Appendix A: Data and Parameterization

A.1. Ecosystem Data

SR - Equilibrium

The initial simulations are run sans human harvesting. There is no single study that contains the data needed to run simulations; however, by consulting a variety of ecological studies of the Alaskan and other ecosystems, a data set was constructed. The parameter values and the variables used to construct the parameters are listed in Table I. All data are from around 1980. The notes for Table I contain the data sources and comments on parameter construction.

To understand some of the issues involved in assembling the data, consider the Steller sea lions. In 1980 the population of sea lions was 125,000 (no distinction is made between adults and juveniles). To make the magnitude of the population more manageable, which becomes very important for the species such as zooplankton with very large numbers, the population was divided by the square kilometers of surface area of the EBS (1,300,000) to obtain the population per square kilometer (0.096154).
The biomass flow or demand of the sea lions was taken from experiments in which the daily caloric requirement of sea lions was measured. The caloric value was converted to a biomass flow by dividing it by the number of calories embodied in a kg of pollock. A complication arises, however, because in the wild sea lions are known to eat octopus and squid and other fish species besides pollock. Because only pollock are in the model, only the sea lion intake of pollock was reflected in their biomass demand. Using studies that estimate 76% of the sea lion diet in the wild is fish, of which 40% is pollock, yields the result of 1332 kg y\(^{-1}\) of pollock.\(^1\) The sea lion demand and population (along with the demand and population for the killer whale) can be substituted into equilibrium condition (33) to obtain the predation parameter \(d_{78}\). The resting metabolic rate was obtained from a formula relating a mammal’s weight to its fixed respiration. Embodied energy \(e_7\) is available in the ecological literature.

For a plant there are two additional parameters. Consider phytoplankton. A rough rule of thumb is that 10% of the energy taken at one trophic level is passed on to the next trophic level, although for marine communities a 20% transfer rule has been estimated. Therefore, equate 20% of the energy taken by phytoplankton to the energy taken by zooplankton: (20%) \(N_1 x_{10} e_{01} = N_2 x_{21} e_1\) and solve to obtain \(e_{01} = 15150\) kcal kg\(^{-1}\) yr\(^{-1}\). The phytoplankton congestion parameter, \(\tau_1\), was obtained by substituting the phytoplankton demand and population into (34). Because the population of phytoplankton was in the sextillions, the population was converted to population units where each unit is 1\(\times\)10\(^{12}\) individuals. Furthermore, the populations were converted to unit km\(^2\) as described above for sea lions. All populations were converted to population units except for sea lions.
Finally, the variable respiration parameters \( r_i \) for all species were obtained through calibration. Assuming that in 1980 the ecosystem was in steady state, then all \( R_i = 0 \) and all species are maximizing their net energies. Therefore, the demands, populations and all parameters for all species, except the \( r_i \) parameters, were substituted into the nine first-order conditions and into (19)-(26) set to zero, and these seventeen equations were solved for the \( r_i \) and the \( e_{io} \). The \( r_i \) were then used as the variable respiration parameters in simulating short-run equilibriums and they also were used to obtain the variable respirations in steady state as needed in the update equations (16) and (17).

**L.R - Population Adjustments.**

All populations were adjusted according to (16) and (17) after each short-run equilibrium simulation. Each simulation and subsequent adjustment takes place in one period, and a period is assumed to be one year. Individuals are assumed to reproduce once per year, which is reasonable for all species except phytoplankton that can reproduce every few days and zooplankton that can reproduce every few weeks, and both of which may have lifespans less than one year. To adjust for the rapid turnover of the planktons, their weights in (17) were multiplied by 365 to put them on a daily basis, and the longevity term was redefined to be length of life divided by the number of times the individual reproduces over the life. (For nonplankton species this redefinition does not change \( s_i \) since they live more than one year and reproduce once per year.)

