

## ELECTRONIC SUPPLEMENTARY MATERIAL

### Predicting synergistic effects of resources and predators on foraging decisions by juvenile Steller sea lions

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#### 1. Model derivation

Here we derive the dynamic state variable model (Clark and Mangel 2000) of foraging decisions by juvenile Steller sea lions (SSLs). The model's terminal horizon,  $T$ , is when overwintering aggregations of adult herring disperse from inshore areas into open water. The time preceding  $T$  is divided into 720 1-hour basic periods,  $t$ , when decisions are made.

The state variable  $X(t)=x$  represents the energetic equivalent of lipid stores at  $t$ . It ranges from 1954.6 to 2017.5 MJ and is discretized into 31 computer values, ranging from  $x_{min}=0$  to  $x_{max}=30$  (see Eq. 2.4 of Clark and Mangel 2000). Based on a lipid energy density of  $39.33 \text{ kJ g}^{-1}$  (Schmidt-Nielsen 1990) and an average body composition of 39.75% lipid (J. Burns unpublished data),  $x_{min}$  and  $x_{max}$  correspond to total body weights of 126.7 and 130.7 kg, respectively. The value of  $x_{max}$  represents the energy stores and body weight that are attainable in 30 days when assuming a potential growth rate of  $0.115 \text{ kg d}^{-1}$  (Rosen and Trites 2004) and a starting weight of 127.1 kg (i.e.,  $X(0)\approx 4$ ). The starting weight is the mean of empirical measurements made in November 2003, when SSLs were captured as 17 month-olds (see legend to Fig. 2). These animals were not re-captured, yet data from other individuals suggest an average increase of  $\approx 12 \text{ kg}$  by 21 months of age the following March (J. Burns unpublished data), the period represented by simulations. Although absolute values for energy stores, stomach capacity and energetic cost might, consequently, be somewhat low in the model (see below) relative to the field, predictions relevant to our objectives depend on relative differences rather than on absolute values.

The state variable  $G(t)=g$  represents stomach fill (i.e. mass of captured fish in stomach) at  $t$ , expressed as the proportion of total body weight  $w$ . Its discretized values are 0–7; with  $g_{min}=0$  representing an empty stomach and  $g_{max}=7$  representing  $0.094w$  (Fiscus and Baines 1966; see also Trumble et al. 2003 and references within). Digestion appears to be most efficient when full meals, rather than small top-up amounts, are consumed (Jobling 1986; Murie and Lavigne 1986; Pierce and Boyle 1991). Thus, we make the simplifying assumption that a foraging animal assimilates energy while filling its stomach, but upon reaching  $g_{max}$  energy cannot be assimilated further unless foraging stops and the stomach content is digested down to  $G(t)=g_{crit}=1$  (i.e.  $0.01w$ ).

Activity state at  $t$ ,  $A(t)=a$ , was required to model digestive constraints in the context of  $g_{crit}$ . If  $A(t)=0$ , then the animal is not foraging (it is resting or traveling) and digestion leads to  $G(t+1)<G(t)$ ; resumption of foraging is unprofitable (energy assimilation is impossible) unless  $G(t)\leq g_{crit}$ . If  $A(t)=1$ , the animal is already foraging and

gaining energy, even if  $G(t) > g_{crit}$ , as long as  $G(t) < g_{max}$ . Foraging can continue into subsequent time periods but energy assimilation stops at  $G(t) = g_{max}$  and the decrease of stomach fill required to resume energy assimilation cannot begin unless foraging stops and  $A(t) = 0$ .

The environmental state  $H(t) = h$  represents location  $h$ . Its values, integers between 0 and 3, are numerical labels identifying the haulout and 3 foraging locations differing in available resources (Fig. 1; Table 1). The decision variable is  $D(x, g, a, h, t) = d$ . Values of  $d$  in the range 0–3 correspond to a location  $h$  represented by the same number. These decisions involve either staying at the same location during  $t + 1$  (i.e.  $d = h$ ), or moving and reaching a new location at  $t + \tau$  (i.e.  $d \neq h$ ), where  $\tau$  denotes the number of hours required for 1-way travel between surface locations. Values of  $\tau$  (Fig. 1) were based on the relative locations of the Glacier Island haulout, fish resources, and the areas where instrumented SSLs spent substantial amounts of time diving. To estimate  $\tau$ , we assumed a surface swimming speed of  $2 \text{ m s}^{-1}$  ( $7.2 \text{ km h}^{-1}$ ), which is approximately the speed of minimum cost of transport (Rosen and Trites 2002). If  $h \neq 0$ ,  $d$  may also have values in the range 4–8, representing decisions in which the transition to  $t + 1$  is spent in a bout of foraging dives. Dive decisions are constrained by location (Fig. 1)). Although components of a dive cycle (time at the surface, traveling the water column, and at a foraging patch) have flexible durations that likely respond to resources and predation risk (Frid et al. 2007a), the model's 1-hour time period required that foraging bouts comprise of contiguous dive cycles with fixed durations (Table S1).

### *Predation risk*

The notation  $\mu\{h, d, v\}$  depicts the probability of mortality during the transition from  $t$  to  $t + 1$  or  $t + \tau$  when at habitat  $h$  and making decision  $d$  during diel period  $v$ . If  $h \neq 0$  and  $d > 3$  (i.e. diving to forage), the calculation of  $\mu\{h, d, v\}$  requires two stages. The first determines  $\mu\{\omega, p, v\}$ , the probability of mortality during dive cycle component  $\omega$ —surface interval  $\phi$ , vertical travel  $\vartheta$ , or patch residence  $U$ —for a dive to depth stratum  $p$  during  $v$ ,

$$\mu\{\omega, p, v\} = 1 - (1 - \eta_{h,d} \mu_w W_p - \mu_s S_p + \eta_{h,d} \mu_w W_p \mu_s S_p)^\zeta \quad (\text{S1})$$

