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FINAL REPORT

Integrate economic-ecological models of pollock and cod

NPRB BSIERP Project B71 Final Report

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Abstract

This project prepared historical catch data and developed an integrated economic component for the BSIERP vertically-integrated ecosystem model, Forage/Euphausiid Abundance in Space and Time (FEAST). The economic component was a fishing effort allocation model in Nash equilibrium (FAMINE) for groundfish stocks accompanied by a time series analysis for Pacific herring, an important forage species in FEAST. Separate fleets were specified in FEAST and FAMINE that target walleye pollock, Pacific cod, and other groundfish stocks, further stratified by i) vessel class (i.e., catcher vessels, catcher processors), and ii) gear type (i.e., trawl, hook-and-line, pot). Herring seine and gillnet fisheries were also included in the forage species component of the ecosystem model. To handle the large number of grid cells in FEAST, FAMINE is structured as a series of large-scale quadratic programs that solve a static optimization problem. In particular, FAMINE assumes vessels minimize costs of catching a given amount of fish in a particular time-period subject to spatial distribution of stocks from FEAST. The spatial distribution of abundance from FEAST times the spatial effort allocation from FAMINE determines the spatial distribution of catch and bycatch (i.e., total removals from fishing). Therefore, the BSIERP vertically-integrated ecosystem model utilizes an authentic two-way coupling with an economic component that determines the spatial allocation of fishing effort and catch for each fleet based on the spatial distribution of pollock and cod.

Key Words: Pacific cod, Pacific herring, quadratic programming, time series analysis, walleye pollock

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Study Chronology

This was a new project and was the first NPRB-funded project for PI Michael Dalton. The award for this project was made mainly to the University of Washington where André Punt was the UW PI for this project and two other closely related BSIERP projects (B70: FEAST, PI Kerim Aydin; B73: Management Strategy Evaluation, PI André Punt). These projects began on October, 1 2007 and ended on February 28, 2014. Semi-annual progress reports were provided to NPRB during this time period. Multiple no cost time extensions were allowed to accommodate delays in B70.

Introduction

Bering Sea pollock and cod stocks supported the largest and most valuable commercial groundfish fisheries by species off Alaska in 2012 (Fissel et al. 2014; see Table 19 for ex-vessel values by area, and Table 4 for breakdown of flatfish catch). This project addressed BSIERP Hypothesis 5: Commercial and subsistence fisheries reflect climate. The specific hypothesis in this project was that the spatial distribution of fishing effort and catch for pollock and cod will be affected by changes over time in the spatial distribution of these target stocks under a climate change scenario. To test this hypothesis, an integrated economic-ecological model for pollock and cod was developed. The general plan for this project was twofold: i) provide historical data on commercial fisheries as an input for the hindcast of the Forage/Euphausiid Abundance in Space and Time (i.e., FEAST) ecosystem model and ii) link an economic model for pollock and cod to simulate fishing effort and catch in forward simulations with the FEAST model. The economic model for pollock and cod was structured as a fishing allocation model in Nash Equilibrium (i.e., FAMINE) among vessels and fleets. In theory, FAMINE satisfies all of the proposed objectives for this project, including Fortran90 code that was linked to FEAST for an authentic two-way coupling. Time trials with different configurations of FAMINE were performed and a version with reasonable computing times was tested.
Overall Objectives

The revised BSIERP proposal appendix for linked modeling outlined a vertically-integrated ecosystem model which related climate scenarios to economic outcomes for 50-year projections. That appendix also proposed a separate set of “competing models” which included “existing models for blended forecasts and management strategy evaluation” (MSE). In particular, the vertically-integrated ecosystem model and MSE were proposed as separate activities. The economic component that was proposed for the vertically-integrated model included the development of time series models for pollock and cod to simulate local rates of fishing mortality. During the project, however, the FEAST and MSE projects were joined which added major new objectives to this project and affected the original objectives by ruling out the use of dynamic economic models. In addition, Pacific herring was added to the forage species in the vertically-integrated model which added an interesting and complex fishery to this project.

Objective 1: Fishing allocation model subject to MSE constraints.

For MSE the simulated rates of local fishing mortality in FEAST would be constrained by annual total allowable catch (TAC) constraints. This type of “global” constraint in the economic component was imposed by ultimately unsuccessful attempts to use the vertically-integrated ecosystem model for MSE. These global catch constraints for MSE upset the basic structure of the vertically-integrated model because it violated the “no global knowledge” state for each grid cell in the Regional Ocean Modeling System (ROMS). Explicitly, the economic component of the vertically-integrated model would simulate local fishing effort to interact with local abundance and produce catch for each grid cell but the allocation of fishing effort to individual grid cells would depend on the entire spatial distribution of the target stock in addition to the TAC. This fundamental change in the basic structure of the economic model presented a daunting challenge that needed a completely different methodology from the one that was proposed. In particular, dynamic economic models were not feasible with the heavy burden of MSE constraints and a somewhat ad hoc static fishing allocation model was developed to compute grid cell level fishing effort and catch based on abundance in each grid cell from the FEAST model and constraints on total catch from the MSE. This static model was predicated on the assumption that deviating from the historical pattern of fishing effort would entail adjustment costs. In the economic model, fleets were assumed to minimize these adjustment costs subject to
the spatial distribution of the target stock and the TAC. Furthermore, the proposal for the economic model applied to pollock, and to a lesser degree cod, but the MSE constraints involved other stocks (e.g., flatfish), gears, and vessel classes, including target catch and bycatch for each. Essentially, the dynamic economic models proposed for pollock and cod were reformulated during the course of this project into a fishing allocation model for the entire Bering Sea groundfish fishery. The structure of this model is the subject of Chapter 1.

**Objective 2:** Link the fishing allocation model to the FEAST model.

The BSIERP proposal for linked modeling promised a 2-way coupling for a fully integrated FEAST economic component. To meet this objective, the fishing allocation model (i.e., FAMINE) was fully integrated as a stand-alone Fortran90 routine in the FEAST-ROMS program to provide a two-way coupling of economic and ecosystem models. This “hard” coupling means that the FEAST and FAMINE models compile and run together. These models were not simply run end-to-end using numerical output from one model as input to the other.

**Objective 3:** Meet computing requirements of FEAST/MSE.

Computing power was an ongoing problem for the vertically-integrated model because of 3-D modeling on a FEAST-ROMS grid which consists of more than 40,000 individual cells (see Figure 1). Time trials were conducted with FAMINE using randomly generated data to evaluate computing times for different numbers of grid cells. Based on these results, simulating fishing mortality on the FEAST-ROMS grid was infeasible. However simulating fishing mortality for statistical (i.e., stat6) fishing areas (see Figure 1) was feasible, and from there, simulated catch for each fishing area could be proportionally downscaled to the FEAST-ROMS grid.

**Objective 4:** Calibrate fishing allocation model with FEAST hindcast results.

All NPRB support for this project was used to assemble and prepare historical catch data for a FEAST hindcast. This objective was not met because the hindcast experienced many delays and was not completed until the end of this project. Preparation of the historical catch data for FEAST was a major undertaking that required a substantial amount of matching time by Alaska Fisheries Science Center staff. Since hindcast results were unavailable to calibrate the fishing allocation model, it was not used in the MSE, nor was it used for any forward runs of the FEAST model under a climate change scenario. Consequently, only about a third of the NPRB funds
scheduled for this project were used to support work in this project. The remainder was split between the FEAST and MSE projects (with the majority going to MSE).

Assembling historical herring catch data for FEAST was supported by NPRB which was challenging and a major activity in this project. These data are the subject of Chapter 3. Fortunately, the Bering Sea herring fisheries were an interesting addition to this project. Data for these fisheries are especially interesting when used with other variables in time series analysis of the type that was originally proposed in this project for pollock and cod. Results from this analysis for hypotheses related to climate change are contained in Chapter 3.

The primary deliverable from this project occurred under this objective which was an extensive set of input files delivered to FEAST that were derived from a processed dataset of recorded and observed catches from 1970-2009 for Bering Sea pollock, cod, salmon, herring, and other species, stratified by fleets with gear type and vessel class, converted to latitude and longitude from Alaska Department of Fish and Game (ADFG) codes, and downscaled to the FEAST-ROMS spatial grid (Figure 1).

Figure 1: ADFG Groundfish Stat6 areas and ROMS grid.
Chapter 1. Economic Model

The original BSIERP proposal for this project was to model fleet dynamics. However, computing time needed to solve dynamic economic models was not available. Moreover, the joining of the vertically-integrated Forage/Euphausiid Abundance in Space and Time (FEAST) ecosystem model with the management strategy evaluation (MSE) imposed total allowable catch (TAC) constraints on the economic model. The economic model subject to these constraints was dubbed the fishing allocation model in Nash Equilibrium (FAMINE) and catch in the vertically-integrated model is equal FAMINE fishing effort times FEAST fishable biomass. Therefore, a static model of fleet behavior under TAC constraints is nontrivial and interesting. A working hypothesis for this static model is that the historical allocation of fishing effort was in a narrow sense “good” in that future deviations from the historical allocation will incur an adjustment cost.

1.1 Overview

FAMINE is an optimization model that allocates fishing effort and catch each year. The FAMINE model specified separate fleets that target walleye pollock, and Pacific cod further stratified by i) vessel class (i.e., catcher vessels, catcher processors), and ii) gear type (i.e., trawl, hook-and-line, pot). There was also an ‘other’ category that included arrowtooth and other flatfish.