Population adjustment equations (16) and (17) contain the steady state variable respiration terms, \( \hat{V}_i \), that are constructed from the \( r_i \) parameters. As populations are adjusted period after period these terms are constant. This raises the question: From what
steady state are these variable respiration terms obtained? The convention adopted here was that the $V_i$ were from the steady state in which there was no human intervention into the ecosystem, and we refer to this as the *natural* steady state. Of course, humans have been intervening in most ecosystems for thousands of years; thus this convention may need to be altered depending on the ecosystem being examined and the problem being addressed. For the Alaskan example, the major human intervention in 1980 from which time the data are taken was commercial fishing. Specifically, about 16% of the pollock population was being harvested, mostly by Russian trawlers. Because the $r_i$ and $V_i$ are to represent the steady state in which there is no human intervention, yet they are obtained via a calibration using biomass demand and population data from 1980 when there was intervention, the following two step procedure is adopted: First, the SR calibration described above was run with its seventeen equations in addition to equations (36) and (37).

$$N_i^4 \left[ p + \frac{(1-p)^{s_i}}{s} \right] \left[ \frac{R_4(\hat{x}_{43};N_i^4)+V_4}{\hat{V}_4} - 1 \right] = h$$  \hspace{1cm} (A1)$$

$$R_4(\hat{x}_{43};N_i^4) = 0$$  \hspace{1cm} (A2)$$

where $p = \frac{d_{45}x_{43}}{w_4}$ is described in (17). The purpose of adding (36) and (37) was to solve for the pollock variable respiration parameter and the pollock biomass demand in a natural steady state. Equation (36) sets the fish population growth from (17) on the left side with the harvest, $h$ (The harvest was about 1 billion kg in 1980 [14].) The $x_{43}$ in (36) is the observed biomass demand in 1980 when harvesting occurred and as shown in Table 1; but the biomass demand, $\hat{x}_{43}$, used to calculate the steady-state variable respiration,
\( \dot{V}_4 \), in (36) was solved for in the calibration. This latter biomass demand was then used in (37) which is the pollock net energy in steady state as if there was no harvesting, and (37) then yields the variable respiration parameter, \( \dot{r}_4 \), as if there was no harvesting.

Second, all the parameters from the calibration are used in short-run equilibrium simulations and population adjustments until a new steady state with new biomass demands and populations is generated. The new demands and populations reflect the no harvesting assumption. Next, these new biomass demands and populations are used in a second calibration to obtain the final variable respiration parameters used in all the results presented below.

**A.2. Economic Data**

Applying HW's [5] methods to the pollock fishery in the BSAI involved estimating parameters \( a, b, q, f, \) and \( v \). Data were gathered for pollock populations, total allowable catches, season lengths, measures of effort, actual harvests and exvessel prices. Most of the data were gathered from a variety of National Marine Fisheries Service (NMFS) sources. Biomass estimates, total allowable catches and actual catches are from Witherell [20]. We assumed the biomass estimates for the fishery are used by both the regulator and industry in their decisions.

Unfortunately, pollock data were limited to the years 1981-2000, and within these years, only since 1991 has the fishery been limited to domestic fleets, further restricting the explanatory power of the data\(^2\). For season lengths we collected closure reports from the NMFS\(^3\). Sorting over pollock by areas within the BSAI, we totaled days closed per year. The residual of yearly closures was assumed to be the season lengths in days per year. Seasons were assumed to be continuous within each year\(^4\).
Measures of effort in the fishery were constructed from annual NMFS Stock Assessment And Fishery Evaluation (SAFE) Reports, Kinoshita, et al. [8, 9, 10] and Hiatt and Terry [4]. Trawlers are the dominant gear in the fishery. We used numbers of vessels as a proxy for seasonal capacity in the fishery\(^5\). Similar to HW, we assumed a constant efficiency of effort across fishery participants\(^6\), and that capacity costs were proportional to actual costs. Finally, exvessel prices were gathered from the same source, expressed in dollars per pound round weight, and they were deflated using the CPI with base year 1982\(^7\).

To obtain parameter estimates, HW estimated the biological growth equation independent of all other equations; but the parameters in our growth equation are taken from the calibrations in A.1. HW also estimate (39) independently using ordinary least squares, and the same procedure is followed here. HW point out that capacity and season length are determined simultaneously; accordingly they estimate (40a) and (40b) jointly with the cross equation restriction of a constant catchability coefficient. Given the limited pollock data, attempts to follow the simultaneous equation estimation of HW proved unsuccessful. Therefore, we separately estimated equations (40a) and (40b)\(^8\) (with additive errors assumed iid) by ordinary least squares. All estimations were performed with LIMDEP software, and results are displayed in Table II.