where  $\mu_w$  and  $\mu_s$  represent relative danger from killer whales and sharks (as elaborated in Frid et al. 2007b), respectively,  $W_p$  and  $S_p$  are the proportions of time that killer whales and sharks spend at  $p$  (Table 2), respectively, and  $\eta_{h,d}$  represents elevated risk when at the surface or diving in inshore herring aggregations (i.e., when  $h=3$  and  $d=3$  or  $d=8$ ). We contrasted predictions between presence and absence of inshore risk,  $\eta_{3,d}=1$  and  $\eta_{3,d}=2$ , respectively, while holding  $\eta_{h,d}=1$  constant for all other habitats and decisions, including surface travel away from inshore areas (i.e.  $h=3$  and  $d \neq 3$  or  $d \neq 8$ ) (see also Table S4). The products  $\eta_{h,d} \mu_w W_p$  and  $\mu_s S_p$ , therefore, are the threat-specific probabilities of mortality that sea lions experience per second ( $\mu_w$  and  $\mu_s$  were scaled accordingly), and exponent  $\zeta$  is the number of seconds in each dive cycle component  $\omega$  (Table S1).

Probability of death by predation per dive,  $\mu\{q, p, v\}$  is

$$\begin{aligned} \mu\{q, p, v\} = & \sum_{\omega} \mu\{\omega, p, v\} - \mu\{\phi, p, v\} \mu\{\vartheta, p, v\} \\ & - \mu\{\vartheta, p, v\} \mu\{U, p, v\} - \mu\{\phi, p, v\} \mu\{U, p, v\} \\ & + \mu\{\phi, p, v\} \mu\{\vartheta, p, v\} \mu\{U, p, v\} \end{aligned} \quad (\text{S2})$$

Probability of predation per 1-hour basic period is:

$$\mu\{h, d, v\} = \begin{cases} 1 - (1 - \mu\{q, p, v\})^c & \text{if diving to forage} \\ 1 - (1 - (\eta_{h,d} \mu_w W_\phi)^{3600}) & \text{if resting or traveling at the surface} \\ 0 & \text{if staying at the haulout} \end{cases} \quad (\text{S3})$$

where  $c$  is the number of dive cycles per hour (Table S1),  $W_\phi$  is the proportion of time killer whales spend at the surface, and 3600 is the number of seconds in an hour.

### Energy gain

Let  $S$  represent the total number of 1-second time units,  $s$ , spent at a foraging patch during a dive and  $s = 1, s = 2, \dots, s = S$ . The probability of encountering and capturing fish during  $s = 1$  at  $h$  during  $v$ ,  $P\{h, v\}$ , is an assumed function of fish density and dispersion,

$$P\{h, v\} = z - z \left( \frac{k}{k + \delta\{h, v\}} \right)^k \quad (\text{S4})$$

where  $k$  is the overdispersion parameter (e.g. Mangel 2006), variable  $\delta\{h, v\}$  is the density of fish (individuals per  $\text{m}^2$ ) at  $h$  during  $v$ . (ie., biomass divided by mass of individual fish: Table 1), and  $z$  scales capture rate to what we assume is a realistic level. We interpret parameter  $k$  as the extent to which clumped spatial distributions of fish (i.e. tight schooling surrounded by empty space) might interact with mean fish density to determine the probability of an SSL encountering fish. Relative values of  $k$  for each foraging location were estimated by multiplying a baseline value of  $k$  by the proportion of the water volume that contained fish, as sampled with echosounder during standard surveys (Tables 1, S2). We lacked empirical data to parameterise  $k$  and, through preliminary calculations that yielded realistic rates of mean energy gain (Fig. S1) we chose a baseline value of  $3.38 \times 10^{-5}$  (see Fig S4 for sensitivity analyses). Empirical data used for parameterising inshore and nearshore locations were available only for night, when herring aggregate in large schools near the surface. During the day, however, herring might disperse along the bottom (Thorne 1977) and diurnal values of  $k$  for these locations were assumed to be a third less than nocturnal values.

The cumulative number of fish caught per dive,  $\lambda_{h,v}$ , is estimated as a decelerating function of patch residence time,

$$\lambda_{h,v} = \sum_{s=1}^S P\{h, v\} r^{s-1} = P\{h, v\} \frac{(1 - r^S)}{1 - r} \quad (\text{S5})$$

where  $r=0.99$  (an arbitrary value) represents depletion, expressed as the proportion of  $P\{h, v\}$  at  $s$  relative to  $s-1$ .

Gross energetic gain (kJ) per 1-hour basic period spent diving to forage at  $h$  during  $v$ ,  $G_{h,v}$ , is,

$$G_{h,v} = c\lambda_{h,v}\Pi_h\Omega\Xi(1 - \Lambda) \quad (\text{S6})$$

where  $\Pi_h$  is the product of mass of individual fish and energy density (Table 1),  $\Omega$  is assimilation efficiency,  $\Lambda$  is the heat increment of feeding, and  $\Xi$  is the proportion of energy gain allocated to lipid stores (rather than lean tissue). We assume that  $\Omega=0.90$  (Rosen et al. 2000),  $\Lambda=0.124$  (value for a 4-kg meal in Rosen and Trites 1997), and  $\Xi=0.59$ . The value of  $\Xi$  lacked an empirical basis—data simply do not exist—and was determined through preliminary simulations that yielded rates of energy gain that appeared to be biologically realistic. While physiological studies clearly are needed for a rigorous parameterisation of  $\Xi$ , we use this parameter only to scale the accumulation of lipid stores; its assumed value should not bias results towards any predation risk scenario.

