (0.057–0.184)	0.031 (0.001–0.154)
Hooking location: mouth			
Blue shark	0.497 (0.475–0.518)	0.548 (0.528–0.568)	0.560 (0.517–0.603)
Loggerhead turtle	0.439 (0.346–0.534)	0.480 (0.381–0.577)	0.746 (0.544–0.892)
Longnose lancetfish	0.857 (0.792–0.908)	0.903 (0.848–0.943)	0.872 (0.740–0.953)
Shortfin mako	0.356 (0.238–0.486)	0.524 (0.418–0.630)	0.379 (0.154–0.650)
Striped marlin	0.759 (0.623–0.869)	0.831 (0.696–0.924)	0.883 (0.660–0.982)
Swordfish	0.528 (0.416–0.637)	0.676 (0.574–0.767)	0.611 (0.405–0.790)
Hooking location: swallowed			
Blue shark	0.483 (0.461–0.505)	0.444 (0.424–0.464)	0.434 (0.391–0.478)
Loggerhead turtle	0.533 (0.438–0.626)	0.438 (0.343–0.537)	0.210 (0.078–0.405)
Longnose lancetfish	0.092 (0.052–0.148)	0.064 (0.032–0.111)	0.046 (0.007–0.145)
Shortfin mako	0.536 (0.405–0.665)	0.365 (0.266–0.472)	0.460 (0.213–0.724)
Striped marlin	0.150 (0.066–0.273)	0.093 (0.030–0.207)	0.048 (0.002–0.234)
Swordfish	0.394 (0.289–0.505)	0.211 (0.136–0.303)	0.343 (0.174–0.550)

Table S3. Estimated haulback mortality rates (median of posterior distribution) by hooking location when squid bait is used and lower and upper limits of Bayesian credible interval (95% highest density interval, HDI) are shown in parentheses.

Species	External	Mouth	Swallowed
Blue shark	0.295 (0.185–0.411)	0.052 (0.044–0.061)	0.157 (0.141–0.172)
Shortfin mako shark	0.496 (0.262–0.729)	0.134 (0.061–0.219)	0.279 (0.176–0.394)
Longnose lancetfish	0.956 (0.810–1.000)	0.860 (0.816–0.899)	0.798 (0.621–0.934)
Swordfish	0.802 (0.595–0.959)	0.776 (0.694–0.853)	0.919 (0.842–0.979)
Striped marlin	0.798 (0.488–0.990)	0.431 (0.315–0.547)	0.968 (0.839–1.000)

Loggerhead turtles were excluded because there were no mortalities and the calculation had not been converged.

Table S4. Haulback mortality rate by hook and bait type (median of posterior distribution) and lower and upper limits of Bayesian credible interval (95% highest density interval, HDI) are shown in parentheses.

Species	Hook type		
	Tuna	Small-C	Large-C
Bait type: squid			
Bigeye tuna	0.734 (0.636–0.823)	0.757 (0.679–0.830)	0.959 (0.813–1.000)
Blue shark	0.084 (0.077–0.093)	0.081 (0.072–0.091)	0.077 (0.062–0.093)
Common dolphinfish	0.154 (0.099–0.215)	0.128 (0.081–0.180)	0.180 (0.110–0.265)
Escolar	0.188 (0.082–0.309)	0.301 (0.165–0.454)	0.182 (0.060–0.340)
Longnose lancetfish	0.901 (0.870–0.930)	0.925 (0.892–0.954)	0.889 (0.826–0.940)
Shortfin mako	0.161 (0.106–0.223)	0.187 (0.123–0.258)	0.181 (0.085–0.300)
Striped marlin	0.532 (0.400–0.665)	0.472 (0.334–0.609)	0.530 (0.318–0.740)
Swordfish	0.829 (0.754–0.895)	0.783 (0.698–0.859)	0.832 (0.711–0.934)
Bait type: fish			
Bigeye tuna	0.473 (0.319–0.622)	0.503 (0.337–0.663)	0.884 (0.573–1.000)
Blue shark	0.078 (0.069–0.088)	0.075 (0.063–0.088)	0.071 (0.056–0.088)
Common dolphinfish	0.238 (0.159–0.326)	0.201 (0.102–0.311)	0.274 (0.162–0.400)
Escolar	0.242 (0.114–0.390)	0.371 (0.179–0.596)	0.233 (0.054–0.469)
Longnose lancetfish	0.909 (0.879–0.936)	0.931 (0.894–0.961)	0.898 (0.841–0.947)
Shortfin mako	0.307 (0.237–0.381)	0.348 (0.226–0.478)	0.339 (0.196–0.493)
striped marlin	0.691 (0.457–0.885)	0.638 (0.375–0.870)	0.691 (0.386–0.925)
swordfish	0.853 (0.727–0.950)	0.811 (0.648–0.934)	0.856 (0.700–0.967)

