

needed to meet the energy demands of a predator is increased by a factor of 10. Similarly, the model is particularly sensitive to uncertainty in the fish condition (i.e., lean versus high-lipid fish) and this can have impacts on both the biomass and numbers of salmon required to meet predator energetic demands (Figs. 2 and 3).

Based on bioenergetics modeling, the relative impacts of different marine mammal predators on Chinook salmon have changed substantially since the passage of the Marine Mammal Protection Act in 1972. Primarily due to increases in harbor seal abundance, since 1970, predation on Chinook salmon runs within Puget Sound has increased approximately ninefold in terms of numbers and doubled in terms of biomass. Large increases in harbor seal predation on smolts have potential impacts that are larger than either current commercial and recreational fisheries or predation by endangered Southern Resident killer whales. Sea lions also consume Chinook salmon; however, these impacts are estimated to be low compared to those from harbor seals. Our model only examines a subset of predators within Puget Sound inland waters and assumes that their Chinook salmon consumption is derived from only Puget Sound Chinook salmon stocks. Chinook salmon in inland waters are a mixture of US and Canadian stocks and it is likely that predators within these waters do not feed exclusively on US stocks. It is also likely that the consumption by marine mammals along the salmon's migration route ranging from California to Alaska (Adams et al. 2016) is also impacting these US stocks. Further, there are other potential predators (harbor porpoise (*Phocoena phocoena*) and cormorants (*Phalacrocorax* spp.)) that are not included in our modeling efforts. We believe that this research is a valuable step toward decoupling the mechanisms that lead toward trends in marine survival in threatened Chinook salmon and provides a framework for coast-wide understanding of predation impacts on Chinook salmon and dependent predators such as Southern Resident killer whales.

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Appendix

Reproduction and growth costs for harbor seals and Steller sea lions

Reproduction costs

The daily production cost can be disaggregated into the gestation/pupping cost (PC) and lactation cost (LC). Depending on the time of year, the reproductive costs (PC and LC) will change for predators of different ages and sex. To account for these temporal effects, we include an additional set of time-varying estimates:

$$P_{h,t} = m_{h,t} \times F_{h,t} \times \left[PC_{h,t} \times \frac{P_{h,t}^{PC}}{\sum P_{h,t}^{PC}} + LC_{h,t} \times \frac{P_{h,t}^{LC}}{\sum P_{h,t}^{LC}} \right]$$

where the variables $P_{h,t}^{PC}$ and $P_{h,t}^{LC}$ are the conditional probability of predator p gestating or lactating on day t given that it is both mature ($m_{h,t}$) and fecund ($F_{h,t}$).

Since males neither lactate nor give birth, $F_{h,male}$ is equal to zero.

The lactation and gestation costs listed below are conditional on a female actually producing offspring. For harbor seals, the

fecundity rate is 0.91 (Howard et al. 2013) and for Steller sea lions, the fecundity rate is 0.63 (Winship et al. 2002). For killer whales, gestation and lactation costs are implicitly assumed to be included within other modeled metabolic costs.

In most instances, the models in the literature (Table A2) describe the annual costs of reproduction. Since $P_{h,t}^{LC}$ and $P_{h,t}^{PC}$ are the daily probability of a reproduction cost, then $\frac{P_{h,t}^{LC}}{\sum P_{h,t}^{LC}}$ and $\frac{P_{h,t}^{PC}}{\sum P_{h,t}^{PC}}$ are the daily fraction of the annual reproduction costs. The killer whale literature does not separate the production costs from the activity costs, since at the population level, they are such a minimal cost compared to the activity costs. The gestation periods of the pinnipeds are based on the following: Tables A1 and A2 and Fig. A1.

Growth costs

The models for growth costs (GC) are different for each predator. The Steller sea lion model is an annual estimate based the change in body mass, while the harbor seal model is a daily estimate for immature individuals. The growth costs for killer whales are integrated into the activity costs (Table A3).