The spatial allocation of catch by fleet to area is based on the assumption that all players (vessels) play an optimizing (i.e., maximizing or minimizing) strategy so the catches are allocated under the assumption of a Nash Equilibrium (NE). The decision rules are linear and static under the assumption that payoffs are linear-quadratic. Under these conditions, static profit-maximization occurs. Static profit-maximization implies a set of Karush-Kuhn-Tucker (KKT) inequalities. Taken together, KKT conditions form a Linear Complementarity Problem (LCP) and a Nash Equilibrium (each player plays a best-response), and every LCP is equivalent to a Quadratic Program (QP).

1.2 FEAST Fishing Sectors

Fishing sectors in the FEAST model are split into three target species: Pacific cod (COD), walleye pollock (PLCK), and other (OTHR) which includes arrowtooth flounder plus flatfish. In addition, sectors are differentiated by gear type: hook-and-line (HAL) for longline and jig, pot...
gear (POT), and trawl (TWL) which includes pelagic and bottom trawl. Each sector is also divided by vessel class: catcher processor (CP) and catcher vessel (CV). Herring seine and gillnet are also included.

1.3 Implementation

The FAMINE algorithm involves solving a QP for a system with \( m = 1, \ldots, M \) grid cells for each fishing sector \( s = 1, \ldots, S \) and each weekly time interval \( t = 1, \ldots, T \). Let \( x_{st} \) be the vector of effort by grid for sector \( s \) during time step \( t \). Given target (e.g., historical average) values for \( x_{st} \geq 0 \) and a general \( M \times M \) symmetric positive definite weighting matrix \( V \), the solution \( x_{st} \geq 0 \) is an \( M \)-dimensional vector that minimizes a sum-of-squared deviations \( (x_{st} - \bar{x}_{st})'V(x_{st} - \bar{x}_{st}) \).

Every solution to this minimization problem satisfies a linear system of constraints \( A_{st}x_{st} \geq b_{st} \), where \( A_{st} \) is an \( L \times M \) constraint matrix and \( b_{st} \) is an \( L \)-dimensional vector; in particular, this system can represent non-negativity constraints \( x_{st} \geq 0 \).

Each fishing sector disaggregates to a triple: \( s \mapsto (i, j, k) \) where \( i \in \{COD, PLCK, OTHR\}, \quad j \in \{HAL, POT, TWL\}, \quad k \in \{CP, CV\} \)\(^1\). However, some of these combinations are null (no catch), i.e., \((PLCK, j, k) : j \in \{HAL, POT\}, k \in \{CP, CV\}\), and \((OTH, POT, CV)\). Therefore, the total number of sectors is \( S = 13 \). Total catch in each fishing sector must satisfy an annual TAC for Pacific cod and EBS Pollock, i.e. \( \sum_{ijkl} c_{ijkl} \leq c_0 \) and \( \sum_{ijkl} p_{ijkl} \leq p_0 \). Scalars \( r_{ijkl} = c_{ijkl} / c_i \) and \( r_{ijkl}^* = p_{ijkl} / p_0 \) are taken as given and used to allocate an annual TAC to sector \( s \) and week \( t \). Two pollock sectors base effort \( \bar{x}_{st} \) on pollock catch \( \bar{y}_{1st} \) for that sector divided (component by component) by its fishable biomass of pollock \( \bar{z}_{1st} \). In addition, twelve sectors are represented by Pacific cod and other, and these sectors base effort \( \bar{x}_{st} \) on cod catch \( \bar{y}_{2st} \) for that sector divided (component by component) by its fishable biomass of cod \( \bar{z}_{2st} \).

---

\(^1\) PLCK=pollock; COD=Pacific cod; OTHER=other species; HAL=hook and line; POT=pot gear; CP = Catcher processors; CV = Catcher vessels.
The 13 QPs can be computed sequentially or simultaneously. Without loss of generality, these can be represented in order $s=1,\ldots,13$. The objective function can be expanded to get a standard representation for the QP:

$$\mathbf{x} - \mathbf{x}_0 \cdot \mathbf{V} (\mathbf{x} - \mathbf{x}_0) = \mathbf{x}_0' \mathbf{V} \mathbf{x}_0 - (2 \mathbf{V} \mathbf{x}_0)' \mathbf{x} + \mathbf{x}' \mathbf{V} \mathbf{x}$$

The first term on the right-hand side of the equation above is a scalar constant that is superfluous in the QP minimization and is dropped from the problem. The remaining terms in the objective function are multiplied by $1/2$ which also does not affect the QP minimization. Suppressing subscripts for fishing sector and time to simplify notation and letting $\mathbf{g} = -\mathbf{V} \mathbf{x}_0$ and $\mathbf{H} = \mathbf{V}$ produces a standard representation of a QP objective:

$$f(\mathbf{x}) = \mathbf{g}' \mathbf{x} + \frac{1}{2} \mathbf{x}' \mathbf{H} \mathbf{x}.$$

Constraints on catch of pollock ($n=1$) and Pacific cod ($n=2$) must be implemented for each QP $s=1,\ldots,13$ and $t=1,\ldots,52$ to satisfy each TAC. A fishing sector $s$ in week $t$ is inactive if $c_{st} = 0$ or $p_{st} = 0$ and the trivial solution $\mathbf{x}_{st} = 0$ is obtained. Otherwise, two active constraints are implemented. These constraints depend on catch $y_{mnst}$ in each spatial cell $m=1,\ldots,M$ for each type of catch $n=1,2$. Each $y_{mnst}$ depends on the available biomass $z_{mnt} > 0$. An exact catch identity is assumed to hold in each cell for each type of catch, $y_{mnst} = x_{mnt} z_{mnt}$, where $s \mapsto (i,j,k)$ such that $i=$pollock if $n=1$, and $i=$Pacific cod if $n=2$. This identity requires multiplying the non-target cod $z_{m2t}$ in the pollock sectors by the ratio $\frac{z_{m1t} y_{m2t}}{y_{m1t} z_{m2t}}$ and non-target pollock $z_{m1t}$ in the cod sectors by $\frac{z_{m2t} y_{m1t}}{y_{m2t} z_{m1t}}$. To express this identity in matrix notation, let

$$\mathbf{z}_{st} = (z_{t1st}, \ldots, z_{t52st})'$$

and form $\mathbf{y}_{nst} = \mathbf{z}_{nst} \mathbf{x}_{st}$. The catch constraints on sector $s$ in week $t$ are $y_{1st} \leq c_{st}$ and $y_{2st} \leq p_{st}$. Rewriting these with decision variables $\mathbf{x}_{st} \geq 0$ yields:

$$z_{1t}' \mathbf{x}_{st} \leq c_{st}$$

$$z_{2t}' \mathbf{x}_{st} \leq p_{st}$$
These constraints hold for all \(s\) and \(t\), i.e., \(L=2\) (excluding non-negativity constraints) such that a pair is included in each QP that is solved. Hence, the constraint vector is \(b_{st} = (-c_{st}, -p_{st})'\) and the \(L \times M\) constraint matrix for sector \(s\) in week \(t\) is \(A_{st} = (-Z'_{st}, -Z''_{st})'\) to form \(A_{st} x_{st} \geq b_{st}\).

In particular, \(A_{st}\) is the same for each sector here but this condition is easily relaxed with sector specific selectivity coefficients for each \(n = 1, 2\).

The approach is implemented in FAMINE by let \(V = I\), the \(M \times M\) identity matrix, such that \(H_{st} = I\). The hindcast data for Pacific cod and EBS pollock \(\{\bar{y}_{1st}, \bar{z}_{1st}, \bar{y}_{2st}, \bar{z}_{2st}\}_{s=1,...,13}\) are then used to compute \(\{\bar{x}_{st}\}_{s=1,...,13}\). Then, \(g_{st} = -\bar{x}_{st}\) in the QP for each sector \(s\) and week \(t\). FEAST produces \(\{z_{st}\}_{s=1,2}\) and FAMINE solves for \(\{x_{st}, y_{st}\}_{s=1,...,13}\) for each \(t=1,...,52\).

A stand-alone F90 version of FAMINE that calls QP solvers IMSL/QPROG or SOL/SQOPT compiles and runs in Windows or Linux with Intel Fortran 12.1. This version of FAMINE compiles with FEAST_WRAP_EXEC.F90. The coupled FEAST-FAMINE program was not run.

**1.4 Benchmark Consistency Test**

Assume that catch and stock biomass for pollock and cod from FEAST hindcast take the form

\[
\{\bar{y}_{1st}, \bar{z}_{1st}, \bar{y}_{2st}, \bar{z}_{2st}\}_{s=1,...,T} \Rightarrow \{\bar{x}_{st}\}_{s=1,...,S}.
\]

Since the FEAST hindcast was not available, random numbers \(\mu, v \sim \text{uniform}(0,1)\) were used such that \(\bar{Z}_{mnt} = 1/\mu\) and \(\bar{Y}_{mnt} = v \bar{Z}_{mnt} \Rightarrow \{\bar{x}_{st}\}_{s=1,...,T}\).