Durbin-Watson statistics were used to test for the presence of autocorrelation. We corrected for first order autocorrelation found in the quota function. Parameter estimates are all of the expected sign and all but 1 significant at the 0.1 level or better. Estimating the quota function presented difficulty due to fairly constant TAC's since the fisheries inception (with relatively stable, large populations). A linear quota rule applied
to the data for the BSAI did not yield a positive \( N_4^{min} \). To expand the sample, data for quotas and biomass for the Gulf of Alaska (GOA) were appended to the BSAI data. In doing this we assumed the NMFS behaves identically in determining the TAC for both regions. Given the expanded dataset, several specifications of Equation (39) were estimated. A quota function with the natural logarithm of biomass gave the best fit.\(^9\)

In light of the variable definitions, magnitudes of the variables are reasonable. In the estimated quota function, the minimum exploitable biomass level was 875,807 metric tons, or 674 individuals per km\(^2\). Fixed and variable costs were $432,000 and $2335, respectively. The catchability coefficient's magnitude is small due to the relatively large size of our measure of variable effort in relation to seasonal catch.

**Notes:**

1. This method whereby a predator’s energy intake is confined to reflect only the prey included in the model was also used for killer whales. It was not necessary to confine the energy intake for the other predator species because they prey mostly on species included in the model. For example, urchin prey exclusively on kelp.

2. Reasonable data for the quota function over the years 1980 through 1999 exists. But, given the institutional change in the fishery, we are limited to using observations on the domestic fleet and seasons from 1991 through 1999.


4. In reality, seasons are fragmented throughout the year and heterogeneous over area. But, the additional complexity needed to add the notion of space and within season temporal distinction is beyond the scope of this paper.
In constructing this measure we use aggregate numbers of vessels of the three major size classes: less than 60 feet, 60 to 125 feet and greater than 125. This neglects any economies of scale that maybe present in larger vessels, but allows us to construct a simple measure of effort from readily available data.

This is admittedly a strong assumption given the above footnote.


Through a linear transformation.

Under this specification the quota function becomes $TAC_t = a + b(ln[N_4^{0.4}])$
References


<table>
<thead>
<tr>
<th>Variables</th>
<th>Phytoplank.</th>
<th>Zooplank.</th>
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<th>Sea otter</th>
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<td>(iii)</td>
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<td>(xii)</td>
<td>(xiii)</td>
<td>(xiv)</td>
<td>(xv)</td>
<td>(xvi)</td>
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<td>1782.7 kg unit$^{-1}$ y$^{-1}$</td>
<td>9300. kg unit$^{-1}$ y$^{-1}$</td>
<td>1332. kg y$^{-1}$</td>
<td>486.6 kg unit$^{-1}$ y$^{-1}$ (Steller)</td>
<td>28.3 kg unit$^{-1}$ y$^{-1}$ (otter)</td>
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<td>(lxxi)</td>
<td>(lxxii)</td>
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<td>(lxxiv)</td>
<td>(lxxv)</td>
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Table I. Notes

NA – not applicable or not needed.
† Individuals are aggregated into population units and the units are divided by ocean surface area
to yield population units per square kilometer. Pelagic populations are divided by $1.3 \times 10^6$
km$^2$, the approximate area of the EBS, and nearshore populations are divided by 26,000 km$^2$,
the approximate area along the Aleutian Islands.

(i) An aggregate of multiple phytoplankton producer and saprophage species (Petipa et al. [17],
Table 1). The data are from the Black Sea but assumed to be transferable to the EBS. Populations
in Petipa et al. are given in individuals per square meter; thus, when extrapolating to the EBS, the
number of individuals is in an unmanageable sextillions. Consequently for phytoplankton and
other species in Table 1 populations are converted to population units, then placed on a square
kilometer basis.

(ii) An aggregate of multiple zooplankton herbivore species (Petipa et al. [17] Table 1). The data are
from the Black Sea but assumed to be transferable to the EBS.

(iii) Pollock estimates around 1980 are $6.3 \times 10^9$ kgs (Witherell [21]). Assuming pollock are 1kg on
average, this is $6.3 \times 10^9$ individuals which converts to $6.3 \times 10^6$ population units. On a km$^2$ basis:
$6.3 \times 10^6$ units/1,300,000 km$^2$ = 4.84615. Recall, 1,300,000 is the ecosystem size in km$^2$.

(iv) The Stellar sea lion population was estimated to be 125,000 [15], and on a km$^2$ basis:
125,000/1,300,000 km$^2$ = 0.096154.

(v) Based on 1024 individuals [15]. Because killer whale habitat includes both ocean and nearshore
systems, the population was divided by 1,300,000 + 26,000 to put on a square kilometer basis.