Efficiency

Efficiency measures the energy that is lost through excretion and digestive heat before it can be converted to maintenance or growth. Our estimate of efficiency (Ef) is the percent energy left after waste (d_w) and digestive heat (d_h) (Table A4). Calculating the conversion efficiency for each species is slightly different based on how the parameters were reported in the literature. Digestive efficiency for killer whales (84.7%) was accounted for in equations used to calculate daily prey energy requirements from field metabolic rates in Noren (2011).

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Fig. A1. Periods for which lactation costs are factored into the bioenergetics model.

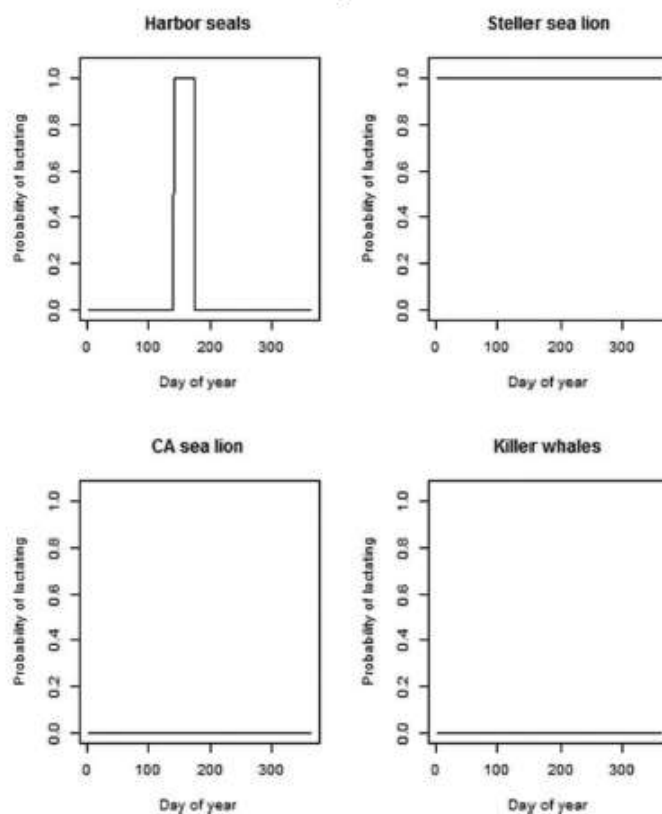


Fig. A2. Estimated annual predator abundance.

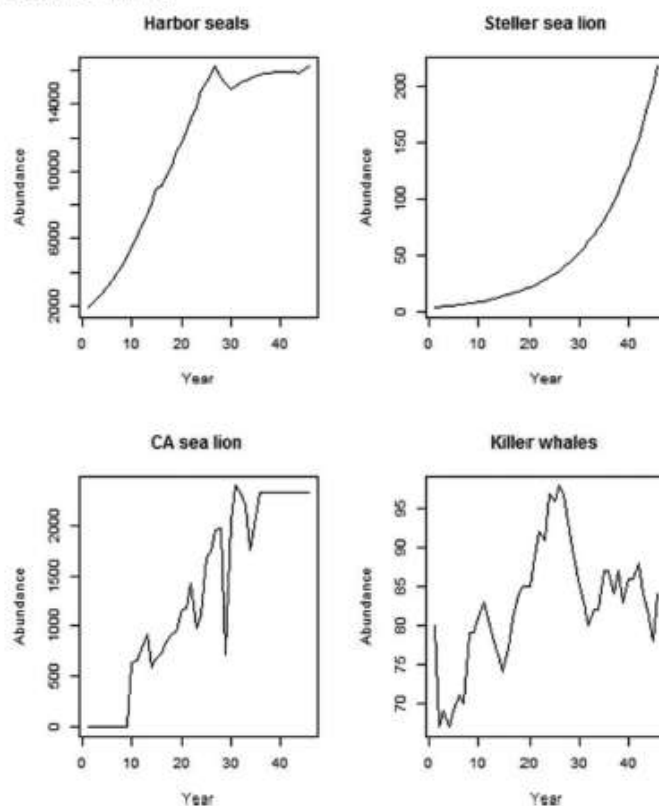


Fig. A3. Probability of the predators being present in inland waters.