The FAMINE benchmark consistency test: Given \(\{\bar{x}_{st}, \bar{z}_{1st}, \bar{z}_{2st}\}_{s=1,...,T}\) and caps \(\{\bar{c}_{st}, \bar{p}_{st}\}_{s=1,...,T}\)

1. Solve effort allocation problems for \(0 \leq x_{st} \leq 1\)
2. Check these solutions to confirm $x_{st} = \bar{x}_n$ and $y_{nst} = \bar{y}_{nst}$.

### 1.5 CPU Times

A random one-sector version of FAMINE with $M = 6000$ cells that called routine

- QPROG solved in 4-5 minutes on i7 @3.33 GHz
- SQOPT solved in 10-11 minutes on i7 @3.33 GHz
- QPROG solved in 10-12 minutes on cluster @2.2 GHz

Using FAMINE with QPROG or SQOPT on the FEAST-ROMS grid is impractical for MSE. However, CPU time is quadratic in the number $M$ of blocks/cells. Therefore, FAMINE was reformulated to work at the much smaller dimension of Stat6 areas. A random one-sector version of FAMINE with $M = 220$ that called SQOPT solved in 0.21 second. For all years and sectors, the Stat6 version of FAMINE would add about 9.1 minutes to a FEAST run on the current cluster with parallelization over the sectors, or 2.1 hours without parallelization. New sparse QP solvers may be much faster.

### 1.6 Random Example

A simple numerical example based on random numbers, two sectors, and $M = 10$ blocks was run with FAMINE to analyze the effort response to zero biomass in one of the blocks. In this example, FAMINE passed the benchmark consistency test which means that if fishable biomass in each block does not change then fishing effort for each sector also remains the same. The numerical experiment considers a change in fishable biomass for one of the blocks (i.e., block 1 without loss of generality) from a positive number down to zero. Results for this example are presented in Figure 2. In response, both sectors stop fishing in block 1. Sector 1 has a complicated response that increases effort in six blocks, with maximum exploitation in five of these, and decreases effort in three, and essentially stops fishing in one of these. In contrast, sector 2 effort in each block does not appear to change much because the benchmark catch for sector 2 is relatively low in block 1 and target abundance is relatively high in block 2. Therefore, sector 2 is able to make up the loss of catch in block 1 with a small increase in effort in block 2.
Figure 2: FAMINE effort response in random example with two sectors and ten blocks. Charts show the effort response in each sector to zero fishable biomass in block 1 compared to benchmark effort.
1.7 Discussion

This chapter documented the structure of FAMINE, the economic component of the BSIERP vertically-integrated ecosystem model. For integration with FEAST and ROMS, FAMINE was coded in the Fortran90 programming language. Fishing sectors were specified in FEAST and FAMINE that target walleye pollock, Pacific cod, and other groundfish stocks, further stratified by i) vessel class (i.e., catcher vessels, catcher processors), and ii) gear type (i.e., trawl, hook-and-line, pot). To handle the large number of grid cells in FEAST, FAMINE was structured as a series of large-scale quadratic programs that solve a static optimization problem. In particular, FAMINE assumes vessels minimize costs of catching a given amount of fish in a particular time-period subject to spatial distribution of stocks from FEAST. The spatial distribution of abundance from FEAST times the spatial effort allocation from FAMINE determines the spatial distribution of catch and bycatch (i.e., total removals from fishing). Hence, FEAST and FAMINE are linked by an authentic two-way “hard” coupling to form a truly integrated economic-ecological model of pollock and cod. The hard coupling of FEAST-FAMINE means the two models compile and run together in contrast to “soft” coupling where models are typically coded in different programming languages, compiled separately, and are run end-to-end with one model using numerical output from the other which involves computationally expensive read and write operations to intermediate files.

In addition, FAMINE was tested with different quadratic program solvers to evaluate computing times on different platforms. A standalone solver SQOPT was selected for FAMINE. While faster solvers were available, the advantage of SQOPT is a perpetual license and the native Fortran code means that the solver compiles from scratch with the FEAST-FAMINE code which maximizes portability. For example, time trials with FAMINE were initially conducted using Intel Fortran Compiler (i.e., ifort) for windows operating system and this same code was moved to the cluster for time trials and compiled with ifort for linux operating system. The time trials demonstrated that FAMINE operating on the FEAST-ROMS grid would be computationally too expensive. However FAMINE operating on the ADFG stat6 grid would add an insignificant amount of computing time to a proposed 50-year run of FEAST under a climate change scenario.
Chapter 2. Catch Data

Overall, the main contribution in this project to BSIERP was assembling and processing historical catch data for input to a Forage/Euphausiid Abundance in Space and Time (FEAST) model hindcast. This chapter documents catch data for groundfish fisheries in the Bering Sea. These data include directed catch of groundfish and prohibited species catch of herring and salmon. In addition, catch data for directed herring fisheries in the Bering Sea and Aleutian Islands (BSAI) were prepared for the forage fish component of FEAST and these data are documented in Chapter 3. For years 1991 and later, groundfish catch data were derived from the Alaska Fisheries Information Network (AKFIN), augmented with data from the North Pacific Groundfish and Halibut Observer Program for spatial detail in the case of catcher-processors, and prorated such that area totals match catch data from the NMFS Alaska Regional Office. Catch of Pacific herring and chum salmon in the BSAI groundfish fisheries were taken from Prohibited Species Catch tables managed by the NMFS Alaska Regional Office. Catch data for the period 1970-1990 are a combination of foreign-reported data and estimates from at-sea observers (both foreign vessels and domestic). All of these data sources were downscaled to the FEAST spatial grid for input to the FEAST model hindcast.

2.1 Spatial Resolution and Standardization

Catch data were available by Alaska Department of Fish and Game (ADFG) statistical reporting units (Stat6) for the eastern Bering Sea. Standard Stat6 units are 0.5 degree latitude by 1.0 degree longitude in area when no land masses intersect. Around land masses (e.g., Pribilof Islands, Alaskan Peninsula), Stat6s are irregularly shaped to conform to the land mass boundary and often much smaller than standard Stat6. To simplify the spatial distribution of catches, a uniform grid of standard size Stat6 area that cover the gridded area of the Forage/Euphausiid Abundance in Space and Time-Regional Ocean Modeling System (FEAST-ROMS). Pre-existing standard Stat6 were not affected but irregular Stat6 were assigned to the overlapping Stat6 from the uniform grid. The final set of Stat6 areas are superimposed on the FEAST-ROMS grid in Figure 3.

2.2 Catch Data Downscaling to FEAST Grid

After the creation of the uniform grid of Stat6 described above, individual FEAST cells were assigned membership to a Stat6 based on degree of overlap. Weekly Stat6 catch data, described below, were then evenly distributed to the FEAST cells within each Stat6. Final catch data for
input to the FEAST model (where further processing occurred) were in tons per day with the weekly catch per FEAST cell divided by the number of days per week (typically seven except for week 52). The number of FEAST cells per Stat6 ranged from 1 to 29, with a mean of 20.

2.3 Vessel Classes

Catch data were also organized by vessel class, a combination of sector, gear, and target species. The two sectors were catcher vessel or catcher processor; gear categories were trawl, longline / hook and line, pot, and a designation “all” for all other gear; target species were Pacific cod, walleye pollock, arrowtooth flounder, and “other” for hauls or trips where the target species was unknown. Target species were determined by the majority of fish by biomass from a haul or a trip. Catches of chum and herring were assigned only to catcher processors using trawl gear and targeting pollock.

2.4 Walleye pollock, Pacific Cod, Arrowtooth Flounder, 1991-2009

2.4.1 Catcher vessels (CV)

CV data preparation for these years and species utilized fish ticket data and prorated catch data from the Catch Accounting System (CAS). The fish ticket data were organized by vessel (anonymous), vessel class, start and end dates of trip, Stat6 (a single Stat6 for each trip), and catch in tons for the three focal species. To assign a single date for each trip, the mid-points of the start and end dates were used. These mid-point dates were then used to assign the trip to a given week (1-52). The weekly catch total for each vessel class, species, and Stat6 combination were tabulated; then the proportion of annual catch from the fish ticket data for each species, week, vessel class, and Stat6 combination were calculated based on weekly catch for a given combination and the total annual catch for the same combination. The weekly proportions from the fish ticket data were then multiplied by the annual prorated CAS catch data for each species, Stat6, vessel class combination for a final weekly catch. These weekly catches were then downscaled to the feast grid cells.

2.4.1.1 Terry Hiatt’s Scripts to Produce BSIERP data

1) get_fit_bsierp_cvs.sql – creates a table in my schema in the AKFIN database. The table holds a list of ADFG numbers of vessels that landed arrowtooth, Pacific cod or pollock on groundfish permits over the time period 1991-2009.
2) *get_cv_ft_new.sql* – retrieves fish-ticket data on landings made on groundfish permits by the list of vessels assembled by the above script.

3) *get_cp_fleetyyy.sps* – makes a list of catcher/processor ADFG numbers from catch-accounting system (CAS) data (these will be used to filter the CV data).

4) *format_cv_ft2009_newer.sps* – processes fish-ticket data retrieved by #2 above. Filters out data for the C/Ps identified by #3 above; classifies vessels into species-gear categories based on the preponderance of catch; divides the data for each vessel into ‘trips’ (distinct, non-overlapping time periods); counts the number of days-at-sea for each vessel/trip; prorates total landings of arrowtooth, pcod and pollock (from CAS data) to each vessel based on the percentages of catch per vessel in fish-ticket data.