(vi) Based on 131,631 individuals extrapolated from Estes and Duggins [3] estimates of populations
in Aleutians island groups.

(vii) Individuals from multiple sea urchin species at 153 randomly selected sites in the Aleutians
(Estes and Duggins [3]).

(viii) Kelp density of multiple species is about 10% of urchin at the same 153 sites in the Aleutians
(Estes and Duggins, [3]).

(ix) A weighted average of phytoplankton species’ body weights ($4.35615 \times 10^{-10}$ kg, Petipa et al.
[17], Table 1), in units of $1 \times 10^{12}$ phytoplankton.

(x) A weighted average of zooplankton species indicates an individual weighs 3.757$x 10^{-6}$ gm. and
consumes 130% of its weight in phytoplankton per day (Petipa et al. [17], Table 1). This yields a
consumption of 1782.7 kg unit$^{-1}$ yr$^{-1}$.

(xi) Trites et al. (1997) p. 186. Pollock eat mostly zooplankton (Witherell [21]) and here they are
assumed to eat only zooplankton.

(xii) Based on Rosen and Trites [19] and [15]. From [15], in 1990s Steller diet was 76% fish of
which 40% was pollock. Therefore, of the 4380 kg/yr taken by an individual sea lion, the pollock
consumption was (.76) (.40) (4380) = 1332kg/yr.

(xiii) Killer whale prey includes sperm and baleen whales, pinnepeds, seabirds, fish, turtles, otter,
and based on the stomach content of one whale, pigs; however, there is no consensus on the
importance of any one prey (Jefferson et al. [6]). We assume that around 1980 the proportion of
Steller sea lions in the killer whale diet was the same as the proportion of the Steller sea lion
population in the sum of the populations of Steller sea lions, harbor seals, Northern fur seals and
walruses in the EBS region as reported in Trites et al. [20]. This amount is about 10% of the
total diet (the total is based on the daily killer whale energy requirement (Estes et al. [2]), and we
also assume that otter made up 5% of the total. Estes et al. indicate killer whales did not consume
significant numbers of otter until recently.
(xiv) Otter eat 20-30% of body weight per day and on average an adult weighs 28 kg (Costa [1]).
Otter eat mostly sea urchins (Mason and Macdonald [13]), and here they are assumed to eat only
sea urchins.
(xv) Based on sea urchin growth rates (Estes and Duggins [3], Table 11).
(xvi) Assumes prey biomass is 1.2 times predator biomass (Kerr [7]), and using the kelp and urchin
populations yields 1.05 kg per individual.
(xvii) Weighted average of caloricty measures of three phytoplankton species groupings (Petipa et
al. [17], Table 7).
(xviii) Weighted average of caloricty measures of three zooplankton species groupings (Petipa et
al. [17], Table 7).
(xix) In a captive situation, the mean daily ration of pollock was 7.2kg d^{-1} which was in energy
33.39MJ d^{-1} (Rosen and Trites [19]); therefore, the embodied energy in the daily ration is
(33.39MJ d^{-1})(1 Mcal/4.184MJ)(1000kcal Mcal^{-1}) (1/7.2kg) = 1108 kcal kg^{-1}.
(xx) Estimated based on blubber content in a sea lion versus otter which have no blubber. (Costa
[1]) (See (xxii)).
(xxi) Not needed because killer whales are at the top of the food web and are not prey.
(xxii) Estes et al. [2].
(xxiii) Costa [1].
(xxiv) Lembi and Waalan [12].
(xxv) A rough rule of thumb is that 10% of the energy taken at one trophic level is passed on to the
next trophic level (See, e.g., Pauly and Christensen [16]). Petipa et al. [17] suggest a 20%
transfer rule for ocean communities. Therefore, equate 20% of the energy taken by
phytoplankton to the energy taken by zooplankton: (20%) N_1 x_{10} e_{01} = N_2 x_{21} e_1 and solve to
obtain e_{01} = 15150. kcal kg^{-1} yr^{-1}. (Note N_1 is from (i), x_{10} from (ix), N_2 from (ii), x_{21} from (x)
and e_1 is from (xvii).
(xxvi)-(xxxi) Not applicable because only plants photosynthesize.
(xxxii) Using the 20% transfer rule (See (xxv),), equate 20% of the energy taken by kelp to the
energy taken by urchin: (20%) N_8 x_{80} e_{08} = N_7 x_{78} e_8 and solve to obtain e_{08} = 13.53 kcal kg^{-1} yr^{-1}.
(Note N_8 is from (viii), x_{80} from (xvi), N_7 from (vii), x_{78} from (xv) and e_8 is from (xxiv).
(xxxiii) An average of respiration as a % of body weight over multiple phytoplankton species yields
6%. (Petipa et al.[17], Table 2). Incoming phytoplankton energy is e_{01} x_{10} = (15149.2)(435.6),
and 6% of this is 395,948 kcal yr^{-1}.
(xxxiv) An average of respiration as a % of body weight over multiple zooplankton species yields
30%. (Petipa et al. [17], Table 2). Calculations are similar to (xxxiii).
(xxxv) Pollock are assumed to follow the 30% estimate in (xxxiv).
(xxxvi) For mammals, resting metabolic rate in kcal d^{-1} (M) is related to body weight (W) by the
formula \( M = 67.61W^{0.756} \pm 5\% \) (Kleiber [30]). Using 200 kg as sea lion weight and extrapolating
to one year yields 391,134 kcal yr^{-1}. The RMB used in the simulations is lowered by (76%)(40%)
to reflect that sea lions are preying on more than just Pollock (See (xii).)
(xxxvii) Use the formula from (xxxvi) and an average weight of 3996 kg. The RMB used in the
simulations is lowered to 10% of this figure to reflect that killer whales are preying on more than
just sea lions and otter (See (xiii).
(xxxviii) Use the formula from (xxxvi) and an average weight of 28 kg and a +5% because otter
have high metabolic rates (Costa [4]).
Urchin are assumed to follow the 30% estimate in (xxxiv).