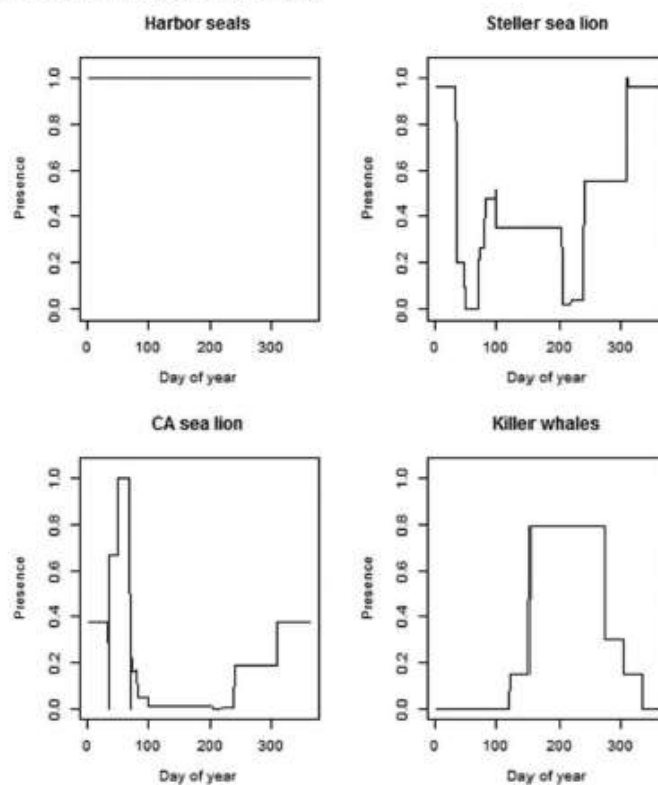


Fig. A4. Population abundance of harbor seals, 1970–2015, in Puget Sound based on an annual 4% decline beginning in 1999.

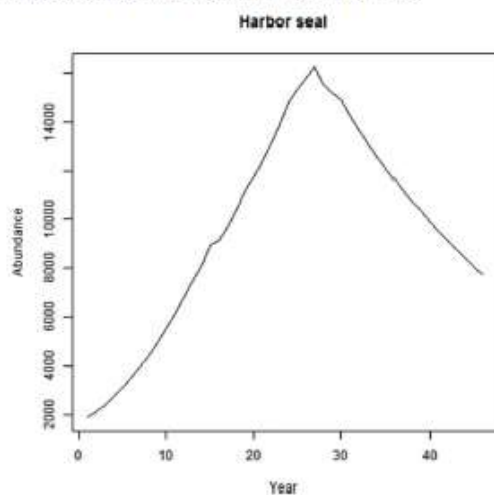


Fig. A5. Estimates of the annual consumption in numbers and biomass of Chinook salmon by marine mammal predators in Puget Sound between 1970 and 2015, assuming a 4% decline in harbor seal abundance beginning in 1999. [Color online.]