This script produces two output files:

- **prorated_cas_cv_catch2009.sav** (translated to .csv)
- **cv_ft_trips2009.sav** (.csv)

2.4.2 Catcher processors (CP)

CP data preparation followed the same general pattern as for CV catch data above. Observer data were organized by vessel class, haul date, Stat6, and species. Weekly catches and the proportion of weekly catches by vessel class, Stat6, and species were calculated. Total weekly catch by vessel class, Stat6, and species were calculated by multiplying the weekly proportions from the observer data by the total prorated annual catch for a given combination from the CAS.

2.4.2.1 Terry Hiatt’s Scripts to Produce BSIERP data

1) *get_blend_yyyy.sql* – retrieves BSAI C/P landings data from blend/CAS data for each year.

2) *get_obs_cpyyyy.sql* – retrieves C/P observer data for each year.

3) *get_cp_fleet2009new.sps* – uses data retrieved by #1 above to assign species classes to C/Ps.

4) *format_obs_cp2009new.sps* – processes data from #2 above. Creates pseudo stat6 code based on latitude/longitude of haul; filters out C/Ps that didn’t appear in CAS data from #1; adds gear type to species classes created in #3; prorates total landings from CAS data to each vessel based on the vessel’s percentage of the catch in observer data.
This script produces two output files:

- prorated_cas_catch2009new.sav (translated to .csv)
- cp_obs_data2009new.sav (.csv)


These data represent a combination of foreign-reported data and estimates from at-sea observers (both foreign vessels and domestic). Since detailed temporal and spatially resolved data were unavailable for this period, the data were scaled to have the same weekly, spatial (by Stat6 area), and sector specific catch for these species. The data were downscaled to the mean values from the observed period to provide consistent resolution when the only data available were on a coarse scale (e.g., monthly instead of weekly, etc). The annual totals for all values were the same as those from foreign-reported datasets. Total catch data for these species and years were available by week (1-52), Stat6, and vessel class (a combination of sector, target, and gear fields). These weekly catch totals were then downscaled to FEAST cells.

### 2.6 Comparison of FEAST Catch Totals with SAFE Values

Total catch values by species prepared for the FEAST model (the sum of CV and CP values) were compared with catch values reported in SAFE documents for pollock, cod, and arrowtooth flounder for the years 1991-2009 (Figure 4). For pollock, annual percentage differences of total FEAST catch values from SAFE values ranged from <0.01 to 7.8% with a mean difference of 1.1%; for cod, differences ranged from -2.2% to 7.2% with a mean of 2.3%; for arrowtooth, differences ranged from -31.5% to 23.4% with a mean of 3.5%.

The source of discrepancies between the SAFE data and the calculated FEAST data is not clear. In data processing, raw data from the Blend/Catch Accounting System (Blend/CAS) were assigned to the stat6 grid used in FEAST. The discrepancies appear to arise from the outer shelf area and the Aleutian Islands area, where some catch on the outer shelf was not included in the FEAST catch, and some catch along the Aleutian Islands may have been included or excluded from either the SAFE or FEAST catches. In any case, the downscaled FEAST totals match the raw Blend/CAS data for the stat6 grid used in FEAST. The stock assessment reports for arrowtooth flounder do not have maps of arrowtooth catches, but based on maps of pollock...
catches, it appears that substantial amount of arrowtooth catch occurs with pollock catch on the outer shelf, right on the boundary of the FEAST catch grid.

2.7 Discussion

To support a FEAST model hindcast, this chapter documents a comprehensive effort to assemble and prepare a historical dataset of catches in the Bering Sea groundfish fisheries from 1970-2009 from all major sources (e.g., AKFIN, Alaska Regional Office, North Pacific Groundfish and Halibut Observer Program). This dataset was prorated to match official area totals from NMFS Alaska Regional Office and then downscaled to the FEAST grid for input to the hindcast. Annual catches of pollock and cod from this dataset match annual catches from the Stock Assessment and Fishery Evaluation (SAFE) reports fairly well, though there are significant discrepancies in some years. The match of FEAST catch data to the SAFE reports is more of a problem for Arrowtooth flounder which in early years could be due to problems identifying and reporting catch of Kamchatka flounder but the largest discrepancies occurred in the last two years of the dataset (i.e., 2008-09). Catch data for directed BSAI herring fisheries is the final piece needed to support a FEAST model hindcast and these data are reported in the next chapter.
Figure 3: Stat6 areas used and the FEAST-ROMS grid.
Figure 4: 1991 – 2009 time series of annual catches by species for SAFE values (grey bars) and total values calculated for FEAST input catch data (lines with circles).
Chapter 3. Forage Fish: Application to Pacific Herring

3.1 Background

The Bering Sea hosts economically-important fisheries and is expected to be sensitive to global climate change. Pacific herring (*Clupea pallasii*) provides a key link between primary production and upper-level piscivores in the Bering Sea. It is highly productive and is recognized as a key forage fish for species of commercial interest, such as salmon and halibut, and species of conservation concern, such as the Steller Sea Lion (*Eumetopias jubatus*). It is also the subject of a long-standing commercial fishery.

Pacific herring is distributed along the Pacific coast of North America from Baja California to the Bering Sea. Bering Sea herring are genetically distinct from Gulf of Alaska herring (Grant and Utter 1984). Bering Sea herring are larger and longer-lived and may also exhibit lower size-specific fecundity (Hay 1985). As with other clupeid species, the biomass of Pacific herring is highly variable. Kawasaki (1991) showed that herring abundance in the Atlantic and the Pacific fluctuated in synchrony, suggesting that large-scale atmospheric change may be a significant driver of recruitment variability. Decreases in herring and other forage fish on the southeastern Bering Sea shelf have been associated with increases in pollock, Pacific cod, and arrowtooth flounder following an apparent regime shift in the late 1970s (Hunt et al. 2002). Rose et al. (2008) examined weight-at-age, recruitment and spawning stock biomass for Pacific herring under four documented climate regimes. Under warm regimes, recruitment was relatively low, biomass low, and growth slow (see also Beamish et al. 2004; MacCall et al. 2005). Physical forcing, in particular air and sea temperature, appears to be a key driver of both recruitment and growth rates. Williams and Quinn (2000) explored environmentally-dependent Ricker spawner-recruit models for Pacific herring. Models with air and sea surface temperature lagged to the year of spawning generally produced the best forecasts. (Bering Sea herring usually recruit into the fishery at age five.) Herring abundance also depends on year class survival. Livingston (1993) found that total removals of herring by natural predators in the eastern Bering Sea were not large relative to exploitable stock size, and that the fishery was the primary remover of herring biomass. The apparent responsiveness to regime shifts and the effects of physical forcing raises the question of how Pacific herring stocks will respond to global climate change, and the implications for dependent species and fisheries.
The Bering Sea herring fishery has been subject to substantial variation in demand patterns, including demand for bait in crab fisheries as well as variability in herring biomass (Woodby et al. 2005). The earliest indigenous inhabitants of Alaska depended on herring for food, and herring remains a key component of the subsistence in some regions of Alaska (Pete 1991). European settlers preserved herring in salt, with pickled herring production peaking after World War I. A bait fishery for herring began in Alaska around 1900, and has remained relatively stable despite large fluctuations in other commercial fisheries for herring. Demand for herring as bait greatly increased with the development of extensive crab fisheries in the Gulf of Alaska. From the 1920s, herring fisheries became increasingly oriented towards production of fish oil and fish meal, but this reduction industry declined in the face of competition from the Peruvian anchoveta fishery which developed in the late 1950s and early 1960s. The last herring reduction plant in Alaska was closed in 1966. A large foreign (Japanese and Russian) trawl fishery developed for herring in the Bering Sea in the 1960s and 1970s, but these fisheries were eliminated following the implementation of the Magnuson Fishery Conservation and Management Act in 1976. The domestic herring roe fishery developed after 1965. This fishery is mainly oriented towards export markets in Japan. Alaska is a source of herring exports from the United States to Japan. Japanese demand increased in the early 1970s, following the decline of local herring stocks. In recent years, herring roe markets have begun to decline as a result of reduced demand in Japan (Carlson 2005).

Alaska herring fisheries are managed in terms of geographically distinct spawning aggregations defined by regulation (regulatory stocks). Given the ecological importance of Pacific herring, the fishery is conservatively managed with a target exploitation rate of 20%. Fisheries are closed if stock biomass falls below the threshold level considered necessary to guarantee sustained yield from the stock (usually 25% of the long-term average of unfished biomass). Lower exploitation rates are usually applied when stocks approach the limit reference point. In most areas, the fishery is limited entry and managed by individual quota.

The largest herring fishery in Alaska is the Togiak fishery in Bristol Bay. The threshold biomass threshold is set at 35,000 short tons. Before opening the sac roe fishery, approximately 1,500 short tons are set aside for the Togiak District herring spawn-on-kelp fishery, and 7% of the remaining available harvest (given the 20% maximum exploitation rate) is allocated to the Dutch Harbor food and bait fishery. After the spawn-on-kelp harvest and the Dutch Harbor food and
bait fishery have been subtracted, the remaining harvestable surplus is allocated to the sac roe fishery. The sac roe fishery comprises a purse seine and gillnet fleet. From 1988 through 2000, 25% of the remaining harvestable surplus was allocated to the gillnet fleet and 75% to the purse seine fleet. Since then, allocations have been adjusted to 30% and 70% respectively. Openings and closings are also set by regulation. The season may be closed before the guideline harvest is landed if roe percentages start to decrease or smaller size fish start being harvested.