Table S5. Standardised catch per unit effort (CPUE) by hook and bait type (median of posterior distribution) and lower and upper limits of Bayesian credible interval (95% highest density interval, HDI) are shown in parentheses.

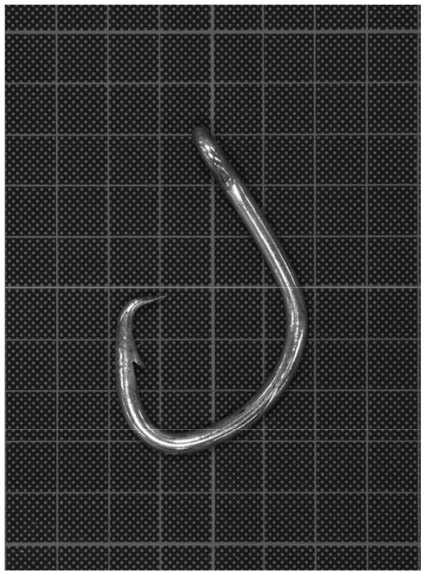
Species	Hook type		
	Tuna	Small-C	Large-C
Bait type: squid			
Bigeye tuna	0.433 (0.057–1.230)	0.825 (0.102–2.340)	0.680 (0.051–2.300)
Blue shark	45.141 (36.893–53.976)	51.084 (41.940–61.337)	43.953 (35.882–53.072)
Common dolphinfish	0.755 (0.384–1.282)	1.280 (0.622–2.172)	0.823 (0.383–1.403)
Escolar	0.199 (0.060–0.409)	0.511 (0.157–1.054)	0.289 (0.079–0.631)
Longnose lancetfish	3.287 (2.514–4.144)	3.598 (2.700–4.604)	3.204 (2.243–4.304)
Shortfin mako	1.087 (0.771–1.433)	1.402 (0.969–1.878)	0.982 (0.615–1.436)
Striped marlin	0.312 (0.140–0.537)	0.282 (0.118–0.493)	0.294 (0.112–0.564)
Swordfish	0.721 (0.441–1.047)	0.825 (0.500–1.231)	0.840 (0.467–1.333)
Bait type: fish			
Bigeye tuna	0.184 (0.020–0.550)	0.352 (0.033–1.047)	0.289 (0.020–1.059)
Blue shark	36.417 (29.748–43.741)	41.224 (33.670–49.667)	35.459 (28.602–42.824)
Common dolphinfish	1.855 (0.897–3.150)	3.146 (1.523–5.431)	2.023 (0.917–3.514)
Escolar	0.437 (0.127–0.918)	1.123 (0.321–2.419)	0.634 (0.159–1.456)
Longnose lancetfish	3.499 (2.643–4.507)	3.829 (2.829–5.003)	3.414 (2.372–4.724)
Shortfin mako	2.294 (1.598–3.089)	2.953 (1.986–4.073)	2.071 (1.258–3.104)
Striped marlin	0.350 (0.131–0.660)	0.316 (0.108–0.617)	0.331 (0.095–0.689)
Swordfish	0.714 (0.395–1.124)	0.817 (0.434–1.308)	0.834 (0.389–1.394)

Table S6. Estimated MPUE by hook and bait type (median of posterior distribution) and lower and upper limits of Bayesian credible interval (95% highest density interval, HDI) are shown in parentheses.