### *Energetic costs*

Variable  $\alpha_{h,d,v}$  represents energy expended (kJ) in the transition from  $t$  to  $t+1$  or  $t+\tau$ . We assume hourly costs of 854.17 kJ if resting at the surface ( $d=h$ ) (Rosen and Trites 2002), and 80% of this value when at the haulout. The hourly cost of traveling between habitats is 1545.48 kJ (i.e.  $d \neq h$  and  $d > 3$ ), which is the expenditure ( $\text{J kg}^{-1} \text{m}^{-1}$ ) of a 162-kg female swimming at  $2 \text{ m s}^{-1}$  in captivity (Rosen and Trites 2002). The expenditure of this captive animal was not scaled down to the lower starting weight assumed in the model as means for considering the energetically more costly conditions found at-sea (e.g. wave action, current).

Litres of oxygen consumed per min while diving to a given depth were estimated from regression coefficient values in Table 1 of Hastie et al. (2006) and then converted to energetic equivalents with standard conversion factors. These costs were then extrapolated for the mean duration of each dive and the number of dives per hour (Table S3).

### *State dynamics*

If a SSL does not switch habitats, either remaining stationary ( $d = h$ ) or foraging ( $d > 3$ ), then

$$\begin{aligned} X(t+1) &= \begin{cases} x + G_{h,v} - \alpha_{h,d,v} & \text{if } d > 3 \text{ and } (g \leq g_{crit} \text{ or } a = 1) \text{ and } g < g_{max} \\ x - \alpha_{h,d,v} & \text{otherwise} \end{cases} \\ G(t+1) &= \begin{cases} g - \mathcal{R} & \text{if } d = h \\ \min \left\{ g + \frac{b_{h,d,v}}{w}, g_{max} \right\} & \text{if } d > 3 \end{cases} \\ A(t+1) &= \begin{cases} 0 & \text{if } d = h \\ 1 & \text{if } d > 3 \end{cases} \\ H(t+1) &= h \\ S\{h,d,v\} &= 1 - \mu\{h,d,v\} \end{aligned} \quad (\text{S7})$$

where  $S\{h,d,v\}$  is the probability of surviving to the next time period (see Eqs S1–S3). Variable  $b_{h,d,v}$  denotes the increment in stomach content (kg) when foraging (Fig S1) and  $\gamma$  is digestion rate. We assumed that  $\gamma = 0.25$ , implying  $\approx 8$  hours of digestion required to drop from  $g_{max}$  to  $g_{crit}$  (Murie and Lavigne 1986). Variable  $w$  represents body mass (kg) at  $t$ , which the model estimates from the discretized values of  $x$  as:

$$w = \frac{LP}{D} \quad (S8)$$

where  $L$  is the ‘real world’ value of  $x$  (Eq. 2.4 of Clark and Mangel 2000) representing the total energetic content of lipid stores (kJ),  $D$  is lipid energy density ( $39.33 \text{ kJ g}^{-1}$ ), and  $P$  is the proportion of body mass assumed to be lipids.

If a SSL switches habitats ( $d \neq h$  and  $d \leq 3$ ), then

$$\begin{aligned} X(t + \tau) &= x - \tau\alpha_{h,d,v} \\ G(t + \tau) &= g - \tau\gamma g \\ A(t + \tau) &= 0 \\ H(t + \tau) &= d \\ S\{h,d,v\} &= (1 - \mu\{h,d,v\})^\tau \end{aligned} \quad (S9)$$

Let  $F(x, g, a, h, t)$  be the maximum expected reproductive success at  $T$ , given

that  $X(t) = x$ ,  $G(t) = g$ ,  $A(t) = a$ ,  $H(t) = h$ , and the animal behaves optimally from  $t+1$  until  $T$ . Let

$V_d(x, g, a, h, t)$  be the fitness value of decision  $d$ , as determined by Eqs. S7 and S9, for a given time period and set of states. For example, when at an offshore foraging location, the fitness value of deciding to dive to deep strata (see Fig. 1) is:

$$V_7(x, g, a, 2, t) = S\{2,7,v\} \times F(X(t+1), G(t+1), A(t+1), 2, t+1) \quad (S10)$$

Thus, the dynamic programming equations (Clark and Mangel 2000) for each location are:

$$\begin{aligned} F(x, g, a, 0, t) &= \max\{V_0(x, g, a, 0, t), V_1(x, g, a, 0, t), V_2(x, g, a, 0, t), V_3(x, g, a, 0, t)\} \\ F(x, g, a, 1, t) &= \max\{V_0(x, g, a, 1, t), V_1(x, g, a, 1, t), V_2(x, g, a, 1, t), V_3(x, g, a, 1, t), \\ &\quad V_4(x, g, a, 1, t)\} \\ F(x, g, a, 2, t) &= \max\{V_0(x, g, a, 2, t), V_1(x, g, a, 2, t), V_2(x, g, a, 2, t), V_3(x, g, a, 2, t), \\ &\quad V_5(x, g, a, 2, t), V_6(x, g, a, 2, t), V_7(x, g, a, 2, t)\} \\ F(x, g, a, 3, t) &= \max\{V_0(x, g, a, 3, t), V_1(x, g, a, 3, t), V_2(x, g, a, 3, t), V_3(x, g, a, 3, t), \\ &\quad V_8(x, g, a, 3, t)\} \end{aligned} \quad (S11)$$

Eq. S11 is solved by backwards iteration from the terminal fitness function,

$$F(x, g, h, T) = \begin{cases} 1 - (1 - (x/x_{max}))^\varphi & \text{if } h = 0 \\ 0 & \text{if } h \neq 0 \end{cases} \quad (S12)$$

We assumed that  $\varphi=3.75$ , a value determined by preliminary simulations that yielded realistic rates of energy gain and mortality (see Fig. S5 for sensitivity analyses).