Herring spawn close inshore in subtidal and intertidal areas, often on submerged vegetation such as kelp. Adults congregate in deeper areas close to spawning sites several weeks or months prior to spawning. Bering Sea herring spawn from May through mid-July. The timing of spawning by different stocks is sequential, with the most northern stocks spawning last. Sac roe fisheries target these spawning aggregations. Fishery timing is critical as roe content is highest immediately prior to spawning (Barnhart 1988).

3.2 Herring Management Areas in the Bering Sea

Herring fisheries occur within 3nm of the coast and are managed by the State of Alaska. Herring management in the Bering Sea is divided into four areas: Aleutian Islands, Kuskokwim, Togiak (Bristol Bay), and Norton Sound. The location of catch is recorded by the Alaska Department of Fish and Game (ADFG) based on a system of 5-digit herring statistical areas that are similar to, but distinct from, the 5-digit areas used for salmon, and unrelated to the Stat6 areas used for groundfish. A first step for assembling spatial time series of herring catch was to identify and locate all unique 5-digit herring codes recorded in ADFG fish tickets from 1977 onwards. This important first step was conducted by contacting ADFG staff in field offices of the Commercial Fisheries Division for each herring management area: Trent Hartill was the ADFG contact for Aleutian Islands (Port Moller), Doug Bue for Kuskokwim, Tim Sands for Togiak, and Joshua Mumm for Norton Sound. They kindly provided local area maps (see Figures 5-9) and other supporting information. For example, Joshua Mumm wrote that stat area 333-70 has been extended further south from what the map shows, and the southern boundary now extends westward from Pt. Romanof. The key step in this section was to relate the four herring management areas to the Forage/Euphausiid Abundance in Space and Time-Regional Ocean Modeling System (FEAST-ROMS) grid (Figure 10).
### 3.3 Catch Data 1970-2009

Herring catch data for 1977 and 1979-2009 were taken from ADFG fish tickets and assigned to two fisheries (seine and gillnet), by week. There were no data in the fish tickets for the Bering Sea for 1976 or 1978 and interpolated values were used to assign missing values. A similar procedure was used to assign values to herring catches in 1970-1975. Figure 10 was used to map catch by seine and gillnet fisheries for each statistical area in the fish tickets to the FEAST-ROMS grid. A set of files (one for each year) was constructed containing the gridded herring catch for each fishery in each week of the year it was active for years 1970-2009. Points on the FEAST-ROMS grid and herring statistical areas are displayed in Figure 11. This figure covers all the Bering Sea statistical areas with recorded catch in the period 1991-2008. However, the exact location of several statistical areas with recorded catch in 1976-1990 is unknown. Our best guess is that these areas were merged or discontinued during this period and no further attempt was made to locate these. Catches with unknown location were a very small fraction of the total catch.

Shapefiles were available for some, but not all, of the ADFG 5-digit statistical areas for herring. For statistical areas without shapefiles, the boundaries of statistical areas were transferred from paper maps of Bering Sea management plan commercial herring districts to GIS. Several of these maps did not include seaward boundaries (i.e. districts are defined by coastal landmarks only). For consistency across all statistical areas, all herring catches were assumed to fall within the 3 nautical mile limit. (This limit corresponds with the seaward boundaries of some, but not all, pre-existing shapefiles.)

Only statistical areas in the Bering Sea were included in the analysis. In some cases, statistical areas were redefined during 1991-2009. Catches from ‘old’ statistical areas were assigned to the current statistical area where information on changes was available. However, it was not possible to trace all statistical areas prior to 1990. Catches from these areas were therefore excluded from input to FEAST. Together, these landings represented less than 0.01% of the landings in the dataset. Where there were no valid cells on the FEAST-ROMS grid in a statistical area (e.g. for statistical areas representing interior bays), the catch for that area was assigned to the nearest statistical area. (See Table 1 for all revisions to the statistical areas in the fish ticket data.)
Shapefiles and boundaries were then overlaid on the ROMS rho grid. The number of rho points in each statistical area was counted and the catch for each recorded trip then divided equally between the rho points in the statistical area.

All herring catches in 5-digit statistical areas were treated as targeted catch even if labeled as ‘bycatch’ in the fish tickets. (For example, all the herring catches during the 1981-84 period are listed as bycatch, including herring caught in purse seines in herring statistical areas in Togiak.).

3.4 Catch, Ex-vessel Revenues, and Effort

Fish tickets record ex-vessel revenues for catch. A weighted average of these (with weights determined by catch-shares, which is equivalent to total revenues divided by total catch) is the standard ex-vessel price. Figure 12 shows Bering Sea herring catch and ex-vessel revenues for 1991-2008, and Figure 13 plots ex-vessel revenues in this period for each management area. Likewise, Figure 14 shows total catch and ex-vessel price for the Bering Sea, and Figure 15 plots ex-vessel price for each area. Fishing effort as number of seadays can be estimated from fish tickets. Figure 16 shows Bering Sea herring catch and fishing effort for 1991-2012, Figure 17 shows effort for each area, and Figure 18 shows catch per unit effort for each area.

An analysis of ex-vessel prices (i.e., revenue per ton) by region and gear was conducted to explore the scope for aggregating across gears. This analysis identified at least three different products, with the Peninsula primarily a bait fishery, Kuskokwim primarily sac roe, and Togiak and Norton Sound combining sac roe and spawn-on-kelp fisheries. Kuskokwim is mainly a herring gillnet fishery, with records for all years from 1991-2006 (Figure 19). Drift gillnet, set gillnet, and purse seine also contribute data in four years. Prices range quite widely in any given year, with prices for the drift gillnet, set gillnet, and purse seine generally falling within the range of prices for the herring gillnet.

The Peninsula and Aleutians seem to be uncorrelated with other areas, at least after 1994 (Figure 20). The purse seine fishery covers the entire period, with herring gillnet since 2001. In both fisheries, there seems to be a set price each year (i.e. the black and blue points in the plot each represent multiple trips) – in some years, there are two different prices in the purse seine fishery, but rarely more. The price in the herring gillnet fishery was constant over the last three years of the series. The single point near $1,000 in 1996 actually represents 6 separate trips, and could reflect sales of sac roe rather than bait.
For the other two regions, prices seem to fall into two distinct categories – purse seine, various
gillnet and beach seine; versus pound, handpicked, and other. It seems likely that this reflects
two completely different products – whole fish with sac roe in the former, and spawn-on-kelp in
the latter. In Togiak, purse seine and herring gillnet fisheries cover the entire period, with several
years of handpicked and one of drift gillnet (Figure 21). Prices in the purse seine, herring gillnet
and drift gillnet fisheries are closely matched, but prices in the handpicked fishery are much
higher, presumably because this is producing a different product although prices for the two
products may well be correlated. Norton Sound is mainly herring gillnet and beach seine, with
set gillnet in one year, and a few records for pound, handpicked, and other (Figure 22). As in
Togiak, prices in the gillnet and seine fisheries are within the same range. Prices in Norton
Sound seem to have been following a slightly different trajectory from those in Togiak and
for the pound fishery are similar to those for the handpicked fishery in Togiak, while those in the
handpicked and ‘other’ fisheries stand out. (The two handpicked records each represent a single
trip, whereas the ‘other’ record represents three separate trips.) However, when compared with
prices in the handpicked, pound, and ‘other’ fisheries across the whole dataset (i.e. including
GoA), they fall well within the price range for these fisheries (Figure 23).

3.5 Time Series Analysis of the Togiak sac roe fishery

3.5.1 Data

We used time series analyses, including vector autoregression, on fish ticket data for the period
1991 to 2008 to explore the dynamics of price, fishing effort and landings in the Togiak sac roe
fishery, and their relationship with biomass estimates and sea-surface temperature (SST). The
goal of the analysis was to investigate whether the fishery is constrained primarily by demand- or
supply-side factors, in particular by stock biomass as indicated by harvest guidelines. We also
investigated whether there has been a structural change in fishery dynamics, associated with
development of a cooperative seine fishery.

Each year, prior to the start of the herring fishery, ADFG makes a preseason forecast based on an
age-structured analysis using catch and age composition data from previous fishing seasons. In
most years, this preseason forecast is supplemented by total run biomass estimates based on
aerial surveys. These biomass estimates are the basis for harvest guidelines for the purse seine
and gillnet fisheries derived by applying the total exploitation rate and allocation rules outlined above. However, in some years, poor weather conditions or other logistical constraints impede aerial surveys, and harvest guidelines are set based on the preseason forecast. Here, we use harvest guidelines for the purse seine and gillnet fisheries as an indicator of stock biomass throughout, as this is the most relevant of the consistent indices available.

The data on prices, fishing effort, and landings are derived from fish tickets completed for individual fishing trips in the Bering Sea from 1991 to 2008. For each trip, the area where fishing occurred, the amount of herring landed, the total revenue, the gear (e.g. purse seine, gillnet), and a unique vessel code is reported. We extracted the data for the Togiak fisheries district. For each year, we calculated the total catch by summing the catch over the year, and the total revenue by summing the revenue over the year. We then calculated the average price for the year. We then converted all prices to 2008 US dollars, based on the U.S. producer price index (UPPI).

