Developing Ecosystem Assessment models for the North Pacific Fisheries Management Council

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ABSTRACT

The North Pacific Fisheries Management Council, as part of its groundfish management process, produces an Ecosystem Considerations chapter as part of its annual Stock Assessment and Fisheries Evaluation Report (SAFE). The aim of this report is to synthesize the ecosystem-wide effects of fishing policies, climate, and other drivers on ecosystem status and function. As part of this work, a variety of tools have been developed that include multispecies and ecosystem models adapted to use in a strategic management context. Here, we present some methods and initial results of recently-developed statistical and model-fitting techniques for food web models used to monitor and report trends in ecosystem guild structure as it pertains to ecosystem-based management of groundfish in Alaska.

INTRODUCTION

Ecosystem-based management strategies for fisheries are being developed around the world to address the larger impacts due to fishing, while incorporating climate impacts. Ecosystem-based fishery management aims at conserving the structure and function of marine ecosystems, in addition to conserving fishery resources. An ecosystem-based management strategy for marine fisheries is one that reduces potential fishing impacts while at the same time allowing the extraction of fish resources at levels sustainable for the ecosystem. Groundfish fisheries in the Bering Sea/Aleutian Islands (BSAI) and Gulf of Alaska (GOA) are managed with conservative single-species harvests, catch and bycatch monitoring and constraints, total removal caps, areas closed to fishing for protection of other species, and forage fish protection (NMFS 2003). Evaluation of the present and likely future fishing effects of groundfish fisheries operating under these constraints from an ecosystem point-of-view may provide understanding of the possible implications of the current management approach.

To that end, the National Marine Fisheries Service Alaska Fisheries Science Center annually produces an Ecosystem Considerations section for the North Pacific Fisheries Management Council's Groundfish Stock Assessment and Fisheries Evaluation (SAFE) report. The primary intent of this report is to summarize and synthesize historical climate and fishing effects on the shelf and slope regions of the eastern BSAI and GOA from an ecosystem perspective and to provide an assessment of the possible future effects of climate and fishing on ecosystem structure and function. The Ecosystem Considerations section of the Groundfish SAFE provides the historical perspective of status and trends of ecosystem components and ecosystem-level attributes using an indicator approach. For the purposes of management, this information must be synthesized to provide a coherent view of ecosystems effects in order to clearly recommend precautionary thresholds, if any, required to protect ecosystem integrity. To this end, the assessment summarizes recent trends by distinct ecosystem properties that require consideration (Table 1).

The eventual goal of synthesis is to provide succinct indices of current ecosystem conditions reflecting these ecosystem properties. In order to perform this synthesis, a blend of data analysis and modeling will need to be employed to place measures of current ecosystem states in the context of history and past and future climate. Here, we focus on integrating data and models to show historical trends in the abundance of functional guilds within each ecosystem, based on point estimates (maximum likelihood estimates) of predator/prey functional responses derived from food web models of the eastern Bering Sea and Gulf of Alaska (Aydin et al. 2007). These fitting procedures, described below, represent a significant advance or at least an alternate methodology for providing point estimates of quantities of interest from ecosystem models such as Ecopath with Ecosim (EwE; Christensen and Walters 2004).

However, while the development of statistical rigor may improve model precision, the question of accuracy remains open. In particular, are current multispecies models evaluated in such a way that reported uncertainty (i.e. error ranges) sufficiently brackets ecological hypotheses to capture the potential surprising consequences of indirect trophic effects? While management advice from multispecies models is currently limited to advisory or strategic evaluation roles rather than to stock assessment, the need to evaluate the uncertainty in the models remains. In particular, models used to investigate strategic alternatives (for example, trading off marine mammals against fish harvesting) may require a different standard from stock assessments. Such a standard is not necessarily "higher"; rather, it should focus on different criteria. A quota-setting, single-species, management model requires setting a single value with the highest possible likelihood; in a tactical sense, model error or bias can be confronted in an adaptive manner with sufficiently regular (e.g. annual) corrections or updates.

On the other hand, a model built for strategic evaluation exists to define a broad policy infrequently; for example, it may be used to define long-term sustainable reference levels, overfishing limits, set asides of prey species for predators, or overall management plan structures. It should be expected that the managerial, scientific, and political will for strategic decisions informed by these models will only be correctable on the scale of a decade or more. For such models, emphasis should be placed not on the single outcomes with the highest likelihoods, but on reporting the "reasonable range of possibilities" with emphasis on looking for surprises or undesirable outcomes that have a moderate probability of occurring.