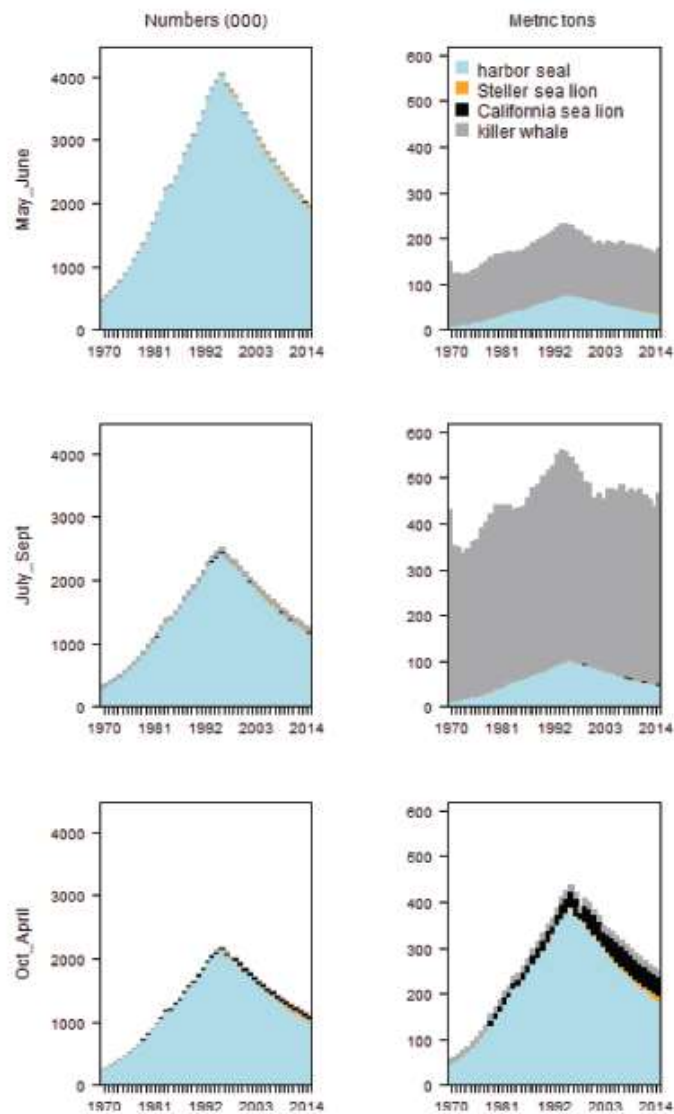
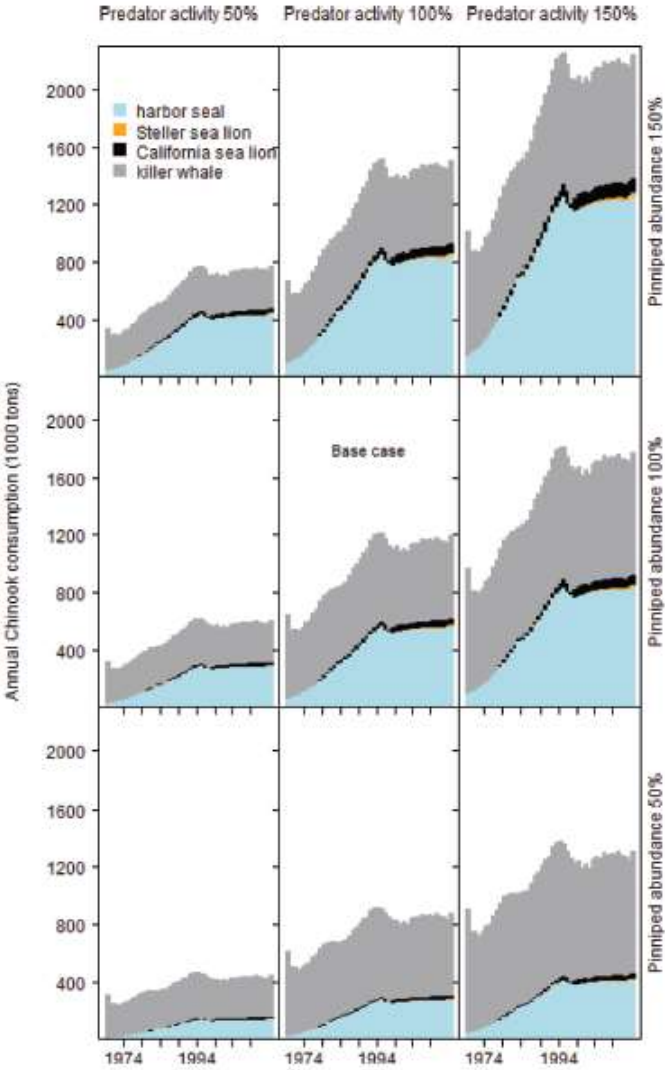


Fig. A6. Annual biomass of Chinook salmon consumed by each predator based on given combinations of pinniped abundance and predator activity. [Color online.]