## 2. Parameterisation

**Table S1.** Parameter values used in the model for diving depth and the duration of dive cycle components when at location  $h$  and making dive decision  $d$ . Values are the mean (weighted by number of dives) recorded with satellite tags during March 2004 for 7 individuals diving to a given stratum and diel period. The exception is dive cycles per hour, which was estimated as  $(\phi + \vartheta + U) / 3600$ .

| <sup>a</sup> Foraging location ( $h, d$ ) | Depth (m)               |              | Surface interval $\phi$ (s) |              | Travel $\vartheta$ (s) |              | Patch residence $U$ (s) |              | Dive cycles per hour |              |
|-------------------------------------------|-------------------------|--------------|-----------------------------|--------------|------------------------|--------------|-------------------------|--------------|----------------------|--------------|
|                                           | <i>Day</i>              | <i>Night</i> | <i>Day</i>                  | <i>Night</i> | <i>Day</i>             | <i>Night</i> | <i>Day</i>              | <i>Night</i> | <i>Day</i>           | <i>Night</i> |
|                                           | Nearshore shallow (1,4) | 23           | 20                          | 105          | 102                    | 35           | 44                      | 66           | 57                   | 17.5         |
| Offshore shallow (2, 5)                   | 25                      | 24           | 125                         | 112          | 45                     | 52           | 56                      | 51           | 15.9                 | 16.8         |
| Offshore mid-depth (2, 6)                 | 85                      | 89           | 110                         | 126          | 93                     | 112          | 134                     | 103          | 10.7                 | 10.5         |
| Offshore deep (2,7 )                      | 147                     | 127          | 129                         | 192          | 12                     | 148          | 135                     | 128          | 9.4                  | 7.7          |
| <sup>b</sup> Inshore. herring (3,8)       | 23                      | 20           | 105                         | 102          | 35                     | 44           | 66                      | 57           | 17.5                 | 17.7         |

<sup>a</sup>Parenthesis indicate the corresponding numerical labels in the model for location  $H(t)=h$  and decision  $D(x, g, a, h, t) = d$  (Fig. 1).

<sup>b</sup>Because juvenile SSLs in the empirical data set rarely dove here, we used the same values as for the Nearshore shallow location.

**Table S2** Parameterisation of resource characteristics (values in Table 1). Numbers identify data sources below.

| Habitat           | Resource type                              | Mean wet mass per fish                         | Mean energy density                    | <sup>a</sup> Mean density and volume with fish                       |                                                                 |
|-------------------|--------------------------------------------|------------------------------------------------|----------------------------------------|----------------------------------------------------------------------|-----------------------------------------------------------------|
|                   |                                            |                                                |                                        | Night                                                                | Day                                                             |
| Inshore herring   | Sources 1, 2; trawl data from sources 3, 4 | Trawl data: source 4                           | Mean of both adult sexes: Source 7     | Source 4 at time and depth intervals of 10 s and 20 m, respectively. | <sup>b</sup> Not sampled, assumed same as night.                |
| Nearshore shallow | Assumption based on source 5               | Average mass of the 3 prey types: sources 4, 5 | Source 7                               | Not sampled, assumed same as inshore herring                         | <sup>b</sup> Not sampled, assumed to be same as inshore herring |
| Offshore shallow  | Assumption based on source 6               | Assumption based on source 4                   | Mean of both adult sexes: Source 7     | Source 6 at 60 s and 20 m intervals                                  | Sources 3 and 5 at 60 s and 20 m intervals.                     |
| Mid-depth         | Assumption based on source 6               | Average mass of the 3 prey types: sources 4, 5 | Mean of the 3 prey types: sources 7, 8 | Source 6 at 60 s and 20 m intervals.                                 | Sources 3 and 5 at 60 s and 20 m intervals.                     |
| Deep              | Trawl data: sources 3, 5                   | Trawl data: sources 3,5                        | Source 8                               | Not sampled, assumed same as day                                     | Sources 3 and 5 at 60 s and 20 m intervals.                     |

<sup>a</sup>Data were collected every second and averaged for the specified time and depth intervals with a BioSonics DT4000 echosounder at 70 kHz (see source 1–6). Means density values were weighted by number of samples.

<sup>b</sup>Although the same volume without prey as night was assumed, the diurnal value of  $k$  was assumed to be 0.66 of the nocturnal value.

#### Data sources for Table S2

- 1) Thomas and Thorne 2001
- 2) Thomas and Thorne 2003
- 3) Thorne 2004
- 4) RE Thorne, unpublished survey data for the Prince William Sound Science Center (PWSSC) Biological Monitoring Program. These particular data are for Two Moon Bay, March 2004.

- 5) RE Thorne unpublished survey data for the PWSSC Biological Monitoring Program, collected March 2006. Walleye pollock data are primarily from surveys in deep water north and west of Hichinbrook Island. Year 1 herring data are from Lake Bay, Simpson Bay, Esther Pass. Year 2 data are from Sawmill Bay. Juv. herring data are from Eaglek Bay.
- 6) Frid et al. 2007b
- 7) Paul, et al. 1998
- 8) Vollenweider (2004: March values in her Table 5)

