**Supplemental Text**

**Section 1. Population size estimates**

Estimating the net energetic and prey consumption of the northern fur seal population requires information about the total population size and its age structure, which must be derived from models due to the inability to physically count all individuals within the population. In a stable population, the numbers at age of adult animals relative to pups are dependent on equilibrium survival and reproductive rates. In a declining or growing population, the age structure is further influenced by the components of the population whose change in vital rates from equilibrium are driving the decline. With respect to models, there are several realistic and justifiable choices that have been developed for northern fur seals that nonetheless differ in their approach and/or life history tables (Lander, 1981; York and Hartley, 1981; Barlow and Boveng, 1991; Loughlin et al., 1994; Towell, 2007). Assumptions regarding which component/s of the population are driving the decline (e.g., adult survival, pup survival) are less constrained. There have been two periods of long-term, sustained decline in the Eastern Pacific Stock of northern fur seals. The first was largely due to the harvest of adult females, but there is indirect evidence that pup survival also contributed to this decline (York and Hartley, 1981; Trites and Larkin, 1989). For the remaining periods of stability and decline, there is little direct published evidence to confirm or refute existing hypotheses (e.g., Fowler, 1987; Trites, 1992; Springer et al., 2003) about population dynamics of the Eastern Pacific Stock. Thus, we estimated the population size of each fur seal sex- and age class using a variety of different approaches (Fig. S1), which are described in further detail below.

**1.1 Lander, York, and Barlow and Boveng models**

In the first approach, we obtained numbers-at-age by performing direct simulations of the annual bulk survival and reproduction of the northern fur seal population through time on St. Paul and St. George Islands. The intent of these simulations – here termed “hindcasts” of the population – was to explore variability among life tables in combination with variability among possible mechanisms driving the decline. Hindcasts used three published life tables for female animals that span a realistic range of equilibrium vital rates and population structures (Lander, 1981; York and Hartley, 1981; Barlow and Boveng, 1991). For each life table, survival rates for different age classes were altered from their equilibrium levels to drive production trends similar to those observed on either island since the 1950s using least-squares fitting. We considered scenarios in which production variability was driven by changes in adult survival, pup survival, or both. Changes in reproductive rates can also drive changes in pup production and population size, but observations of pregnancy rates on St. Paul Island collected during the period of most recent decline do not provide evidence of differences from pre-decline levels (Testa et al., 2010) and so was not considered here.

Separate hindcasts were run for each life table, island, and scenario. Each run was initialized in summer 1950, during a period of stable pup production on both islands (1950 - 1955; York and Hartley, 1981). The initial numbers-at-age (0 - 26) were based on the age structure expected from equilibrium vital rates and the average 1950 - 1955 pup production. Thereafter, the run advanced forward in one-year increments. Pup production in a given summer was estimated as the sum of the products of age-specific reproductive rates and numbers-at-age of females in that year. Annual survival rates were then applied to the numbers in each sex and age class (ages 0 - 24) and the run advanced to the following year. Differing life tables and methods for incorporating commercial, pelagic, and subsistence harvests were applied to the female and male components of the population as described below.

**1.1.1 Females**

The life tables used to model the female component of the population are those published by York and Hartley (1981; their Table 3), Lander (1981; his Table 4, “expected” curve in right-most column, and Table 7), and Barlow and Boveng (1991; their Table 1). Reproductive rates for females were held constant through time. Female vital rates are assumed to be independent of the male population and therefore modeling only the female component is necessary for simulating pup production.

Through 1970, the hindcasts relied on observed and estimated levels of survival and harvest. During this period, adult natural survival rates were held at equilibrium levels, while female pup (age 0 - 2) survival by year was taken from Table 4 of York and Hartley (1981); these estimates are in turn based on male pup survival estimates of Lander (1979). As described below, survival between ages 0 - 2 is considered to be the relevant pup parameters through all hindcasts. To extract numbers of age-1 animals, a constant 80% survival from age 1 - 2 was assumed in all years. Survival in this age is poorly constrained due to low observability (Lander, 1981; Bigg, 1986); the rate of survival specified here is consistent with previous assumptions of steadily increasing survival with age towards values representative of young adults (Lander, 1981). Altering this assumption — which would only affect the numbers of age-1 animals — would likely have minimal or no impact on the results given there were very few age-1 animals included in simulations (214 - 604 seals; see section 2.1). The age- and year-specific commercial (1956 - 1968) and pelagic (1958 - 1974) harvests of adult females (Riley, 1967; York and Hartley, 1981; Towell, 2007) were removed from the numbers-at-age of females prior to estimating pup production in a given year. Eighty percent of the pelagic harvest of females was assigned to St. Paul Island (York and Hartley, 1981). Application of these female pup survival and harvest schedules led to a hindcasted decline in pup production through 1970 in good agreement with observations under all three life tables.