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Fig. A7. Annual number of Chinook salmon consumed by the predators based on given combinations of pinniped abundance and predator activity. [Color online.]

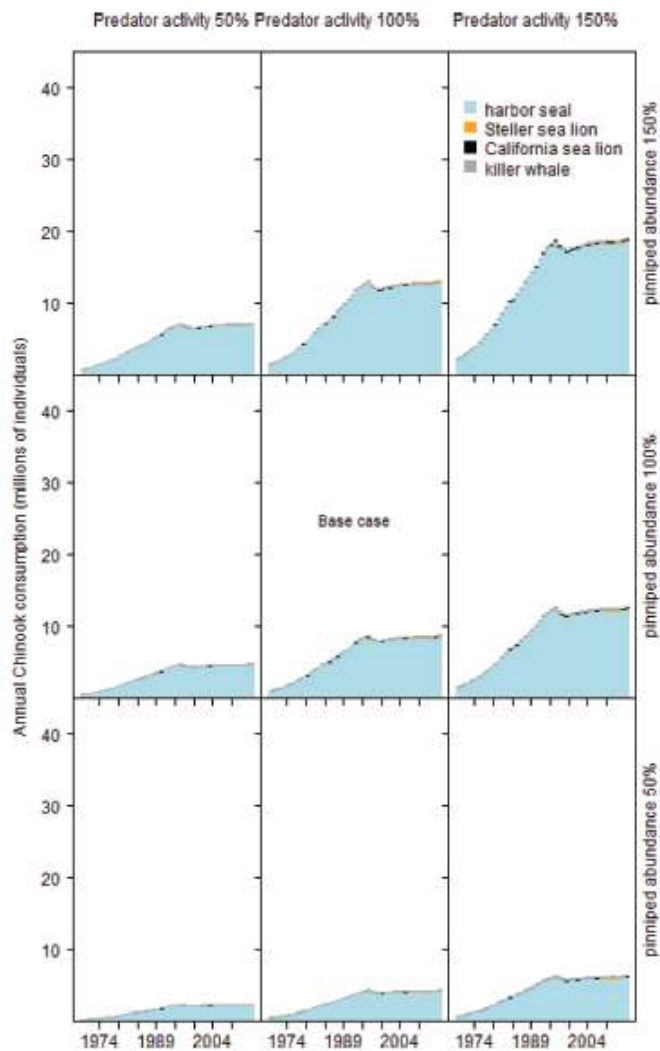


Fig. A8. Annual number of Chinook salmon consumed by the predators based on given combinations of smolt length and smolt fraction in the predator diets. [Color online.]