### Parameterisation of Computer Experiment on Herring Scarcity

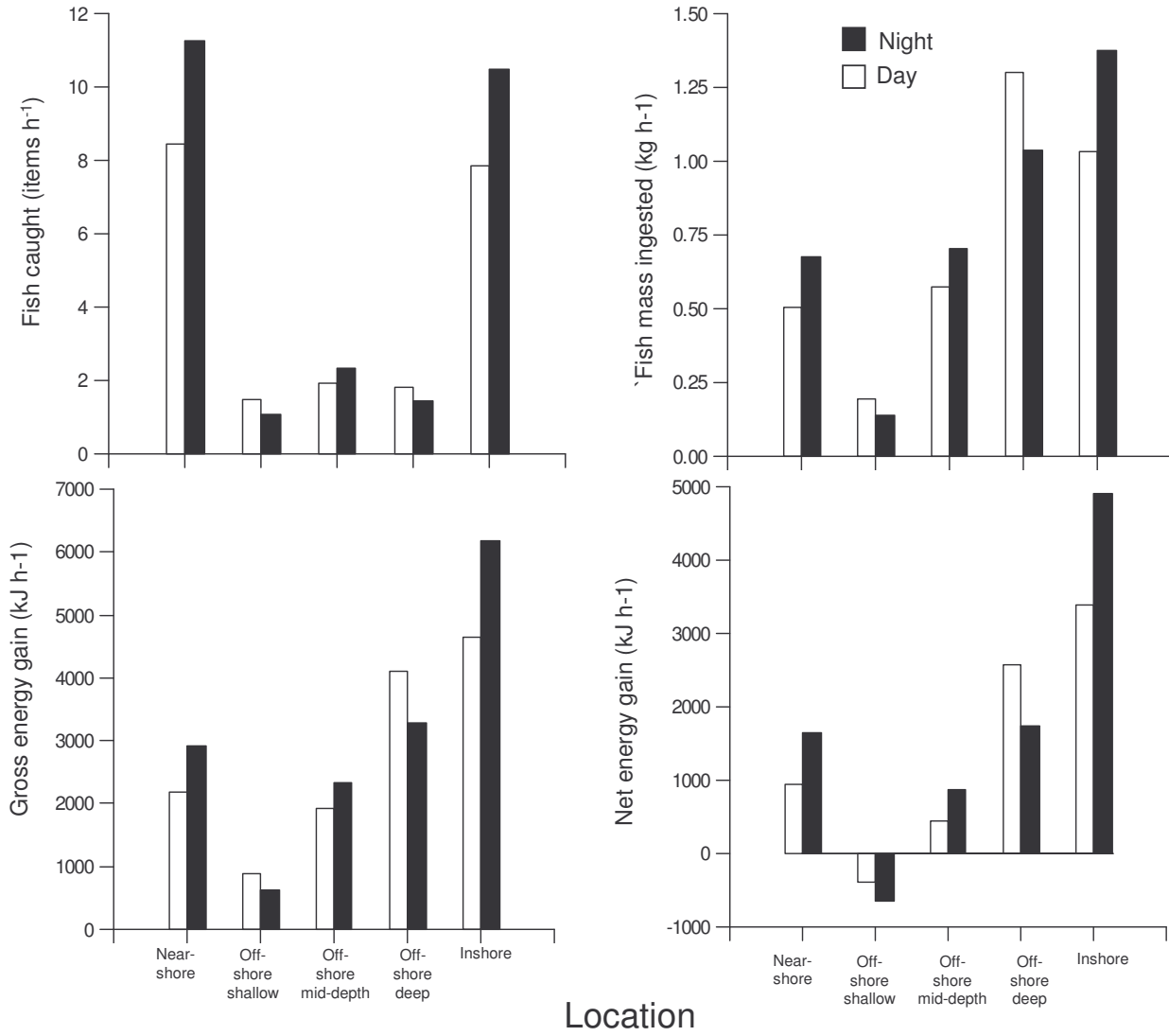
Figure 4 shows the output of computer simulations comparing the theoretical scenario 12 (“Baseline”) against a 90% decline in herring density. The herring decline was simulated by multiplying  $\delta\{4, v\}$  and  $\delta\{8, v\}$  by 0.10 in Eq. S4 while holding remaining parameters at the level of scenario 12.

**Table S3.** Parameter values used in model for energetic costs (kJ) per 1-hour period  $t$  spent foraging.

| Location ( $h, d$ )            | Cost (kJ h <sup>-1</sup> ) |        |
|--------------------------------|----------------------------|--------|
|                                | Day                        | Night  |
| Nearshore (1, 4)               | 1246.3                     | 1266.9 |
| Offshore shallow<br>(2, 5)     | 1275.3                     | 1277.2 |
| Offshore mid-<br>depth (2, 6)  | 1477.4                     | 1469.1 |
| Offshore deep<br>strata (2, 7) | 1533.8                     | 1556.8 |
| Inshore (3,8)                  | 1246. 3                    | 1266.9 |

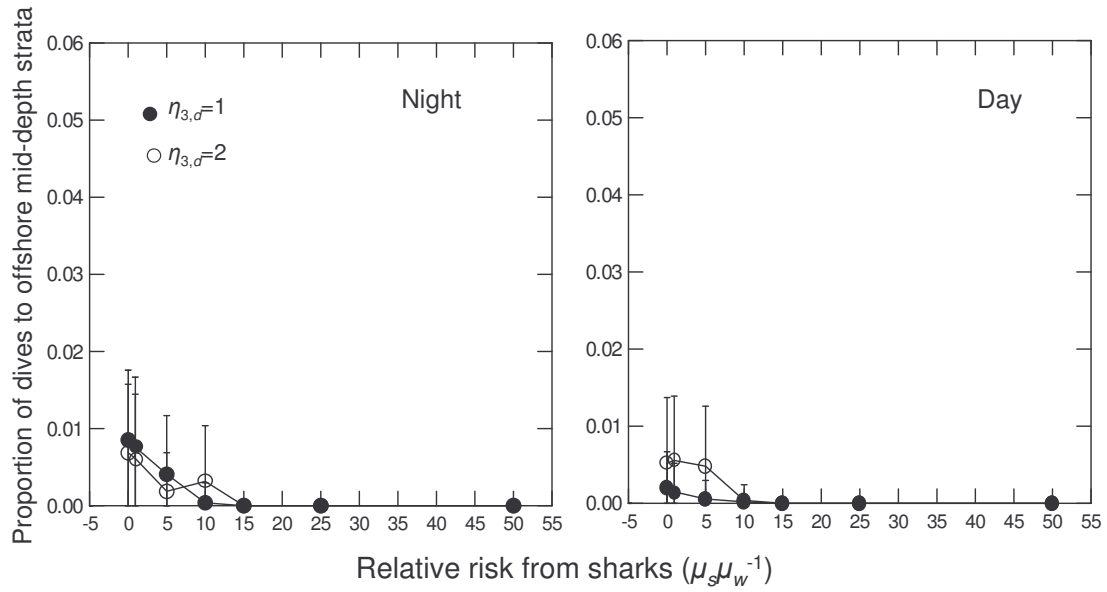


**Fig. S1.** Parameter values influencing energy gain per 1-hour period  $t$  (see Eqs. S4-S6 and Tables 1, S1).



### 3. Additional Figures

**Fig. S2.** Proportion of dives to offshore mid-depth strata predicted by simulations. Data are the means ( $\pm 1$  SD) of 1000 forward iterations (minus 10-24 simulations in which mortalities due to starvation or predation occurred, depending on treatment combination). Closed and open circles represent the low and high inshore risk scenarios, respectively.