METHODS

While the ECOPATH with ECOSIM modeling methods (Christensen and Walters 2004) allow for flexibility and "manual adjustments" to model balancing, these methods were not used for developing the eastern Bering Sea, Gulf of Alaska, and Aleutian Islands food web models, as substantial data was available. For most species, estimates of biomass, ration, diet composition, catch, and production rates were available or could be calculated directly from existing data as described in sections 4-6, below. Therefore, the only calculated quantity for each species ("solved" by ECOPATH linear equations) was M_0, or residual natural mortality (the difference between total mortality and predation + fishing mortality), using the equation in section 2, below. Furthermore, during fitting to time series, the ECOPATH estimate of M_0 was treated as a starting rather than ending point for maximum likelihood estimation.

For species for which biomass estimates were unreliable due to low catchability of the surveys (primarily forage, benthos, and lower trophic levels), biomass was estimated by fixing M_0 to be 20% of production, and calculating the biomass required to sustain consumption (section 1, below). The only situations in which manual "tuning" was necessary were for a few isolated cases of prey identification issues in diets (primarily for gelatinous species of zooplankton) and to account for the mismatch between survey and fishery areas in the Aleutian Islands. This latter issue was a particular difficulty as the shelf survey extended only to 500m depth, however a substantial portion of area, ecosystem processes, and fisheries

occur at greater depths, and this mismatch had a great impact due to the extremely narrow shelf around the islands. Therefore, high production shown in the Aleutians is a reflection of oceanic and deep processes "concentrating" on the narrow continental shelf.

All cases in which biomass was estimated through fixing M_0 or where manual tuning was performed were considered to be "lower" data quality and are indicated as such on results graphs, except in cases where likelihood estimation was applied to these initial calculations.

It is important to note that the critical parameter for all of these processes is mortality; mortality not only affects production rates, but affects the relative contribution of different age classes to ration and diet compositions. Here, we do not fit or calculate total mortality but rather use single-species assessment estimates or literature values; therefore uncertainty in the single-species estimates of M are propagated into the ECOPATH food web model. Since our estimation process explicitly fits mortality components, cases where the data is sufficient to provide estimates of predation mortality and M_0 may be improvements over single-species assumptions.

A full documentation of this process and all data used as inputs to these models is available in Aydin et al. (2007).

1. Estimates of biomass and catchability from minimum consumption estimates.

Forage species are not sampled well by current gear in the Bering Sea and Gulf of Alaska. However, relative biomass (CPUE) from surveys is reported with annual CVs less than interannual variation, implying that CPUE may be useful as an index. To sum these indices, converting to a standard assumption on catchability is necessary. In order to do this, calculating the minimum biomass required to support measured groundfish consumption is one possibility, as follows:

The biomass (B), ration (Ration), and diet composition (DC, % wet weight) are calculated for groundfish predators within a reference (base) year. Equations for DC and ration calculations are described in Appendix sections 4 and 5, respectively. For the Bering Sea, the base year is 1991, while for the Gulf of Alaska the default years are 1990 and 1993 combined. Minimum required biomass of prey is then calculated as the sum of consumption by its predators as a fraction of its mortality as follows:

$$\hat{B}_{cons,f}^{1991} = \frac{\sum_{pred}\left(B_{pred}^{1991} \cdot Ration_{pred}^{1991} \cdot DC_{pred,f}^{1991}\right)}{0.8 \cdot Z_{f}^{1991}} \tag{1.1}$$

Here, Z is the mortality (equilibrium production rate) of the forage species, generally taken from single-species estimates from literature review (Appendix section 6). 0.8 is a "default minimal" assumption that 20% of the forage fish production is "unexplained" (attributed to M_0). When fit to time trends, this assumption of M_0 is a fit parameter; however for summing relative forage biomass it is a default assumption to this method.

After biomass for the reference year is calculated, the catchability q of the survey for the forage species is calculated as:

$$\hat{q}_{cons,f}^{survey} = \frac{CPUE_{survey,f}^{1991}}{\hat{B}_{cons,f}^{1991}} \tag{1.2}$$

Then, for years other than the reference year, survey CPUE may be converted to biomass using the

conversion:

$$\hat{B}_{cons,f}^{year} = \frac{CPUE_{survey,f}^{year}}{\hat{q}_{cons,f}^{survey}}$$ (1.3)

A future improvement will be to specifically estimate q over multiple years of diet and mortality data to evaluate the stability of this calculation of q.