Kelp are assumed to follow the 6% estimate in (xxxiii).

Phytoplankton are plants; therefore, weight is given in (ix).

Average of multiple zooplankton herbivore species (Petipa et al. [17], Table 1).

Average of adult and juvenile, both are taken by fisheries and Steller sea lions. (See (iii.).)

Based on weights of immature sea lions in Rosen and Trites [19].

Average of adult and juvenile, both are taken by fisheries and Steller sea lions. (See (iii.).)

Average of multiple zooplankton herbivore species (Petipa et al. [17], Table 1).

Average of adult and juvenile, both are taken by fisheries and Steller sea lions. (See (iii.).)

Average of male and female adults is 3996 kg (Estes et al. [2]).

Average of male and female adults is 28 kg (Costa [1]).

Urchins at six locations in the Aleutians averaged 8.76 gm each with a wide variance (Estes and Duggins [3], Table 2). We rounded to 10 gm.

Kelp are plants; therefore, weight is given in (xvi).

# Calculated from the short-run equilibrium (i.e., market clearing) conditions using benchmark values for populations, biomasses and biomass flows (i.e., demands) from the first two table rows.

% Calculated using the plant congestion conditions and assuming that at the benchmark values for populations, biomasses and biomass flows, the plants fully occupy the available water space.

$ Derived from calibration. The benchmark biomasses and biomass flows were used as parameters in the eight net energy objective functions set to zero and in the nine first-order conditions to derive values for the variable respiration terms, \( r_i \), and the energy prices, \( e_{ij} \). The derived energy prices are benchmark energy prices in the simulations.
Table II. Parameter Estimates

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<td>$B$</td>
<td>475200.0879</td>
<td>431725.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(72931.371)***</td>
<td>(222615.3)*</td>
<td></td>
</tr>
<tr>
<td>$F$</td>
<td></td>
<td>2332.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1347.36)</td>
<td></td>
</tr>
<tr>
<td>$V$</td>
<td></td>
<td></td>
<td>0.535x10^{-5}</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(.8877x10^{-6})***</td>
</tr>
<tr>
<td>$q$</td>
<td></td>
<td></td>
<td>0.80448</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(.08436)***</td>
</tr>
<tr>
<td>$\rho$</td>
<td></td>
<td></td>
<td>0.37487</td>
</tr>
<tr>
<td>Durbin Watson</td>
<td></td>
<td></td>
<td>-0.8725**</td>
</tr>
<tr>
<td>Adjusted $R^2$</td>
<td>0.7544</td>
<td>0.459</td>
<td></td>
</tr>
</tbody>
</table>

* = significant at the .1 level  
** = significant at the .05 level  
***= significant at the .001 level  
# Standard errors in parentheses  
% Linearized equation does not posses an intercept, allowing a non-positive adjusted $R^2$  
(Pindyk and Rubinfeld [18], page 77).