**Fig. S3.** Predicted minus observed proportions of dives at each foraging location, stratified by individual and diel period. Arrows point to values corresponding to Scenario 12, which had the best fit to empirical data (Table 3).

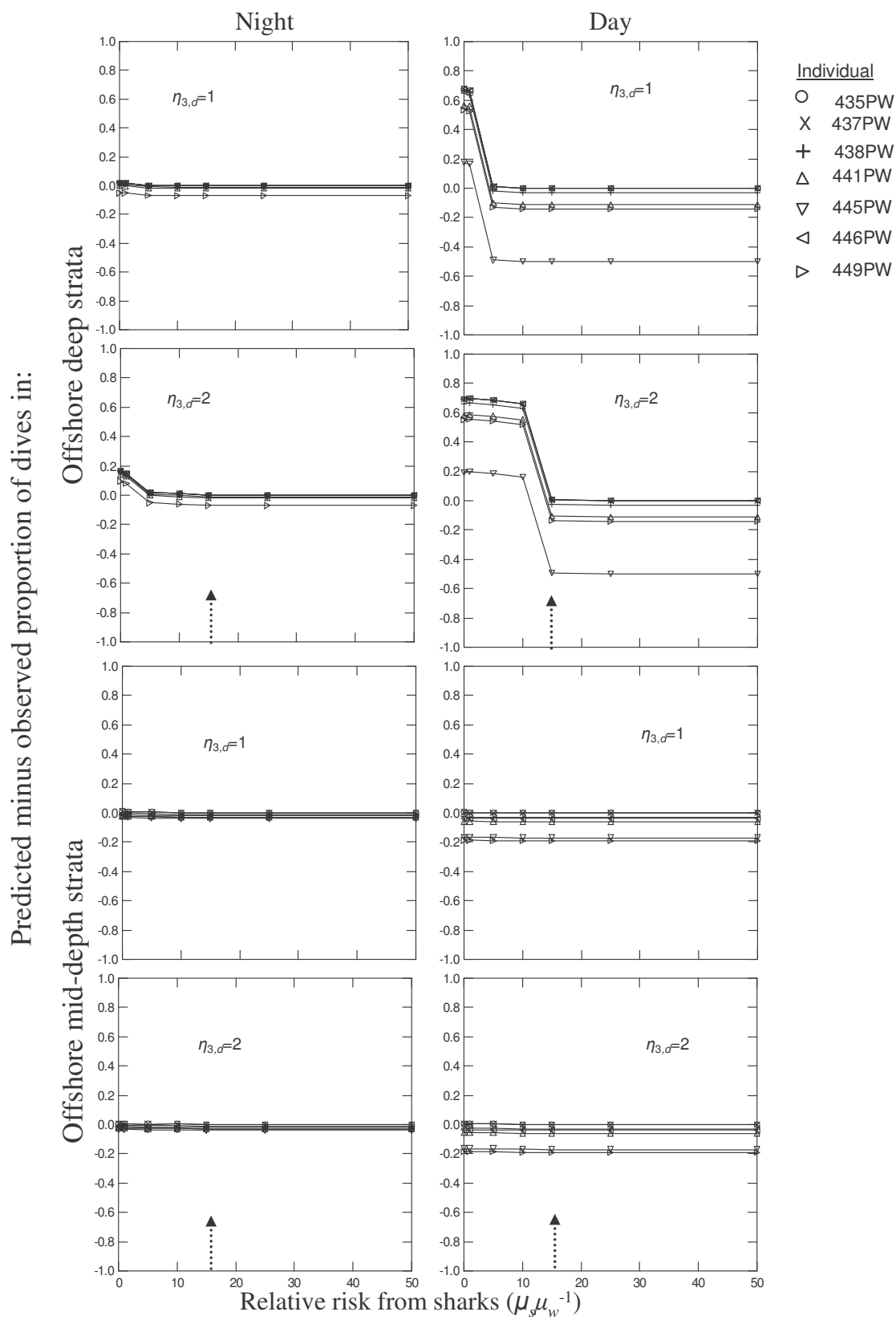
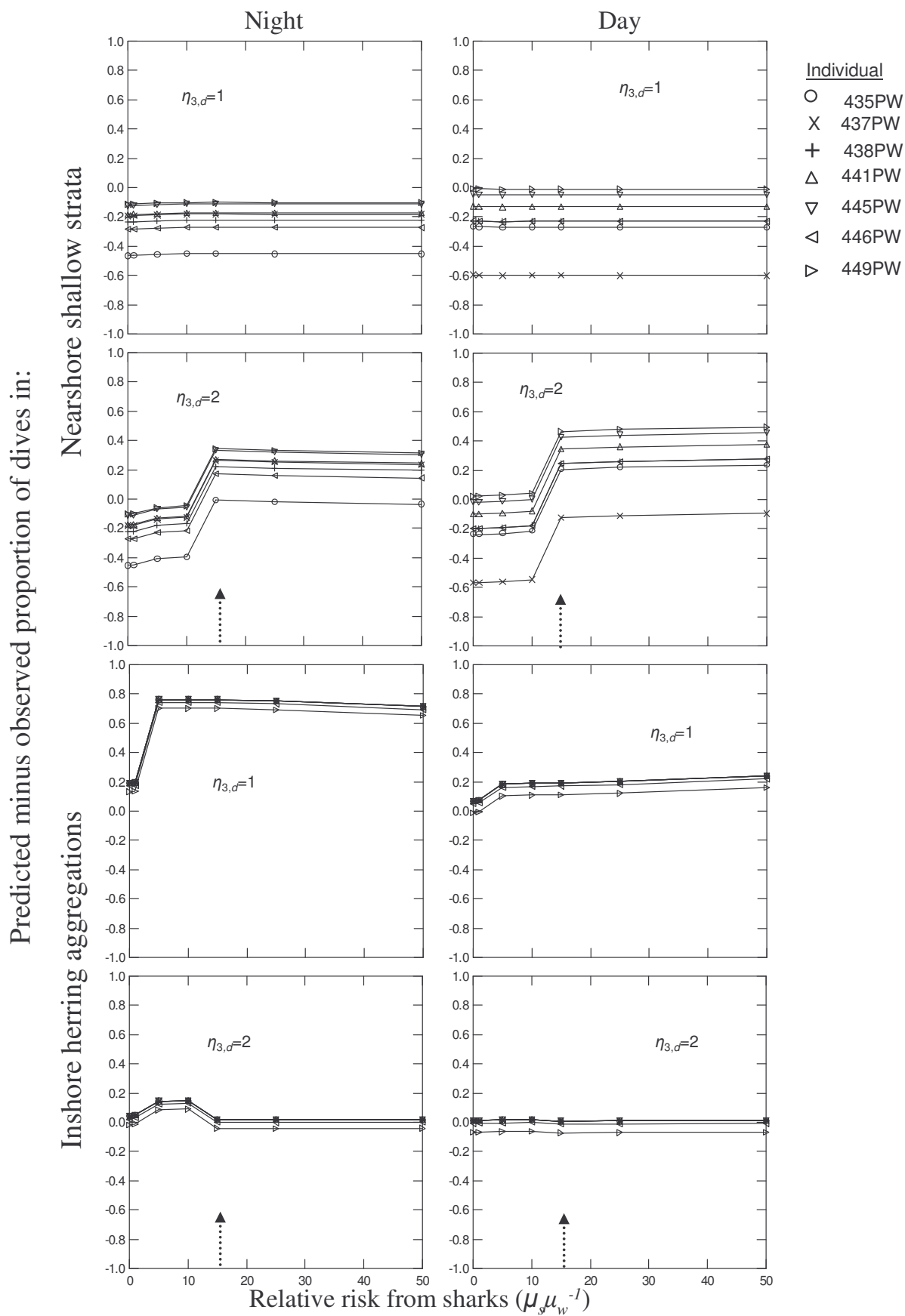