2. Estimates of unaccounted mortality (M_0).

Residual ("unexplained" or "unaccounted") natural mortality (M_0) for a population is calculated from species biomass B_f, predator biomass (B_{pred}), ration (Ration), and diet composition (DC, % wet weight) of the prey in the predators' diets in a reference (base) year. Equations for DC and ration calculations are described in Appendix sections 4 and 5, respectively. For the Bering Sea, the base year is 1991, while for the Gulf of Alaska the default years are 1990 and 1993 combined. M_0 is then calculated using the following formula:

$$M_{0f} = Z_f^{1991} - \frac{\sum_{pred}\left(B_{pred}^{1991} \cdot Ration_{pred}^{1991} \cdot DC_{pred,f}^{1991}\right)}{B_f^{1991}}$$ (2.1)

Here, Z is the mortality (equilibrium production rate) of the forage species, generally taken from single-species estimates from literature review (Appendix section 6). It is possible for M_0 to be negative, indicating that consumption is greater than a declining population. In this case, the rate of decline during the reference year is estimated from time series data and added to prey biomass and the value is recalculated.

If one or more predator biomass levels are unknown, M_0 must be estimated simultaneously with predator biomass as described in Equation 1.1. In this case, the vector of unknowns M_0 or B (one for each species) is solved simultaneously: this solution is the "ECOPATH balance" solution for the food web.

3. Maximum likelihood estimation for a biomass dynamics model

The food web model estimated from rates as described in sections 1 and 2 is turned into a biomass dynamics model as follows:

$$\frac{dB_i}{dt} = \sum_{prey} GE \cdot c(B_i, B_{prey}) - M_0 B - FB - \sum_{pred} c(B_{pred}, B_i) + \varepsilon$$ (3.1)

GE and M_0 are fit parameters for growth efficiency and unaccounted mortality, F is year-specific fishing rate, ε is process error and c() is the following consumption equation:

$$c(B_{pred}, B_{prey}) = Q_{link}^{*}\left(\frac{X_{link} \cdot Y_{pred}}{X_{link} - 1 + Y_{pred}}\right)\left(\frac{D_{link} \cdot Y_{prey}^{\theta_{link}}}{D_{link} - 1 + Y_{prey}^{\theta_{link}}}\right)$$ (3.2)

where $Yi = B_i^t / B_i^*$. B* and Q* are biomass and consumption rates in a base year; this base year does not need to be an equilibrium state of the model. X_{link} is a predator/prey pair specific value greater than 1

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which determines predator density dependence on foraging (the numerical response) while D_{link} is a predator/prey specific value greater than 1 which determines the satiation of handling time/predation mortality for that link. θ_{link} is a shape parameters which determines if predation is constant with prey density ($\theta_{link}=0$), saturating (Type II functional response; $\theta_{link}=1$) or prey switching (Type III functional response; $\theta_{link}=2$). θ_{link} can take on intermediate values. Since these parameters are link-specific, the dimensionality is reduced by assuming predator and prey specific foraging behavior for each species that is additive for each predator/prey pair, so that:

$$X_{link} = 1 + \exp\left(x_{prey} + x_{pred}\right),$$
$$D_{link} = 1 + \exp\left(d_{prey} + d_{pred}\right), \text{ and}$$
$$\theta_{link} = \left(\theta_{prey} + \theta_{pred}\right).$$

Overall, this gives 8 parameters per species to fit: GE, M_0, x_{prey}, x_{pred}, d_{prey}, d_{pred}, θ_{prey}, and θ_{pred}.

To run simulations, equation 3.1 is integrated using Adams-Basforth integration with monthly timesteps (finer timesteps did not appreciably affect results). To obtain parameter point estimates, three weighted error functions are used assuming lognormal error (log sum-of-squares minimization criteria):

1. For 1965-2005, stock assessment biomass for species with age-structured assessments and catches are assumed to be "perfectly known" and the annual process error (change in biomass) required to follow these biomass trends is calculated and applied. Functional response parameters are fit to minimize this process error: a future extension of this method may be to apply a nonlinear Kalman filter to allow for error specification within each time trend.
2. For species with no age-structured stock assessments the difference between the dynamic model-predicted 1990-93 average biomass and the initial food web model biomass (e.g. coming from trawl survey data or consumption estimates) was considered as observation error.
3. Finally, there is a persistence criteria: any parameter set which causes one or more species to go extinct (be reduced to below 1/1000 of its initial biomass) following 50 years of equilibrium fishing pressure is rejected; as all species in the model have persisted over the modeled time period this criterion simply establishes a thermodynamic (trophically bounded) parameter set.