From 1971 onward, female survival rates were altered experimentally to give the best fit between hindcasted and observed pup production. For each island and life table combination, scenarios I and II allowed alterations to only pup (age 0 - 2) or adult (age 4+) survival changes, respectively. In scenario III, the alterations to adult survival were fixed at 50% of those determined in scenario II, and the best fit was then determined using residual pup survival variations. Thus, scenario III provides a rough approximation of a case in which adult and pup survival variations contribute equally to variability in production.

Rather than determine annual variations in survival, which would drastically increase the number of parameters to be estimated, we assumed constant vital rates within three separate periods after 1970, the boundaries of which could be altered to optimize the fit to observed pup production. The fitting procedure considered boundaries between 1975 - 1988 for the first break and 1988 - 2001 for the second break in rates on St. Paul, and 1980 - 1992, 2000 - 2010 respectively for St. George. These ranges were chosen to reflect obvious breaks in long-term pup production trends at each island.

In summary, for each island/life table/scenario combination, the fitting procedure determined survival variations in three periods after 1970, along with the duration of these periods, that minimized the sum of squares between simulated and observed pup production through 2018. The best-fitting set of parameters for each hindcast was obtained using a nonlinear unconstrained minimization routine implemented by the *fminsearch*function in MATLAB (The Mathworks, Inc.).

**1.1.2 Males**

While male pup production was equal to that of females in each island/life table/scenario combination, male survival from 0 - 2 was assumed to be 10% less than that of females, consistent with the assumptions in the female pup survival estimates of York and Hartley (1981) that were used to initialize the hindcasts as described above. The ratio was held fixed through time in absence of additional information. Note that there are few available data to constrain this assumption (Trites and Larkin, 1989); to cover a range of approaches, other models used in this study (see sections 1.2 and 1.3) include equal survival of males and females to at least age 2. Male survival rates of seals aged 2+ in each run were based on those published by Lander (1981), since the other two life tables used here considered only females. The effect of the commercial harvest of males was included indirectly by using reduced annual survival rates of males age 2 - 5 through 1972 on St. George and 1984 on St. Paul. These rates were determined using the method of Lander (1981; his Table 2), though with an assumed natural survival rate for these ages equal to that of females in his Table 7, rather than his assumed 80%. This increased natural survival gave better agreement at both islands between the observed commercial harvests of males and the implicit harvests in the hindcasts (i.e., the difference between natural and harvest-influenced annual survival).

Following 1972 (St. George) or 1984 (St. Paul), natural survival of males age 2 - 5 was assumed equal to Lander (1981) females of the same ages, and any further harvests were applied directly for each island and year as described above for females (Riley, 1967; Towell, 2007). The subsistence harvest from 1985-on was assumed to be spread equally among ages 2 - 4. Survival of males age 6+ in all hindcast runs was set equal to the annual natural survival estimated for St. Paul males in Lander’s (1981) Table 7. For estimating numbers of males in hindcasts of scenarios II or III, male survival age 4+ was reduced or increased consistent with the best-fitting results from the females of the same scenario.

**1.2 Towell model**

In the second approach, we employed model output from Towell’s (2007) alternative “complex” age-, sex-, island-structured model, which provides the numbers of fur seals by age and by year for St. Paul and St. George Islands for the years 1868 to 2004. The output only included 3 of the 6 target years (1995, 1996, 2004); the remaining target years (2005, 2006, 2010) had to be estimated without the ability to rerun the model with updated parameters. To do this and extend the model through 2018, we used the pup production survey estimates conducted on even-numbered years between 2006 and 2018. We estimated the number of pups born in the non-survey odd-numbered years between 2005 - 2017 by calculating the difference between the adjacent survey years (e.g., 2006 and 2008) and adding the midpoint of the difference to the previous year. We then applied the age-, sex-, and island-specific survival schedule from the last year of the model and fixed it to all the years from 2005 - 2018. The results were then extracted for the three remaining target years. This model provided an upper limit to the number of adult males in the Pribilof Island population (Fig. S1).