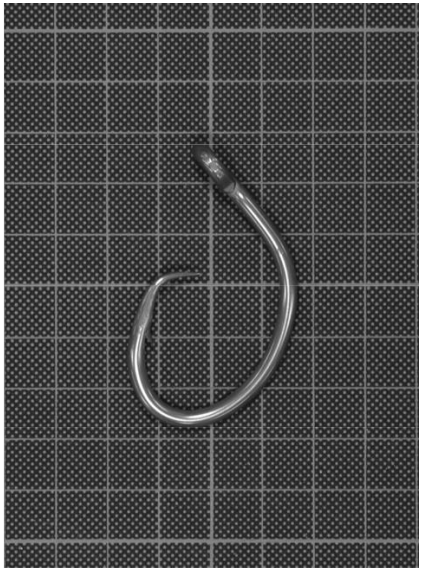
Species	Hook type		
	Tuna	Small-C	Large-C
Bait type: squid			
Bigeye tuna	0.316 (0.035–0.899)	0.623 (0.078–1.774)	0.637 (0.051–2.173)
Blue shark	3.802 (3.031–4.628)	4.143 (3.263–5.120)	3.383 (2.494–4.401)
Common dolphinfish	0.115 (0.048–0.211)	0.163 (0.067–0.301)	0.148 (0.056–0.279)
Escolar	0.037 (0.008–0.088)	0.152 (0.035–0.345)	0.052 (0.007–0.140)
Longnose lancetfish	2.960 (2.255–3.734)	3.322 (2.457–4.225)	2.839 (1.986–3.849)
Shortfin mako	0.174 (0.096–0.261)	0.260 (0.144–0.397)	0.177 (0.066–0.328)
Striped marlin	0.165 (0.068–0.294)	0.132 (0.051–0.243)	0.153 (0.048–0.320)
Swordfish	0.595 (0.353–0.866)	0.643 (0.388–0.971)	0.694 (0.369–1.109)
Bait type: fish			
Bigeye tuna	0.087 (0.008–0.266)	0.174 (0.017–0.540)	0.241 (0.014–0.906)
Blue shark	2.844 (2.232–3.519)	3.094 (2.359–3.935)	2.527 (1.816–3.348)
Common dolphinfish	0.438 (0.176–0.800)	0.627 (0.213–1.238)	0.550 (0.197–1.057)
Escolar	0.104 (0.019–0.250)	0.407 (0.086–0.996)	0.144 (0.015–0.439)
Longnose lancetfish	3.177 (2.389–4.094)	3.558 (2.611–4.651)	3.055 (2.075–4.207)
Shortfin mako	0.703 (0.444–1.004)	1.020 (0.547–1.586)	0.697 (0.312–1.196)
Striped marlin	0.237 (0.075–0.469)	0.195 (0.054–0.413)	0.219 (0.051–0.497)
Swordfish	0.601 (0.323–0.960)	0.653 (0.324–1.065)	0.703 (0.320–1.201)

Komatsu Keisaku:
Tuna hook 4.0 sun

Hisamatsu Tankichi:
Uruwa hook BKN 3.8 sun



Doitomi:
Tuna circle hook SS-170 #4



Komatsu Keisaku:
Modified circle hook 4.0 sun

Komatsu Keisaku:
Modified circle hook 4.5 sun

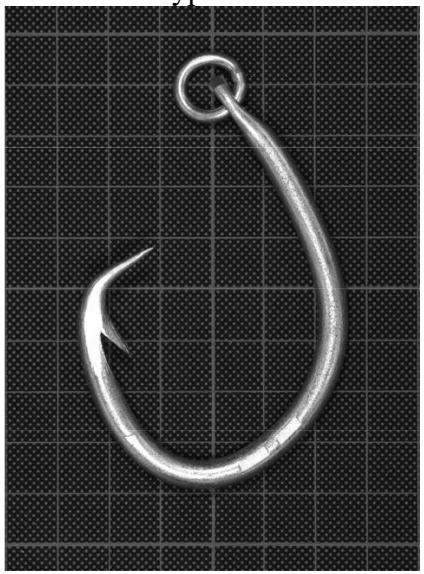
Komatsu Keisaku:
Modified circle hook 4.8 sun

No image available

Fig. S1. Figure of hooks used in the experiment, including a 1-cm^2 background. Images for Hisamatsu Tankichi, Uruwa hook BKN 3.8 sun; Doitomi, Tuna circle hook SS-170 #4; Komatsu Keisaku, Circle hook type North America 5.2 sun; and Pacific Fishing Tackle MFG., CO. Circle hook 18/0 were copied from Yokota *et al*. (2006).