Fig. S3 (cont.)



#### 4. Post hoc analysis of a third level of inshore risk

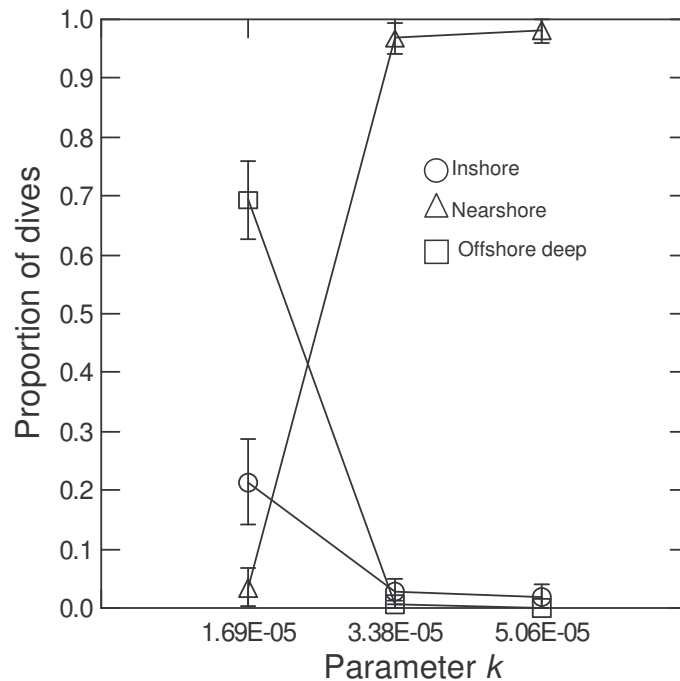
**Table S4:** Post hoc assessment of the fit to the empirical data of theoretical scenarios with very high inshore risk ( $\eta_{3,d}=3$ ) combined factorially with 7 levels of shark risk,  $\mu_s\mu_w^{-1}$ . The best fit scenario selected during a priori analyses (last row in italics; also see Table 3), which had more moderate inshore risk ( $\eta_{3,d}=2$ ) and  $\mu_s\mu_w^{-1}=15$ , remained superior. See footnotes of Table 3 for details.

| Shark risk<br>$\mu_s\mu_w^{-1}$ | Inshore<br>risk $\eta_{3,d}$ | RSS by individual sea lion |             |             |             |             |             |             | Total<br>RSS |
|---------------------------------|------------------------------|----------------------------|-------------|-------------|-------------|-------------|-------------|-------------|--------------|
|                                 |                              | 446PW                      | 445PW       | 441PW       | 438PW       | 449PW       | 437PW       | 435PW       |              |
| 0                               | 3                            | 0.68                       | 0.10        | 0.48        | 0.63        | 0.41        | 0.85        | 0.78        | 3.93         |
| 1                               | 3                            | 0.68                       | 0.10        | 0.48        | 0.63        | 0.41        | 0.86        | 0.78        | 3.95         |
| 5                               | 3                            | 0.53                       | 0.05        | 0.38        | 0.50        | 0.35        | 0.72        | 0.58        | 3.11         |
| 10                              | 3                            | 0.35                       | 0.06        | 0.27        | 0.34        | 0.28        | 0.50        | 0.35        | 2.15         |
| 15                              | 3                            | 0.18                       | 0.58        | 0.31        | 0.22        | 0.47        | 0.11        | 0.09        | 1.95         |
| 25                              | 3                            | 0.18                       | 0.59        | 0.32        | 0.22        | 0.48        | 0.10        | 0.10        | 1.99         |
| 50                              | 3                            | 0.19                       | 0.60        | 0.32        | 0.22        | 0.48        | 0.09        | 0.11        | 2.01         |
| <i>15</i>                       | <i>2</i>                     | <i>0.17</i>                | <i>0.57</i> | <i>0.30</i> | <i>0.21</i> | <i>0.46</i> | <i>0.10</i> | <i>0.09</i> | <i>1.91</i>  |