**1.3 Loughlin model**

In the third approach, we estimated population size using the method of Loughlin et al. (1994). This method was a modified version of the Kozloff et al. (1985) northern fur seal population assessment model to estimate the total population of northern fur seals in 1992. The model applies a series of multipliers to a 3-year running average of the estimated number of pups born to calculate the number of yearlings, 2-year olds, 3-year old males and females, and 4+ males and females (see Table 4 in Loughlin et al*.*, 1994). Fur seals in the 4+ male category were further partitioned into age classes (age 4, age 5, age 6, age 7, age 8+) based on the average proportion of males in each age class from the 10 other models. Since pup production estimates are not conducted in every year, we estimated the number of pups born in non-survey years using methods described above for the Towell model.

**Section 2. Population simulations**

We created a series of individual-based simulations to estimate the energy intake of northern fur seals from the time they arrived on the Pribilof Islands to the time they departed on their last trip that led to their annual migrations. Because of this, energy intake of pups after weaning are not included in these estimates, nor is time spent in the Bering Sea by non-pups before migrating southward. As mentioned in the main text, we separated the population into five demographic groups due to large differences in behavior and/or energetic costs: 1) lactating females (females age 4+ years with a pup), 2) non-lactating females (females age 4+ with no pup), 3) juveniles (ages 1 - 3 years), 4) subadult males (age 4 - 7 years), and 5) adult males (age 8+ years). Simulations were designed to mimic the natural behavior of fur seals during the breeding season, with variables that were largely parameterized using unpublished and published estimates of fur seal physiology and behavior from the Pribilof Islands. Many of the parameters described below were drawn from distributions to incorporate the natural variability present within populations, and either remained fixed throughout the season (e.g., arrival date) or varied with each foraging trip (e.g., trip duration). Where applicable, the distribution of each parameter was assumed to be normal unless there were sufficient data to determine the appropriate distribution among three distributions (normal, lognormal, and gamma). For trip and shore durations, if the AIC value of alternate distributions was more than 2 ΔAIC from the most common distribution for that parameter (normal for trip durations and lognormal for shore durations), than we used the distribution with the lowest AIC value. A complete list of parameter values for each demographic group can be found in Tables S1 - S6.

**2.1 Population sizes at each rookery complex**

At the start of the simulation, all fur seals were designated to an island based on the island-specific population models described above. They were further designated to a rookery complex based on the proportion of pups born at each complex on that island as determined from yearly pup counts. Since pup counts are not conducted every year, we used linear interpolation between successive pup counts to estimate these values in non-count years. Rookery complexes were based on geography and dietary differences (Zeppelin and Ream, 2006), with three complexes at St. Paul (East, English Bay, Reef Point) and two at St. George (North, South). The number of lactating females was estimated based on the number of pups born in each population model and the year- and island-specific pup mortality rate (e.g., Testa, 2007). Dead pup counts typically occur relatively early in the season (August), and our approach for calculating the number of lactating females essentially assumed that these pups were never born (i.e., these females were assigned as non-lactating females). The number of non-lactating females was calculated by subtracting the number of lactating females from the total population size of age 4+ females. The number of yearlings in simulations was severely reduced because most weaned pups do not appear to return to the land until they are two years of age. Resight data indicates only 0.5% of flipper-tagged individuals that survived were observed as yearlings (MML unpublished data), and we used this value to correct for the number of yearlings in the simulations. The sex of yearlings that returned was assumed to be 84% males (Bigg, 1986).

