

Energy and prey requirements of California sea lions under variable environmental conditions

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Description of Negative Binomial model used to predict the effects of reduced prey availability on pup growth rates

To examine the effects of changes in prey availability on pup growth rates, we developed a relatively simple model that accounted for the two behavioral strategies female otariids use to cope with environmental change (Costa 2008). To do so, we assumed that pup growth rates could be predicted based on the length of the maternal cycle, which consists of a foraging trip to sea and energy delivery to the pup onshore. Because California sea lions do not appear to alter the amount of time spent ashore in response to trip duration (McHuron et al. 2016), changes in the length of the maternal cycle are primarily driven by trip duration. Thus, we used the Negative Binomial Distribution (NB) to predict the average duration of a foraging trip under varying prey availability by altering the probability of finding food (Mangel 2006). Parameter values used in the model described below can be found in Table S1.

A foraging trip can be decomposed into its two main components, travel time (τ) and time spent finding and acquiring prey. We assumed that a female did not terminate a foraging trip until she acquired enough energy to meet a predetermined energetic target that was based on her own energy needs and those of her pup. This assumption was based on the finding by Costa et al. (1989) that female Antarctic fur seals (*Arctocephalus gazella*) stayed at sea until they achieved a substantial proportional change in body mass, even though extending the duration of the trip resulted in reduced growth rate of their pup. The average energetic target for a female of mass M whose pup needs are N_{pup} (kJ day⁻¹) and who spends the average number of days at sea and on land are

$$\bar{N} = \frac{(\bar{d}_{sea} FMR_{sea} M^{0.75} + \bar{d}_{land} FMR_{land} M^{0.75} + (\bar{d}_{sea} + \bar{d}_{land}) N_{pup})}{P_{metabolized}} \quad (1)$$

The average trip duration at sea can be further decomposed into

$$\bar{d}_{sea} = \bar{s} + \bar{k} + 2\bar{\tau} \quad (2)$$

where \bar{s} is the average number of days of successful foraging, \bar{k} is the average number of days of unsuccessful foraging, and $\bar{\tau}$ is the average travel time to a foraging ground. The average number of successful days of foraging (\bar{s}) is a function of the average daily energy value of food (\bar{Y}) and the average energetic target, such that

$$\bar{s} = \frac{\bar{N}}{\bar{Y}} \quad (3)$$

We parameterized \bar{N} (based on an 80 kg female with a 15 kg pup), \bar{s} , $\bar{\tau}$, and \bar{Y} using the behavior and energetics data described for the bioenergetic model. Specifically, we estimated (1) \bar{s} based on the proportion of time at sea spent diving combined with estimates of the maximum consumption rate

based on the kg of prey needed to meet \bar{N} , (2) $\bar{\tau}$ based on existing tracking data, and (3) \bar{Y} by rearranging Eqn 8. The values of female and pup mass were arbitrarily chosen for illustrative purposes.

The appropriate probability distribution for the number of unsuccessful days of foraging (k) is the NB distribution (Mangel 2006), which describes the probability of waiting for a fixed number of successes. In particular, we set

$$p(k | s, \lambda) = \Pr\{k \text{ days of unsuccessful foraging before the } s^{\text{th}} \text{ day of successful foraging given that the probability of success on a day is } \lambda\} \quad (4)$$

The NB distribution for k is

$$p(k | s, \lambda) = \binom{s+k-1}{k} \lambda^s (1-\lambda)^k = \frac{(s+k-1)!}{k!(s-1)!} \lambda^s (1-\lambda)^k \quad (5)$$

The terms in Eqn 10 can be evaluated iteratively without having to compute the factorials by noting that $p(0 | s, \lambda) = \lambda^s$ and for $k \geq 0$

$$p(k+1 | s, \lambda) = \binom{k+s}{k+1} (1-\lambda) p(k | s, \lambda) \quad (6)$$