Komatsu Keisaku:
Circle hook type Koshina 4.5 sun

Komatsu Keisaku:
Circle hook type North America 5.2 sun



Komatsu Keisaku:
Modified circle hook 5.2 sun

Pacific Fishing Tackle MFG., CO.:
Circle hook 18/0

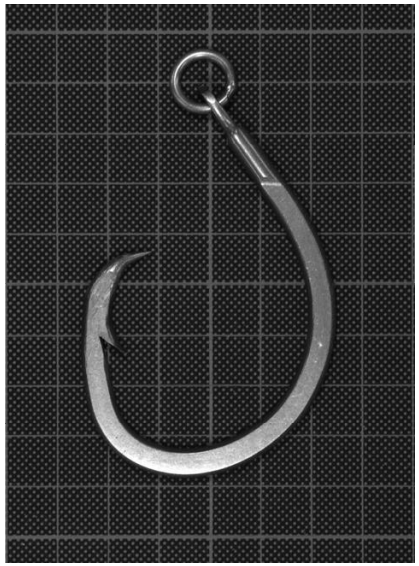


Fig. S1. (*Cont.*)

(a) MODEL 1

```
data {
  int HK_cat;
  int<lower=1> N1;
  int<lower=1> LOC_cat;
  int<lower=1, upper=LOC_cat> LOC[N1];
  int<lower=1, upper=HK_cat> HK[N1];
  int<lower=0, upper=1> M[N1];
  int L;
  matrix[N1, L] X1;
  int N2;
  int  Catch[N2];
  int L2;
  matrix[N2, L2] X2;
  vector[N2] O;
  int YRID;
  int YR[N2];
}

transformed data{
  vector[HK_cat] Zeros;
  Zeros = rep_vector(0, HK_cat);
}

parameters {
  matrix[HK_cat, LOC_cat - 1] theta_raw;
  vector[L] beta;
  vector[L2] beta2;
  vector[YRID] r;
  real<lower= 0> sigma;

}

transformed parameters {
  vector[N2] mu;
  vector[N1] phi;
  matrix[HK_cat, LOC_cat] theta;
  phi = inv_logit(X1 * beta);
  theta = append_col(Zeros, theta_raw);
  for(i in 1:N2)
  mu[i] = X2[i,] * beta2 + r[YR[i]];

model {
  sigma ~ student_t(4, 0, 2.5);
  r ~ normal(0, sigma);
  for(n in 1:N1){
  M[n] ~ bernoulli(phi[n]);
  target += categorical_lpmf(LOC[n]|softmax(theta[HK[n],]'));
  }
  Catch ~ poisson(exp(mu + log(O)));
}
```

Fig. S2. Stan code used for MCMC sampling of (a) Model 1 and (b) Model 2.

(b) MODEL 2

```
data {
  int HK_BAIT_comb;
  int<lower=1> N1;
  int<lower=0, upper=1> M[N1];
  int L;
  matrix[N1, L] X1;
  int N2;
  int  Catch[N2];
  int L2;
  matrix[N2, L2] X2;
  vector[N2] O;
  int YRID;
  int YR[N2];
}

parameters {
  vector[L] beta;
  vector[L2] beta2;
  vector[YRID] r;
  real<lower= 0> sigma;
}

transformed parameters {
  vector[N2] mu;
  vector[N1] phi;
  phi = inv_logit(X1 * beta);
  for(i in 1:N2)
  mu[i] = X2[i,] * beta2 + r[YR[i]];
}

model {
  sigma ~ student_t(4, 0, 2.5);
  r ~ normal(0, sigma);
  for(n in 1:N1){
  M[n] ~ bernoulli(phi[n]);
  }
  Catch ~ poisson(exp(mu + log(O)));
}
```