**2.2 Duration of foraging season**

The length of the foraging season for each fur seal was determined from arrival times and departure dates (Tables S1 - S4). Arrival dates of lactating females were determined based on observations by Gentry (1998), who reported that the number of females ashore increased from 0 on June 15th to 100% of the annual peak between July 7th and July 14th across a 15-year period. Arrival times for the remaining demographic groups were based on values in Bigg (1986) that described the date at which all seals in each sex- and age class had arrived upon the rookery or hauling grounds. Lactation durations from empirical observations of mom-pup pairs were used to determine departure dates for lactating females in each year (Goebel 2002; MML unpublished data). Departure dates for all other demographic groups were estimated based on the start of the migration of satellite-instrumented animals (i.e., the departure from the island at the start of their migratory trip). This distribution did not vary among years due to data limitations.

**2.3 Duration of onshore visits and foraging trips**

Within the foraging season, we simulated foraging trips and resting periods ashore to mimic the natural behavior of fur seals. Upon arrival at the breeding rookeries, adult males typically undergo an initial period of fasting while they attempt to hold territory. Similarly, once they give birth, females have an extended fast (6 - 8 days, perinatal duration) before they depart on their first foraging trip to sea. The duration of the perinatal period (lactating females) and breeding fast (adult males) were determined using data from Gentry (1998) and added to the arrival and birth time (1 day after arrival; Gentry, 1998) to determine the departure date for the first foraging trip. The length of each foraging trip and following shore duration were drawn from distributions generated using data from a combination of visual observations and biologging devices (unpublished MML data; Donohue, 1998; Goebel, 2002; Sterling and Ream, 2004). For lactating females, we used separate distributions for each year, island, and month whenever possible (Table S6), but did not have sufficient data to further parse these estimates to the level of rookery complexes. Parameter values for trip and shore durations for the remaining demographic groups did not vary among years, islands, or months because of data limitations (Tables S2 - S4).

**2.4 Initial mass and mass changes**

Individual seals were assigned an initial mass based on age- and sex-specific distributions (MML unpublished data; Scheffer and Wilke, 1953; Gentry, 1998). The mass loss of adult males across the breeding fast was calculated based on the length of the breeding fast and daily mass loss estimates (Gentry, 1998) and subtracted from arrival mass to determine mass at departure on the first foraging trip. We did not account for mass loss across the perinatal fast for lactating females because we used mass data from the postnatal period to parameterize the model. While there was slight variation in mean body mass of instrumented females across target years, it was unclear if this was simply a sampling artifact or indicative of any real trend. As such, we pooled all years to estimated body mass of lactating females. Body mass was updated at each time step based on mass gain (or loss) per foraging trip and mass loss while onshore, except for adult females where we assumed body mass remained unchanged throughout the season (Tables S2 - S4). The value of mass gain was allowed to vary across foraging trips to account for the fact that individuals may experience variable foraging success, but the value of mass loss was fixed for an individual across the season because it was assumed FMR was the most likely driver of onshore mass loss.

**2.5 Field metabolic rate (FMR)**

Energy expenditure at sea was calculated from FMR as described in the main text and the length of the foraging trip. At-sea FMR was fixed for each seal within the non-molt period; FMR during the molt period was based on the mass at departure on the first foraging trip. The timing of the molt was based on sex- and age-specific estimates from Scheffer and Johnson (1963). For lactating females, we simply used the molt or non-molt value for each foraging trip depending on whether the trip began before (non-molt) or after September (molt). Because the foraging trips of the remaining demographic groups can be upwards of several weeks, we calculated the number of molt and non-molt days of each foraging trip and multiplied each of these values by their respective at-sea FMRs. For adult females, we fixed onshore FMR for each seal per season (summer, fall); onshore FMR during fall was calculated based on summer onshore FMR and the percentage increase in FMR between seasons to ensure that individuals on average experienced a net increase in FMR.