In principle, k can be unbounded, but both in nature and computationally it cannot. Thus, we chose a

maximum value for k , K_{\max} , so that $\sum_{k=0}^{K_{\max}} p(k | s, \lambda)$ was close to 1 (i.e., 0.999) and then renormalized so that it was equal to 1. When k follows the NB distribution given in Eqn 11, its average value is $\bar{k} = \frac{\bar{s}(1-\bar{\lambda})}{\bar{\lambda}}$. Consequently, Eqn 7 can be rewritten as

$$\bar{d}_{sea} = \bar{s} + \frac{\bar{s}(1-\bar{\lambda})}{\bar{\lambda}} + 2\bar{\tau} = \frac{\bar{s}}{\bar{\lambda}} + 2\bar{\tau} \quad (7)$$

and inverted to obtain the average daily probability of foraging success given the average trip length and average number of successful foraging days needed to match energy demands

$$\bar{\lambda} = \frac{\bar{s}}{\bar{d}_{sea} - 2\bar{\tau}} \quad (8)$$

We introduced environmental variability by multiplying $\bar{\lambda}$ by a value between 0 and 1, representing the proportion reduction in food relative to “average” conditions. To account for the ability of females to increase effort to offset this reduction, we assumed that if the current probability of finding food was λ , a female increased her effort by ε so that

$$(1 + \varepsilon)\lambda = \bar{\lambda} \quad (9)$$

We assumed that females were only able to increase their effort by 50% ($\varepsilon_{\max} = 0.5$) so that there are situations in which environmental conditions are so poor that she will not be able to reach $\bar{\lambda}$ through increases in effort alone. We denoted the probability of finding food given λ and ε as λ_{adj} .

The daily pup growth rate (G) for each value of k was calculated by converting the milk delivery rate in MJ day⁻¹ to growth rate in kg day⁻¹ using the equations in Oftedal et al. (1987) where

$$\text{Milk delivery rate} = \frac{N_{pup}}{\bar{s} + k + 2\bar{\tau} + \bar{d}_{land}} \quad (10)$$

The expected pup growth rate is then

$$E\{G\} = \sum_{k=0}^{k_{max}} p(k | \bar{s}, \lambda_{adj}) G(k) \quad (11)$$

with variance

$$V\{G\} = \sum_{k=0}^{K_{max}} G(k)^2 p(k | \bar{s}, \lambda_{Adj}) - E\{G\}^2 \quad (12)$$

We set a maximum limit on growth rate assuming that females would not allocate all surplus energy to the pup if they were unusually successful. We calculated expected pup growth rates assuming that (1) females increased effort before trip duration, or (2) that females only increased trip duration to account for changes in prey availability. Under this framework, expected growth rates of pups is predicted to increase during better than average foraging conditions because females reach \bar{N} faster than expected; thus the same amount of milk energy is being delivered over a shorter time interval. The opposite occurs under poor environmental conditions when trip durations increase because the same amount of energy (or potentially less) is being delivered over a longer time interval than expected.

Table S1. Description and values of parameters used to model the effects of prey availability on pup growth.

Variable	Description	Value	In-text equation	Data Source
\bar{N}	Energy needs per foraging trip	305 MJ	Equation 6	See Table 1
M	Female mass	80 kg		
FMR_{sea}	Mass-specific at-sea field metabolic rate	1.35 MJ day ⁻¹		See Table 1
\bar{d}_{sea}	Duration of foraging trip	4.5 days	Equation 7	McHuron et al. 2016
$\bar{\tau}$	Travel time to foraging patch	0.5 days		Estimated
\bar{s}	# successful foraging days	2.5 days		from
\bar{k}	# unsuccessful foraging days	1 day		empirical data
FMR_{land}	Mass specific onshore field metabolic rate	0.60 MJ day ⁻¹		See Table 1
\bar{d}_{land}	Time on land	1.5 days		McHuron et al. 2016
N_{pup}	Energy needs of pup	114 MJ		
M_{pup}	Pup mass	15 kg		See Table 1
$Milk\ intake$	Mass-specific milk intake rate	1.38 MJ day ⁻¹		
$P_{metabolized}$	Metabolizable energy	0.87		See Table 1
\bar{Y}	Daily energy gain from successful foraging	122 MJ	Equation 8	Calculated
G_{max}	Maximum allowed pup growth rate	0.11 kg day ⁻¹		Leising et al. 2015

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