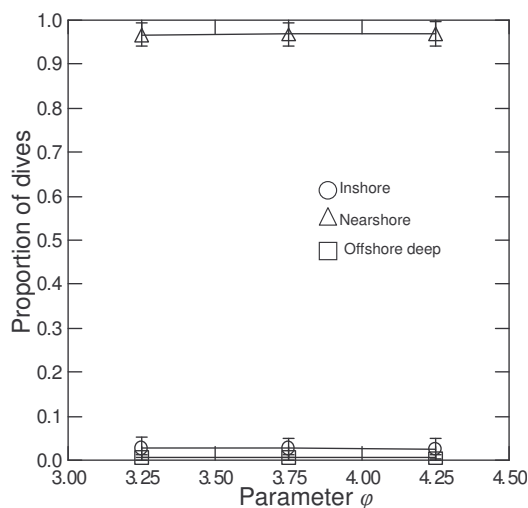
## 5. Sensitivity analyses

Figures S4-S6 assess the model's sensitivity to overdispersion parameter  $k$ , the terminal fitness function, and initial energy state. In each figure, one of these parameters was varied while holding remaining parameters at the values of theoretical scenario 12, which had the best fit to empirical data (Table 3). Data are the mean ( $\pm 1$  SD) proportion of dives to the three main foraging habitats (N=1000 forward simulations per treatment minus simulations in which mortality occurred.)

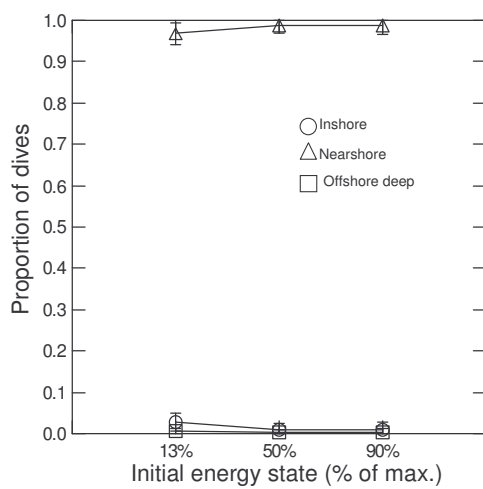
**Fig. S4.** Sensitivity analysis of overdispersion parameter  $k$  (as scaled by parameter  $z$ : Eq. S4). The baseline value used in simulations ( $k=3.38E-05$ ,  $z=75$ ), was contrasted against values that were half ( $k=1.69E-05$ ,  $z=95$ ) and 1.5 times ( $k=5.06E-05$ ,  $z=55$ ) the baseline value of  $k$ . At half the baseline value of  $k$ , encounters with clumped herring school are too infrequent to be profitable and most dives are to deep strata, where pollock can be encountered more predictably (see 'Volume with fish' column in Table 1). Predictions, however, differ little between the baseline and 1.5 times the baseline values of  $k$ , with most dives being to nearshore shallow strata in both cases.



**Fig. S5.** Sensitivity analysis of the terminal fitness function under different values of  $\varphi$  (Equation S12). Although  $\varphi$  had little effect on proportion of dives, other sensitivity analyses (not shown) predicted slight decreases in the absolute number of dives and of the terminal energy state with increasing values of  $\varphi$ . (Mean terminal energy states for  $\varphi=0.5, 3.25, 3.75, 4.25$  and  $7$  were, respectively, 97%, 95%, 93%, 91% and 75% of the maximum attainable.)



**Fig. S6.** Sensitivity analysis of initial energy state,  $X(0)=x$ . The lowest initial energy state,  $X(0)=4$  or 13.3% of the maximum attainable, was the value used in main analyses. Although initial energy state had little effect on proportion of dives, other sensitivity analyses (not shown) predicted slight decreases in absolute number of dives to riskier habitats at higher levels of initial energy state (On average, 182 dives to deep strata and 36 dives to inshore herring aggregations, the two most dangerous locations, occurred at the lowest initial energy state. At higher energy states, 56-61 dives were made to deep strata and 20-22 dives were made to inshore herring aggregations. Terminal energy state differed little between treatments.)



## 5. Structural changes in the model relative to our earlier models on sympatric harbour seals

A brief discussion on the trade-offs inherent to modeling decisions is warranted, as the current model contains both improvements and compromises relative to our earlier models of sympatric harbour seals. Digestive constraints were absent in the seal models but were included in the present work to improve physiological realism (see Rosen and Trites 2004). Inclusion of digestive constraints, however, did not yield new insight into the risk-energy trade-offs inherent to foraging on walleye pollock, the resource with the lower energy density, beyond what the seal work had already suggested (Frid et al. 2007b; 2008). In fact, inclusion of digestive constraints required a reallocation of computer memory that compromised our ability to model dive cycle organization. Specifically, the current model has a 1-hour basic time period in which dive cycles of fixed duration are repeated contiguously during foraging. In contrast, the seal models used a 20-s basic time period, which allowed dive cycle components to respond to predation risk, energy gain, and stored oxygen level at a fine temporal scale (Frid et al. 2006, 2008). Ideally, allocation of computer memory would be better optimized so that both dive cycle flexibility and digestive constraints can be included. Also, model tractability required that we use only one offshore and one near shore location in the model, which may under-represent the many options for optimising travel costs between similar sites that may actually exist.

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