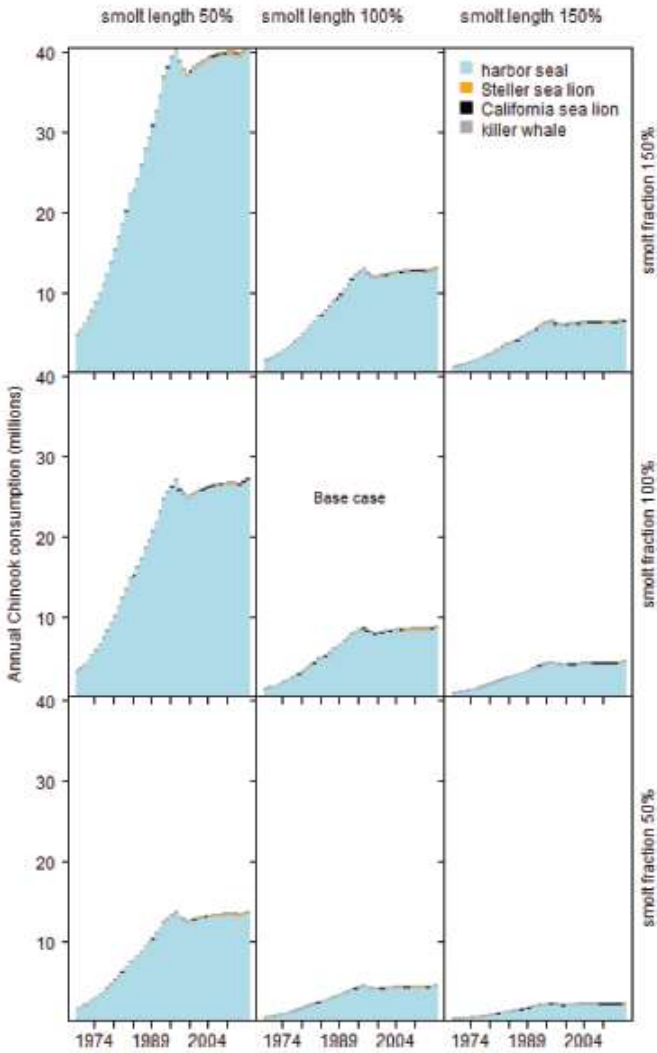


Table A1. Summary of reproduction costs by predator.

Variable	Predator	Model	Source
$P_{n,i,j}^C$	Harbor seal	93 000 000 J/year	Howard et al. 2013
	Steller sea lion	$wt_{n,i,j-1} \times [p_{up}ED_{up} + (1 - p_{up})(1 - p_w)ED_{pre}] \times \frac{1}{d_h \times d_a}$ J/day	Winship et al. 2002
$LC_{n,i,j}$	California sea lion	Implicita	Weise and Harvey 2008
	Killer whale	Implicita	Noren 2011
	Harbor seal	$24\ 000\ 000 \times (wt_{n,i,j})^{0.75}$ J/year	Howard et al. 2013
	Steller sea lion	$\frac{\sum aAC_n}{(d_h - 0.1) \times d_a} - \frac{\sum aAC_n}{d_h \times d_a}$ J/day	Winship et al. 2002
	California sea lion	Implicita	Weise and Harvey 2008
$P_{n,i,j}^F$	Killer whale	Implicita ^a	Noren 2011
	Harbor seal	0.91	Howard et al. 2013
	Steller sea lion	0.63	Winship et al. 2002
	California sea lion	Implicita ^a	
	Killer whale	Implicita ^a	

^aThe assumption is that these costs are implicit in bioenergetics models.

Table A2. Lactation and gestation periods for the each of the predator species.

Parameter	Predator	Initial day	N days	Source
$P_{n,i,j}^C$	Harbor seal	9 months before pupping	214 (9 months)	Temte 1991, 1994
	Steller sea lion ^a	9 months before pupping	214 (9 months)	Pitcher and Calkins 1981
$P_{n,i,j}^{LC}$	Harbor seal	May 25	28–42	Muelbert et al. 2003
	Steller sea lion ^a	May	6 months	Mathisen and Lopp 1963

^aAlthough some studies indicate that sea lions lactate for up to 9 months, many sea lions are seen lactating with 1–2 year old juveniles.

Table A3. Sources and model for determining growth costs for the predators.

Variable	Predator	Model	Source
$GC_{n,i,j}$	Harbor seal	$P_{n,i,j}^m \times 0.0165 \times 321 \times 86400$	Howard et al. 2013
	Steller sea lion	$(wt_{n,i,j} - wt_{n,i-1,j})[p_{up}ED_{up} + (1 - p_{up})(1 - p_w)ED_{pre}]$	Winship et al. 2002
	California sea lion	Implicita ^a	Weise and Harvey 2008
	Killer whale	Implicita ^a	Noren 2011

^aThe assumption is that these costs are implicit in bioenergetics models.

Table A4. Efficiency calculations for the predator species.

Predator	Efficiency calculation	d_a	d_h	Source
Harbor seal	$Ef = d_a - d_h$	0.90	0.08	Howard et al. 2013
Steller sea lion	$Ef = d_a \times d_h$	(pup, others) 0.95, 0.85	0.88	Winship et al. 2002
California sea lion	$Ef = d_a \times d_h$	(pup, others) 0.95, 0.85	0.88	Winship et al. 2002
Killer whale	$Ef = 0.847$			Noren 2011