**2.6 Pup parameters**

Parameters associated with the pup included pup sex and mass at birth, the duration of the perinatal period, pup growth during the perinatal period, pup growth rate during the rest of the season, and the duration of lactation (Table S5). Pup sex was assigned based on island- and year-specific sex ratios (e.g., Testa, 2007). These ratios tended to be slightly but consistently biased towards male pups, with an average of 54% male pups and 46% female pups. Mass at the end of the perinatal fast was calculated based on birth mass (Gentry, 1998), the duration of the perinatal period (Gentry, 1998), and the daily mass gain expressed as a percentage of initial birth mass (Costa and Gentry, 1986; Costa and Trillmich, 1988). Whenever possible, estimates of pup growth rates for the remainder of the season were based on repeated measurements of individual pups (Donohue, 1998; Goebel, 2002; MML unpublished data); in years where these data were unavailable, pup growth rates were estimated based on the relationship between pup growth rate, sex, and the ratio between the sum of trip durations and visit durations (Table S5). Pup mass increased throughout the simulation in accordance with their mass at the end of the perinatal fast, growth rate, and duration of the maternal cycle. In nature, growth across the maternal cycle is not linear because pups experience mass gains while their mother is ashore and lose mass while she is absent (Gentry, 1998); however, this level of detail is unnecessary here because the result with respect to pup mass at the start of a suckling period is the same. Growth rates do vary across the foraging season, with increased absolute growth rates during the post-molting period that has been attributed to increased thermoregulatory capabilities of the pup (Donohue, 1998). To incorporate this variation, we partitioned the assigned growth rate into two time periods (before and after Oct 1) assuming a 57.1% increase in growth rates between pre and post molt (Donohue, 1998).

**2.7 Bioenergetic Model and Prey Consumption Equations**

*Lactating female*

The gross energy (MJ) a lactating female needed to acquire on a single foraging trip was calculated as

where FMR is the daily metabolic costs experienced by a female based on mass-specific metabolic rates, season, and her starting body mass (Table S1), trip and shore are the duration (days) of the foraging trip and subsequent visit to shore, milk is the total milk energy allocated to the pup during the visit to shore, and ME is the metabolizable efficiency (Fig. S9). The milk energy allocated to the pup was calculated as

where mass is the mass of the pup at the start of the suckling period and the values are the equation from Donohue et al. (2002) that provide an estimate of daily milk energy intake (MJ day-1). The mass of the pup at the start of the suckling period was calculated as

where mass is dependent on the pup’s mass at the end of the last suckling period, the growth rate (in kg per day), and the duration of the current foraging trip.

*Non-lactating female*

The gross energy (MJ) a non-lactating female needed to acquire on a single foraging trip was generally similar to that of a lactating female with the exceptions that there were no lactation costs and FMR was separated into molt and non-molt days for trip and shore durations (not shown for brevity) such that

*Subadult male and juveniles*

The gross energy (MJ) a subadult male or juvenile needed to acquire on a single foraging trip was calculated as

where FMR is the daily metabolic costs experienced by a subadult male/juvenile based on mass-specific metabolic rates, whether it is the molt or non-molt period, and starting body mass (Tables S2 - S3), trip is the duration of the foraging trip (days) split into the number of days that encompassed the molt and non-molt period, and fat and protein are the energy invested in fat and protein deposition. The energy invested in fat deposition was calculated as

where 0.75 is the proportion of mass gain allocated to fat and 39.3 is the energy density of fat (MJ kg-1). Similarly, the energy invested in protein deposition was calculated as

where the values for the proportion of mass deposited as protein and the energy content of protein have replaced the corresponding fat values. The mass gain was calculated as

where the mass gain for a single trip was based on the mass at departure, the daily proportion of mass gain as a function of body mass, and the duration of the foraging trip (Tables S2 - S3). The mass at the end of the foraging and shore duration was calculated as

where the far right hand side of the equation represents the mass loss while on land using the equation from Baker et al. (1994) and the distributions in Tables S2 and S3 for the proportion of daily mass loss while on land.

*Adult males*

The gross energy (MJ) an adult male needed to acquire on a single foraging trip was calculated similarly as juveniles/subadult males with the main exception that the amount of mass gained on a foraging trip was often negative. As a result, this value ended up being negative and thus subtracted from FMR costs. In addition, mass loss while on land was calculated without the exponent function, and the ratio of fat:protein deposition/catabolism was 5:1 instead of 3:1 (Table S4).

*Population-level intake and prey consumption*

The gross energy (MJ) intake of fur seals at each rookery (*r*) is simply the sum of the total gross energy of each individual (*i*) at that rookery, which itself is a sum of all costs experienced by individual *i* in each foraging trip (*t*)

This value was summed across all five rookery complexes to get the population-level estimate of energy intake in each target year

Complex-specific diet estimates were combined with to estimate the total and species-specific prey consumption of northern fur seals

where is the proportion of the diet (by energy) comprised of prey *p* at rookery complex *r*.

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