Data on mean SST from January to April at Mooring 2 in the Bering Sea and mean May SST for the southeastern Bering Sea, together with anomalies relative to the 1961-2000 mean, were extracted from the Bering Climate time series http://www.beringclimate.noaa.gov/bering_status_overview.html. From these data, we constructed time series for real ex-vessel price, fleet size, landings, and harvest guidelines for the Togiak seine and gillnet sac roe fisheries, as well as mean May SST and M2 SST for 1991 to 2008 (Figure 24). We tested the combined price, fleet size, and catch time series for stationarity using the Augmented Dickey-Fuller Unit Root test. Results indicated that the first two time series were non-stationary. We therefore transformed all the time series to first differences and tested again for non-stationarity. Results indicated that all three first-differenced time series were stationary. We therefore based all our analyses on first differences (Figure 25).

3.5.2. Regression equations

The first-difference operator is denoted by the delta symbol Δ. For each first-differenced time series, we explored four main structural frameworks:

• seine and gillnet fisheries pooled, no structural break;
• seine and gillnet fisheries distinct, no structural break;
• seine and gillnet fisheries pooled, structural break;
seine and gillnet fisheries distinct, structural break

For the structural break models, we examined all possible structural breaks. For the price time series, we compared the following models across structural frameworks using AICc.

\[ \Delta \text{pricet} \sim \varepsilon \] (P1)
\[ \Delta \text{pricet} \sim \mu + \varepsilon \] (P2)
\[ \Delta \text{pricet} \sim \Delta \text{fleetsizet-1} + \varepsilon \] (P3)
\[ \Delta \text{pricet} \sim \Delta \text{landingst-1} + \varepsilon \] (P4)
\[ \Delta \text{pricet} \sim \Delta \text{guidelinet} + \varepsilon \] (P5)
\[ \Delta \text{pricet} \sim \Delta \text{MaySSTt} + \varepsilon \] (P6)
\[ \Delta \text{pricet} \sim \Delta \text{JanAprSSTt} + \varepsilon \] (P7)

For the time series on fleet size, we compared the following models across structural frameworks using AICc:

\[ \Delta \text{fleetsizet} \sim \varepsilon \] (N1)
\[ \Delta \text{fleetsizet} \sim \mu + \varepsilon \] (N2)
\[ \Delta \text{fleetsizet} \sim \Delta \text{pricet} + \varepsilon \] (N3)
\[ \Delta \text{fleetsizet} \sim \Delta \text{pricet-1} + \varepsilon \] (N4)
\[ \Delta \text{fleetsizet} \sim \Delta \text{landingst-1} + \varepsilon \] (N5)
\[ \Delta \text{fleetsizet} \sim \Delta \text{guidelinet} + \varepsilon \] (N6)
\[ \Delta \text{fleetsizet} \sim \Delta \text{MaySSTt} + \varepsilon \] (N7)
\[ \Delta \text{fleetsizet} \sim \Delta \text{JanAprSSTt} + \varepsilon \] (N8)

For the landings time series, we compared the following models across structural frameworks using AICc:

\[ \Delta \text{landingst} \sim \varepsilon \] (L1)
\[ \Delta \text{landingst} \sim \mu + \varepsilon \] (L2)
\[ \Delta \text{landingst} \sim \Delta \text{pricet} + \varepsilon \] (L3)
\[ \Delta \text{landingst} \sim \Delta \text{fleetsizet} + \varepsilon \quad (L4) \]
\[ \Delta \text{landingst} \sim \Delta \text{guidelinet} + \varepsilon \quad (L5) \]
\[ \Delta \text{landingst} \sim \Delta \text{MaySSTt} + \varepsilon \quad (L6) \]
\[ \Delta \text{landingst} \sim \Delta \text{JanAprSSTt} + \varepsilon \quad (L7) \]

For all models, the error term, \( \varepsilon \), was assumed to be normally distributed with mean zero and constant variance.

In order to analyze the three time series as an integrated system, we also constructed a vector autoregression (VAR) with price, fleet size, and landings as endogenous variables and the harvest guideline, and May SST and January to April SST as exogenous variables. Data were pooled across the seine and gillnet fisheries.

3.5.3. Results

3.5.3.1 Price time series

For all price models considered (i.e. P1-P7), model comparison using AICc indicated that the data for the seine and gillnet fisheries could be pooled, and that there was a structural break in 2001 or 2002. The model with greatest support from the data was a random walk model with no drift but a structural break in 2002, \( \Delta \text{price}_t \sim \varepsilon \), i.e. model P1.

3.5.3.2 Fleet size time series

For the times series on fleet size, models with the seine and gillnet fisheries pooled or separated received similar levels of support for most models. For all models considered, the data support a structural break, mostly in 2003. The model with lowest AICc sets the break point in 2000, but the same model with the break point in 2002 receives similar levels of support (\( \Delta \text{AICc} = 1.55 \)). The model with greatest support from the data indicates that fleet size is a function of the change in prices in the previous time period, with the two fisheries modeled separately and a structural break in 2000 or 2002, \( \Delta \text{fleetsize}_t \sim \Delta \text{price}_{t-1} + \varepsilon \), i.e model N4.

3.5.3.3 Landings time series

For the landings time series, all models indicate a structural break early in the time series, mostly in 1995. In general, model comparison supports pooling the two fisheries, with the exception of
the model based on fleet size (L4) which is the model that receives greatest support. However, several other models receive similar levels of support:

\[
\Delta \text{landings}_t \sim \Delta \text{MaySST}_t + \epsilon \quad \Delta \text{AICc} = 0.61
\]

\[
\Delta \text{landings}_t \sim \epsilon \quad \Delta \text{AICc} = 1.48
\]

\[
\Delta \text{landings}_t \sim \Delta \text{JanAprSST}_t + \epsilon \quad \Delta \text{AICc} = 1.69
\]

The best model with harvest guidelines as the independent variable - \( \Delta \text{landings}_t \sim \Delta \text{guideline}_t + \epsilon \) (L5) had a delta AICc of 2.67.

3.5.3.4 Vector autorgeression

The VAR results for the price equation indicate that the lagged difference in fleet size and in landings are significant at the 5% level. For the fleet size equation, the lagged difference in price was significant at the 0.1% level and in landings at the 5% level. For the landings equation, the differences in mean May SST was significant at the 1% level and in M2 SST at the 5% level.

A limited number of diagnostic plots were available. Figure 26 shows the Togiak herring VAR model fit, and autocorrelation plots that raise some concern about autocorrelation at lag 2. Figure 27 compares model predictions to observed data. The model does not perform well in 1997 and is influenced by that data point after 1997 but model predictions are closer to observed values towards the end of the time series.

3.5.4. Discussion

Analysis of the price time series indicates that price dynamics are similar across the seine and gillnet fisheries. In the Bering Sea sac roe fisheries, a small number of processing companies play a key role in setting ex-vessel prices, taking conditions in the main consumer market into account. The time series analysis does not indicate that prices are a function of supply in terms of either landings or harvest guidelines. Model comparison indicates a structural break between 2001 and 2002. From 2001 onwards, the Togiak seine fishery has been managed as a processor-controlled cooperative. This appears to have stabilized prices in both the seine and gillnet fisheries. The residual standard error for the first part of the time series (1993-2001) was 427.2 on 18 degrees of freedom, compared to 20.27 on 14 degrees of freedom for the second part (2002-2008).
Analysis of the time series for fleet size indicates some differences between the seine and gillnet fisheries. Again, the data support a structural break. In most models, this break is indicated between 2002 and 2003, after the formation of the cooperative seine fishery, although the model with greatest support indicates that the break may have occurred earlier. As with the price time series, the data show reduced variance in fleet size in both fisheries after the formation of cooperatives in the seine fishery, suggesting that this also served to stabilize fleet size but that the transition occurred over a longer period than for prices. The Togiak sac roe fishery is not a limited entry fishery. According to ADFG, fleet size is influenced by conditions in both herring markets and markets for salmon and other fish. Herring prices paid to permit holders in the prior year and run timing also affect effort. Our results also indicate that price trends in the previous year have a significant effect on fleet size.

The results for the landings are more equivocal. There was considerable variability in landings in the first three years of the time series, such that all models indicated a structural break early in the time series, mostly in 1995. While several models receive similar levels of support from the data, none significantly out-perform the random walk model. The model with greatest support indicates that landings depend on fleet size. Since the formation of the seine cooperative fleet, fleet size may be acting as a proxy for processing capacity and hence demand conditions. In the context of limited markets, the processing companies that control the seine fleet probably manage the composition of these cooperatives to maximize efficiency, thereby influencing the number of participants. However, the formation of these cooperatives does not appear to have triggered a structural change in the landings time series, in contrast to the time series for price and fleet size.

The harvest guideline, which we use as an indicator of stock biomass does not feature in any of the selected models. Since 2001, the processing companies have carefully managed the cooperative seine fleets to ensure that harvest levels maintain processing lines running at full capacity after accounting for the gillnet harvest. Processing capacity therefore acts as a major constraint on daily harvest rates during the season. Since 2001, there have been three years when landings were more than 10% below the harvest guideline in both the seine and gillnet fisheries - 2002, 2004, and 2007. The reasons for these underages vary. In 2002, the fishery was closed before harvest guidelines had been reached due to an excess of recruit-age herring in fishing sets. In 2004, the run was not as strong as expected based on the pre-season forecast and most fish had
spawned out before the harvest guideline was reached. In 2007, processing capacity was the
lowest for the study period, and it was therefore clear from before the season started that the
harvest guideline would not be approached. Our analysis does not indicate that stock biomass is a
major driver for this fishery during the time period covered.
Table 1: ADFG 5-digit statistical areas for herring catch recorded in fish tickets for the Bering Sea with revisions.