In addition, two broad groups of species, whales and commercial crabs, were subjected to substantial depletion through fishing during the modeled time period. For these species, historical catch time series were applied, and the criteria that the 1990-3 biomass of these species be near their food web biomass levels resulted in estimating ecosystem parameters that could support substantially higher "pre-modern exploitation" levels of biomass.

Two methodological concerns are raised by the fitting method. The first is the matter of degrees of freedom; a total of 8 parameters per species for each of the 119 species in the model results in 952 parameters while the biomass time trends currently used give a total of 672 "data" points for fitting. However, the constraints applied by the persistence criterion (#3, above) greatly influence the parameter covariance, e.g. the predation of upper trophic levels combined is not permitted to greatly exceed lower trophic level production. If parameters are chosen randomly and independently from uniform distributions, over 90% of parameter sets are rejected, indicating that the degrees of freedom for the model are lower than 952 independent parameters. Still, many of the resulting maximum likelihood estimates are not strongly discriminating of whether prey switching may be taking place; the future addition of direct fitting to historical diet data will improve these results.

Second, using single-species stock assessment model outputs as "known" biomass trends requires the multi-species model to try to match the single-species blanket assumption of constant natural mortality, which has the potential for introducing the single-species metaphor of fixed species interaction into a

more dynamic simulation. This is partially mitigated by the fact that the adult biomass time trends come from assessments of large groundfish predators, for which predation morality is generally low. For several of these groundfish species, the ecosystem model tracks separate juvenile and adult components; in these cases, juvenile biomass levels from the stock assessment are not used. The one place this remains an issue is for walleye pollock, which initial results indicate show an increase in adult natural mortality in recent years. One possibility for removing this circularity is to iterate between the ecosystem and single-species models; using the M reconstructed from the ecosystem model to derive a new single-species estimate for biomass, then using that new biomass in the ecosystem model, iterating until an agreement between the models is reached; this work is planned for the near future.

4. Diet composition calculations

Notation:
DC = diet composition
W = weight in stomach
n = prey
p = predator
s = predator size class
h = survey haul
r = survey stratum
B = biomass estimate
v = survey
a = assessment
R = ration estimate

The diet composition for a species is calculated from stomach sampling beginning at the level of the individual survey haul (1), combining across hauls within a survey stratum (2), weighting stratum diet compositions by stratum biomass (3), and finally combining across predator size classes by weighting according to size-specific ration estimates and biomass from stock assessment estimated age structure (4). Ration calculations are described in detail below.

Diet composition (DC) of prey n in predator p of size s in haul h is the total weight of prey n in all of the stomachs of predator p of size s in the haul divided by the sum over all prey in all of the stomachs for that predator size class in that haul:

$$DC_{n,p,s,h} = W_{n,p,s,h} \bigg/ \sum_n W_{n,p,s,h} \qquad (4.1)$$

Diet composition of prey n in predator p of size s in survey stratum r is the average of the diet compositions across hauls within that stratum:

$$DC_{n,p,s,r} = \sum_h DC_{n,p,s,h} \bigg/ h \qquad (4.2)$$

Diet composition of prey n in predator p of size s for the entire area t is the sum over all strata of the diet composition in stratum r weighted by the survey biomass proportion of predator p of size s in stratum r:

$$DC_{n,p,s,t} = \sum_r DC_{n,p,s,r} * B^v_{p,s,r} \bigg/ \sum_r B^v_{p,s,r} \qquad (4.3)$$

Diet composition of prey n in predator p for the entire area t is the sum over all predator sizes of the diet composition for predator p of size s as weighted by the relative stock assessment biomass of predator size s times the ration of predator p of size s:

$$DC_{n,p,t} = \sum_s DC_{n,p,s,t} * B_{p,s}^a * R_{p,s} \Big/ \sum_s B_{p,s}^a * R_{p,s} \qquad (4.4)$$

5. Ration Calculations

Size specific ration (consumption rate) for each predator was determined by the method of fitting the generalized Von Bertalanffy growth equations (Essington et al. 2001) to weight-at-age data collected aboard NMFS bottom trawl surveys.