Fig. S2. (*Cont.*)

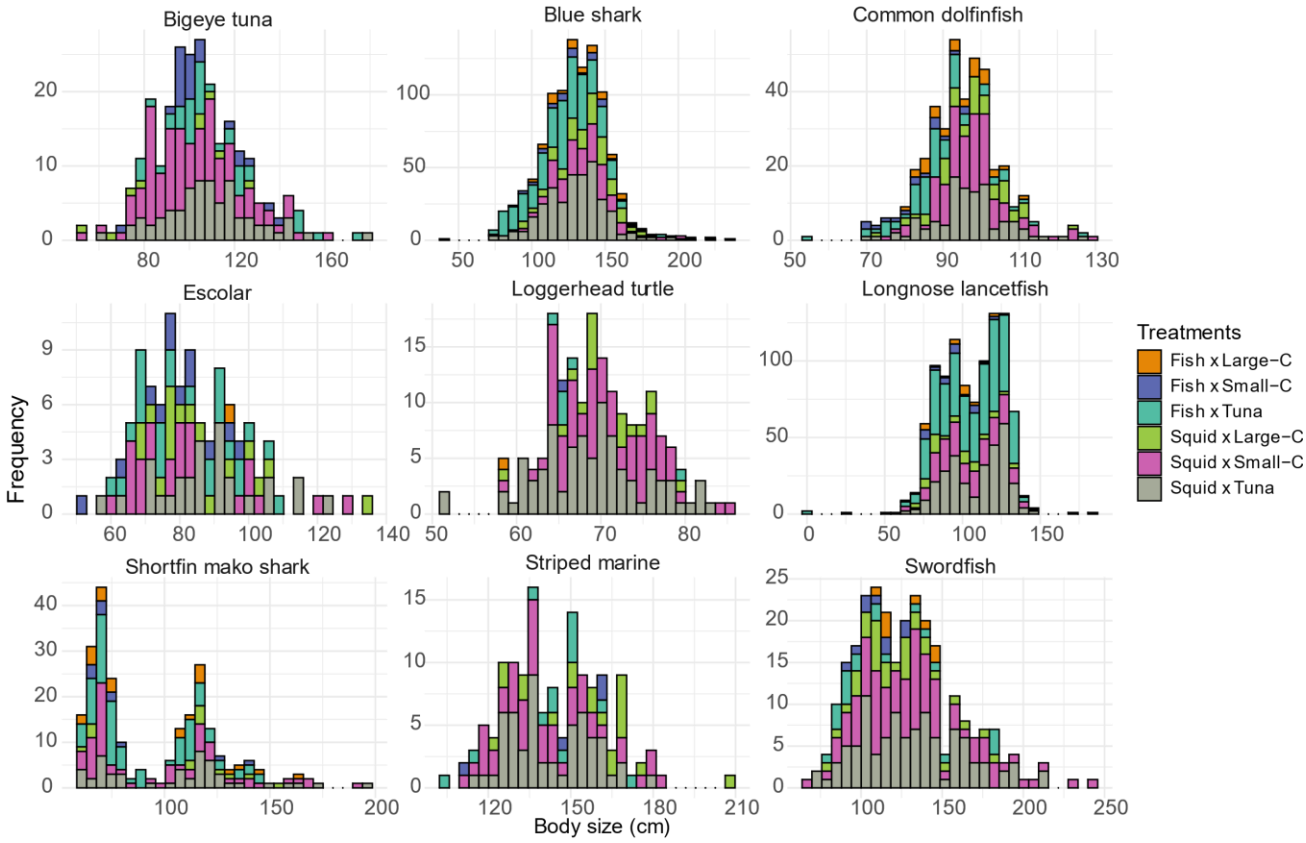


Fig. S3. Size distributions by species for the major species captured in the study, with body length as an index of precaudal length for blue sharks and shortfin mako sharks, straight-line carapace length for loggerhead turtles, eye-to-fork length for striped marlin and swordfish, and fork length for all other species.