Table of Bering Sea 5-digit statistical areas

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Figure 5: The Togiak herring district in Bristol Bay, Alaska.
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Chapter 4. Economic Model Extensions: Catch Shares and Regression Equations

The purpose of this chapter is to briefly review the scope of work that was actually carried out in this project compared to the original objectives in the BSIERP proposal, and describe a statistical model extension of the optimization model in Chapter 1 that meets the original objectives. The time series model for herring in Chapter 3 was closest to the model what was originally proposed for pollock and cod. The calibration method proposed for the original Fishing Allocation Model in Nash Equilibrium (referred to as FAMILN1 in this chapter) in Chapter 1 set parameters to average values based on historical catch and biomass levels in a grid cell, and the optimization was with respect to a static model. This specification of the optimization problem, and shortcut on statistics, was the simplest, and therefore safest, specification in an otherwise complicated and fully constrained Forage/Euphausiid Abundance in Space and Time-Regional Ocean Modeling System (FEAST-ROMS) modeling environment. However, a slight modification to this specification leads to a rich and important class of models in econometrics that are based on dynamic and spatial adjustment costs. Since spatial and temporal autocorrelation are implied, na"ive calculation of averages may not be a good estimation method for FAMILN parameters.

In other research, Dalton has collaborated for many years with the Integrated Assessment Modeling group at the National Center for Atmospheric Research (NCAR). He presented a theoretical version of the FAMILN model a few years ago in a summer meeting at the Mesa Lab. In land-use context, FAMILN links land-supply and industry use of land (e.g., agriculture) in a global economic growth model to spatial biophysical land-surface model. Graduate Student Prasanth Meiyappan and Professor Atul Jain of the Department of Atmospheric Sciences at the University of Illinois Urbana-Champaign were at the NCAR meeting, and subsequently, modified the code for FAMILN to downscale land-use decisions to grid-cell level based on aggregate land-use totals for crop and pasture land. This use of FAMILN in a land-use setting links the iPETS model at NCAR to land-surface models such as CLM and ISAM. In addition, Meiyappan et al. (2014) linked a global downscaling procedure based on FAMILN to a fractional regression model with dynamic and spatial adjustment costs (i.e., spatial and temporal autocorrelation) and logit functions for a set of physical (e.g., soil, climate), and socioeconomic (e.g., population density, GDP) as explanatory variables for each grid-cell. They used this econometric model and optimization-based downscaling procedure to simulate global land-use
patterns over the past two hundred years or so. This hindcast of global land-use patterns combined optimization-based downscaling and fractional regression model with temporal and spatial autocorrelation. These hindcast results compared well with the global datasets for land-use during this period. It is worth reviewing FAMINE1 with this new perspective.

4.1 Original Objectives and a Critique

In the broadest terms, the original plan was to integrate economic and ecological models of pollock and cod by

1) developing multivariate autoregressive models for the temporal spatial distribution of catch and fishing effort using spatial time series data for the fleets/spp. in the FEAST model; and

2) using these models to forecast the spatial distribution of catch and fishing effort for the FEAST model.

To implement TAC constraints for the MSE, FAMINE1 was not an autoregressive model, nor was it based on a particular economic model. Instead, the first version was ad hoc. It was based on an objective of minimizing deviations from an expected harvest rate (e.g., long-run average) for each fishing-area and time-period in the FEAST model subject to TAC constraints (for each year and all areas). With FAMINE1, simulated data for spatial abundance and catch from FEAST hindcasts was to be used to calculate average harvest rates for each fishing-area, spp., and fleet in the FEAST model. Testing the performance of FAMINE1 would require running FEAST again using the FAMINE1 generated catch distribution, which would not be feasible except perhaps for a few fishing seasons or years. Even if a limited comparison of this type were possible, the outcome would be questionable because FAMINE1 intentionally left out important autoregressive relationships to simplify the objective function for work on implementing the structure of fleets and TAC constraints.

The new version, FAMINE2, gets back to the original aim of using autoregressive models. The major innovation in FAMINE2 is to recast FAMINE1, where the minimization is over harvest rates, into an equivalent formulation with catch shares where these shares sum to unity and represent the share of a given TAC for each fishing-area. In FAMINE2, the target catch shares are derived from a simple (static) microeconomic model of minimizing harvest costs, and under special conditions, the catch shares are derived from the target (i.e., average) harvest rates used
in FAMINE1. Solving for target catch shares with a general quadratic cost function implies these are complicated functions of abundance levels. However, adding spatial and temporal autocorrelation to catch share equations that include the target catch share functions is tractable. The additional structure for allowing spatial and temporal autocorrelation extends the adding-up property of the target shares (i.e., the property that the sum of shares for all areas is equal to unity) to the observed catch shares. How does it work?

The original model, FAMINE1, posited that the harvest rates for each fishing-area would follow a process that minimized a weighted sum of squared deviations from historical harvest rates. In FAMINE2, the minimization problem is transformed into a mathematically equivalent form where minimization is with respect to catch shares in place of harvest rates. Catch shares have a convenient property of adding up to one which is not true for the harvest rates. In addition, the target catch shares in FAMINE2 are derived from minimizing an economic cost function whereas FAMINE1 specified target harvest rates through an informal empirical rule based on historical averages. The cost function approach in FAMINE2 demonstrates the exact assumptions on costs necessary to derive the informal rule for target harvest rates in FAMINE1. In this case, the target catch share for each area is equal to the ratio of squared abundance divided by the sum of squared abundances for all areas. With a general quadratic cost function, the target catch share for each area is a complicated function of this ratio, and abundance levels for all areas. This formulation of target catch shares is added to a dynamic and spatial adjustment cost model to form FAMINE2, and because adjustment costs depend on first-differences of catch shares, the derived system of equations preserves the adding-up property.

4.2 FAMINE2

The heart of the FAMINE model for each fishing period ‘t’ is a quadratic program:

\[
\text{Min } \sum_{i} (x_i - \bar{x}_i)' V_i (x_i - \bar{x}_i) \text{ s.t. } x_i' z_i = r_i
\]

where \( x_i \) is a vector of fishing effort (i.e., harvest rate) for each grid-cell during a fishing period, \( z_i \) is a given vector of abundance for each grid-cell, \( V_i \) is a known matrix, and \( r_i \) is the given TAC (or share of the TAC for each period, a scalar). The vector \( \bar{x}_i \) represents a given target harvest rate for each grid-cell.
Let ‘M’ denote the total number of grid-cells, which are indexed by ‘m’. Spatial data on harvest rates for each grid-cell are denoted by a vector of averages (e.g., calculated using data for fishing periods before ‘t’) for each fishing period \( \overline{y}_t \), and spatial data on abundance by a vector of averages \( \overline{z}_t \). A vector of spatial statistics for \( \overline{x}_t \) assumes \( \overline{x}_{mt} = \overline{y}_{mt} / \overline{z}_{mt} \), \( m = 1, \ldots, M \). To simplify the problem, consider \( V_t = I \), the identity matrix, for each fishing period ‘t’. Given these spatial statistics, equation (1) is a fully operational constrained optimization problem for the spatial allocation of fishing effort for each fishing period ‘t’. However, this empirical form, while appealing, does not have an obvious connection to economic theory. In particular, treating each \( \overline{x}_{mt} \) as a time-average is a reduced-form version of equation (1) because it was not derived from economic theory.

### 5.2.1 Simple Quadratic Catch Shares Model

A model that is closely related to equation (1) is based on \( y_t \), which contains shares of the total catch,

\[
\text{Min}_{y_t} (y_t - s_t)(y_t - s_t) \quad \text{s.t. } \mathbf{1}'y_t = 1
\]

where \( \mathbf{1} \) is a column vector of ones. To derive a catch share for each grid-cell, suppose that each grid-cell is subject to decreasing returns in its harvest rate \( x_{mt} \) which is the same for each grid-cell and takes the form of a quadratic cost. Then, the economic objective is to minimize the sum of these costs subject to a unit TAC constraint,

\[
\text{Min}_{x_t} \sum_{m=1}^{M} x_{mt}^2 \quad \text{s.t. } \sum_{m=1}^{M} x_{mt} z_{mt} = 1 \Rightarrow x_{kl} = \frac{z_{kt}}{\sum_{m=1}^{M} z_{mt}^2} \Rightarrow y_{kl} = x_{kl} z_{kl} = \frac{z_{kt}^2}{\sum_{m=1}^{M} z_{mt}^2} \equiv s_{kl}.
\]

Clearly, catch shares defined in equation (3) sum to unity, \( \sum_{m=1}^{M} s_{mt} = 1 \). These are the theoretical catch shares (and harvest rates). Based on the theoretical catch shares, the minimization problem in equation (2) can be transformed into an equivalent form as equation (1).