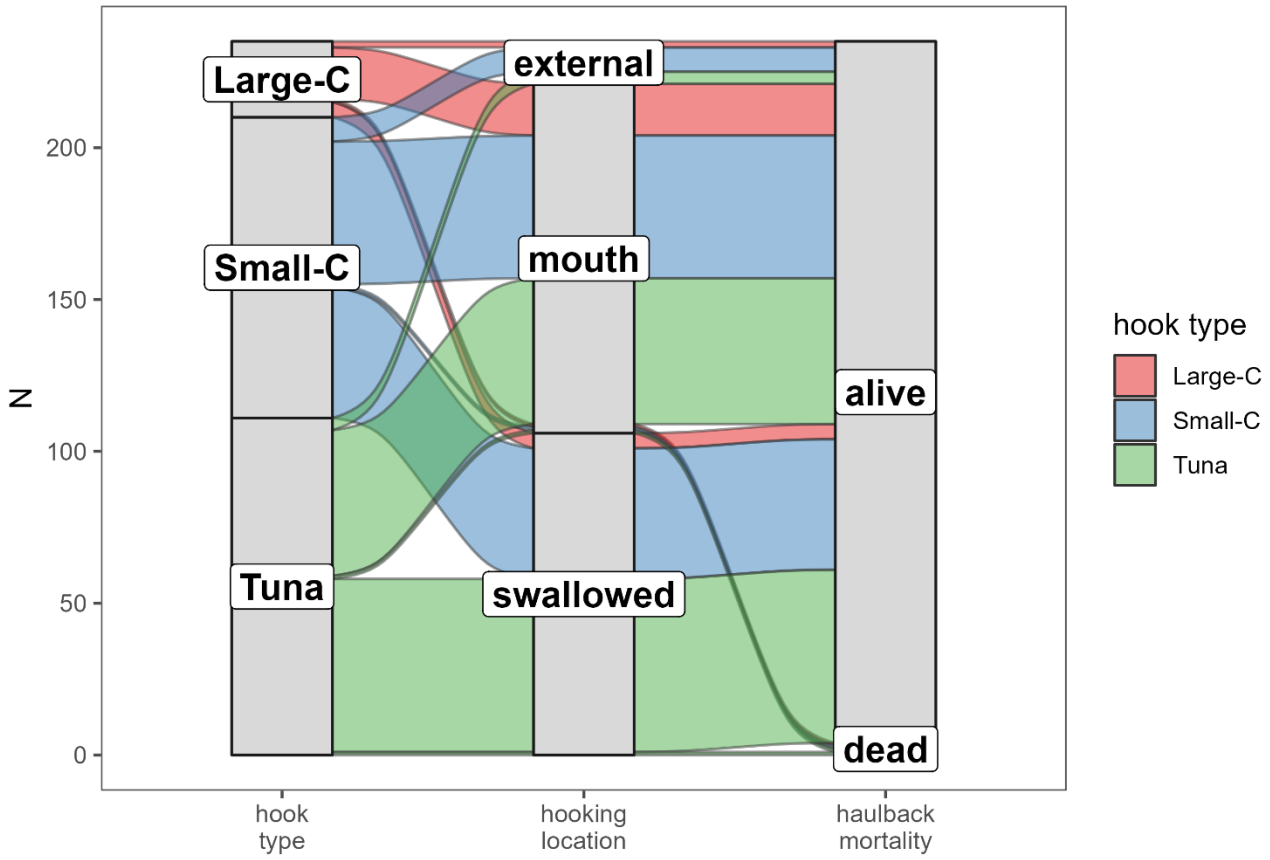


Fig. S4. Alluvial plot of hooking locations and associated haulback mortality rates of loggerhead turtles by hook when squid bait is used.

Reference

Yokota K, Minami H, Kiyota M (2006) Measurement-points examination of circle hooks for pelagic longline fishery to evaluate effects of hook design. *Bulletin of Fishery Research Agency* **17**, 83–102