Let \( Z_t \) denote the diagonal matrix with diagonal components \( z_{mt} \), \( m = 1, \ldots, M \). Thus, the vector of catch shares is \( y_t = Z_t x_t \). Furthermore, the target catch share vector is \( s_t = Z_t z_t / z_t' z_t \), with the
property that these sum to unity, $\mathbf{1}' s_i = \mathbf{1}' \mathbf{Z}_i z_i / z_i' z_i = z_i' z_i / z_i' z_i = 1$. Upon substitution of these definitions into equation (2), an equivalent problem for the harvest rates in place of the catch shares is

$$\min_{x_i} \left( \mathbf{Z}_i x_i - \frac{1}{z_i' z_i} \mathbf{Z}_i z_i \right)' \left( \mathbf{Z}_i x_i - \frac{1}{z_i' z_i} \mathbf{Z}_i z_i \right) \text{ s.t. } x_i' z_i = 1$$

(4)

$$\Leftrightarrow \min_{x_i} \left( x_i - \frac{1}{z_i' z_i} z_i \right)' \mathbf{Z}_i' \mathbf{Z}_i \left( x_i - \frac{1}{z_i' z_i} z_i \right) \text{ s.t. } x_i' z_i = 1.$$
(5) \[ \min_{x_t} C'x_t + x'_t D x_t \text{ s.t. } x'_t z_t = \tau. \]

This quadratic program is solved directly with a Lagrange multiplier. First-order conditions for this problem imply \[ C + D x_t - \lambda z_t = 0 \Rightarrow x_t = \lambda D^{-1} z_t - D^{-1} C \Rightarrow x'_t z_t = \lambda z'_t D^{-1} z_t - C'D^{-1} z_t = \tau. \]

Therefore, \[ \lambda = (\tau + C'D^{-1} z_t) / z'_t D^{-1} z_t \Rightarrow x_t = (\tau + C'D^{-1} z_t) / z'_t D^{-1} z_t \]

In this case, the target catch-shares which are associated with the solution of the minimization problem in equation (5) are determined from the optimizing solution \( x_t \) in the previous expression and the diagonal abundance matrix \( s_t = Z_t x_t \) which implies \[ s_t = (\tau + C'D^{-1} z_t) / z'_t D^{-1} z_t \] \( Z_t D^{-1} z_t - Z_t D^{-1} C \). Since \( 1'Z_t = z'_t \), direct verification confirms that \( 1's_t = \tau \).

4.2.3 Temporal Autocorrelation

Given data \( \{x_t, z_t\}_{t=1}^T \), catch shares \( s_t \) can be calculated, and regression equations formulated in terms of harvest rates, or catch shares as endogenous variables. The structure of the error process depends on which endogenous variable is specified. However, the formulation that uses catch shares for the endogenous variable is consistent with estimation of a fractional spatial and temporal autocorrelation model (see equations 1 and 2 in the notes on the land use allocation model):

\[ \min_{\{y_t\}} (y_t - y_{t-1})'A(y_t - y_{t-1}) + (y_t - s_t)'(y_t - s_t) \text{ s.t. } 1'y_t = 1 \]

The simplest case is represented by matrix \( A = aI \) for a positive scalar ‘a’ and ‘I’ is the identity matrix. Formally, the unconstrained version of the minimization problem in equation (6) implies a set of first-order necessary conditions

\[ a(y_t - y_{t-1}) + (y_t - s_t) = 0 \Leftrightarrow y_t = \frac{1}{1+a} s_t + \frac{a}{1+a} y_{t-1} \equiv (1-\rho) s_t + \rho y_{t-1}. \]

The value of ‘y’ that minimizes the objective in equation (1) generalizes to vectors of AR(1) processes with time-varying means in the form of the target catch shares, i.e., ‘s’ variables. The
‘s’ variables are fractional shares of catch for each grid-cell, which implies the ‘s’ variables for each grid cell sum to one.

4.2.4 Regression Equations

Let \( \varepsilon_t \) denote a vector of random variables, each with mean zero, that satisfy \( \mathbf{1}'\varepsilon_t = 0 \). In addition, assume that \( \mathbf{1}'y_{t-1} = 1 \). Regression equations associated with equation (7) are

\[
y_{it} = (1 - \rho)s_{it} + \rho y_{i,t-1} + \varepsilon_{it}.
\]

In the land use model, the ‘s’ variables were replaced by logit functions of grid-cell level explanatory variables. In the fishing allocation model, the ‘s’ variables are replaced by the optimizing target catch shares that are derived above from solutions to equation (5). Substituting this expression for the ‘s’ variables implies a system of nonlinear regression equations

\[
y_t = (1 - \rho)\mathbf{Z}_t\mathbf{D}^{-1}\left(-\mathbf{C} + \mathbf{D}^{-1}\mathbf{z}_t'\mathbf{D}^{-1}\mathbf{z}_t\right) + \rho y_{t-1} + \varepsilon_t.
\]

For example, expanding equation (9) in the simplified case of a ‘D’ matrix that is proportional to the identity matrix, \( \mathbf{D} = d\mathbf{I} \), and a general ‘C’ vector \( \mathbf{C} = (c_1, \ldots, c_M)' \) implies a regression equation for the catch share of each grid-cell

\[
y_{it} = (1 - \rho)(\tau + d^{-1}\sum_{m=1}^{M} c_m z_{mt}) \frac{z_{it}^2}{\sum_{m=1}^{M} z_{mt}^2} - (1 - \rho)d^{-1}c_i z_{it} + \rho y_{i,t-1} + \varepsilon_{it}.
\]

Equation (10) partitions effects of temporal autocorrelation and abundance, with weights \( \rho \) and \( 1 - \rho \), respectively, which preserves the fractional shares property of the ‘y’ variables. The first term is a global effect and it is the product of a function of global costs and a fraction of squared abundance. Summing equation (10) over ‘i’ shows that the first and second terms offset each other to derive the fractional shares property of the ‘y’ variables. Let \( \gamma_i \) denote the global effect, and \( \bar{z}_i \) denote the fraction of squared abundance to rewrite equation (10) in a reduced-form

\[
y_{it} = \gamma_i \bar{z}_i + \beta_i z_{it} + \rho y_{i,t-1} + \varepsilon_{it},
\]

which suggests that OLS estimation for each grid-cell with

\[
y_{it} = \alpha + \beta z_{it} + \rho y_{i,t-1} + \varepsilon_{it}
\]

ought to give consistent estimates for each parameter, although ‘d’ in
equation (10) cannot be identified with OLS (assuming the ‘M’ grid-cell estimates of ‘alpha’ are used to solve for estimates of ‘M’ different ‘c’ parameters).

An equivalent version of equation (10) is closer in form to a linear regression. Let \( \bar{z}_{it} = \frac{z_{it}^2}{\sum_{m=1}^{M} z_{im}^2} \) denote the squared abundance shares. Expanding equation (10) further gives

\[
y_{it} = (1 - \rho)\bar{z}_{it} + (1 - \rho)d^{-1}\sum_{mzt} c_m [\bar{z}_{it}z_{mt}] + (1 - \rho)d^{-1}c_i [(\bar{z}_{it} - 1)z_{i\cdot}] + \rho y_{i,t-1} + \epsilon_{i,t}.
\]

In addition to the new data variable \( \bar{z}_{it} \), the terms in brackets contain two other instances of easy data transformations. In this form, let \( \alpha = 1 - \rho \), \( \beta_m = (1 - \rho)d^{-1}c_m \), and then,

\[
y_{it} = \alpha \bar{z}_{it} + \beta_i [(\bar{z}_{it} - 1)z_{i\cdot}] + \sum_{mzt} \beta_m [\bar{z}_{it}z_{mt}] + \rho y_{i,t-1} + \epsilon_{i,t}.
\]

This equation is a linear form of autoregressive model based on FAMINE. Maximum likelihood is a consistent estimation method. In particular, this equation shows how catch and fishable biomass are related.
Overall Conclusions

This project addressed BSIERP Hypothesis 5: Commercial and subsistence fisheries reflect climate. The specific hypothesis in this project was that the spatial distribution of fishing effort and catch for pollock and cod will be affected by changes over time in the spatial distribution of these target stocks under a climate change scenario. This hypothesis was to be tested using an integrated bioeconomic model of pollock and cod, calibrated to a hindcast of a vertically-integrated ecosystem model, and then run forward with the ecosystem model under a climate change scenario. However as the project deadline approached, it was apparent that the proposed research plan to test this project’s BSIERP hypothesis was infeasible because the ecosystem model hindcast was unavailable and plans to run the vertically-integrated ecosystem model under a climate change scenario were dropped. Nevertheless the economic model designed for this BSIERP project was flexible. Fortunately a separate opportunity arose to test a spatiotemporal climate hypothesis with the economic model using historical global data for agricultural land-cover and land-use change. This terrestrial application was successful and lead to a state-of-the-art method for spatial downscaling and a publication that is currently third on the list of most downloaded articles in Ecological Modelling.

BSIERP and Bering Sea Project Connections

This project was integrally linked to BSIERP projects B70 (FEAST) and B73 (MSE). In particular, this project assembled and prepared spatial time series of catch data that were key inputs to the FEAST model and the MSE project utilized these data by using FEAST as an operating model. In addition, the FAMINE model from this project would have been essential to the MSE project for computing the spatiotemporal allocation of catches.

Management or Policy Implications

Since this project did not achieve its objective of testing the relationship between climate and fisheries, there were no implications for management of pollock and cod.

Publications

Outreach

There was no activity to report.

Poster and oral presentations at scientific conferences or seminars


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References