The generalized Von Bertalanffy growth equation assumes that both consumption and respiration scale allometrically with body weight, and change in body weight over time (dW/dT) is calculated as follows:

$$\frac{dW_t}{dt} = H \cdot W_t^d - k \cdot W_t^n \qquad (5.1)$$

Here, W_t is body mass, t is the age of the fish (in years), and H, d, k, and n are allometric parameters. The term $H \cdot W_t^d$ is an allometric term for "useable" consumption over a year, in other words, the consumption (in wet weight) by the predator after indigestible portions of the prey have been removed and assuming constant caloric density between predator and prey. Total consumption (Q) is calculated as $(1/A) \cdot H \cdot W_t^d$, where A is for a fractional conversion between prey and predator wet weights that accounts for indigestible portions of the prey and differences in caloric density. The term $k \cdot W_t^n$ is an allometric term for the amount of biomass lost yearly as respiration.

Based on an analysis performed across a range of fish species, Essington et al. (2001) suggested that it is reasonable to assume that the respiration exponent n is equal to 1 (respiration linearly proportional to body weight). In this case, the differential equation above can be integrated to give the following solution for weight-at-age:

$$W_t = W_\infty \cdot \left(1 - e^{-k(1-d)(t-t_0)}\right)^{\frac{1}{1-d}} \qquad (5.2)$$

Where W_∞ (asymptotic body mass) is equal to $(H/k)^{\frac{1}{1-d}}$, and t_0 is the weight of the organism at time=0. If the consumption exponent d is set equal to 2/3, this equation simplifies into the "specialized" von Bertalanffy length-at-age equation most used in fisheries management, with the "traditional" von Bertalanffy K parameter being equal to the k parameter from the above equations divided by 3.

From measurements of body weight and age, equation 2 can be used to fit four parameters (W_∞, d, k, and t_0) and the relationship between W_∞ and the H, k, and d parameters can then be used to determine the consumption rate $H \cdot W_t^d$ for any given age class of fish. For these calculations, weight-at-age data available and specific to the modeled regions were fit by minimizing the difference between log(observed) and log(predicted) body weights as calculated by minimizing negative log likelihood: observation error was assumed to be in weight but not aging. A process-error model was also examined but did not give significantly different results.

Initial fitting of 4-parameter models showed, in many cases, poor convergence to unique minima and shallow sum-of-squares surfaces: the fits suffered especially from lack of data at the younger age classes that would allow fitting to body weights near t=0 or during juvenile, rapidly growing life stages. To counter this, the following multiple models were tested for goodness-of-fit:

1. All four parameters estimated by minimization;
2. d fixed at 2/3 (specialized von Bertalanffy assumption)
3. d fixed at 0.8 (median value based on metaanalysis by Essington et al. 2001).
4. t_0 fixed at 0.
5. d fixed at 2/3 with t_0 fixed at 0, and d fixed at 0.8 with t_0 fixed at 0.

The multiple models were evaluated using Aikeike's Information Criterion, AIC. In general, the different methods resulted in a twofold range of consumption rate estimates; consistently, model #3, d fixed at 0.8 while the other three parameters were free, gave the most consistently good results using the AIC. In some cases model #1 was marginally better, but in some cases, model #1 failed to converge. The poorest fits were almost always obtained by assuming that d was fixed at 2/3.

To obtain absolute consumption (Q) for a given age class, the additional parameter A is required to account for indigestible and otherwise unassimilated portions of prey. We noted that the range of indigestible percentage for a wide range of North Pacific zooplankton and fish summarized in Davis (2003) was between 5-30%, with major zooplankton (copepods and euphausiids), as well as many forage fish, having a narrower range of indigestible percentages, generally between 10-20%. Further, bioenergetics models, for example for walleye pollock (Buckley and Livingston 1994), indicate that nitrogenous waste (excretion) and egestion resulted in an additional 20-30% loss of consumed biomass. As specific bioenergetics models were not available for most species, we made a uniform assumption of a total non-respirative loss of 40% (from a range of 25-60%) for all fish species, with a corresponding A value of 0.6.

Finally, consumption for a given age class was scaled to population-level consumption using the available numbers-at-age data from stock assessments, or using mortality rates from stock assessments and the assumption of an equilibrium age structure in cases where numbers-at-age reconstructions were not available.

6. Production rates

Production per unit biomass (P/B) and consumption per unit biomass (Q/B = R, ration above) for a given population depend heavily on the age structure, and thus mortality rate of that population. For a population with an equilibrium age structure, assuming exponential mortality and Von Bertalanffy growth, P/B is in fact equal to total mortality Z and Q/B is equal to (Z+3K)/A, where K is Von Bertalanffy's K, and A is a scaling factor for indigestible proportions of prey (Aydin 2004). If a population is not in equilibrium, P/B may differ substantially from Z although it will still be a function of mortality.

For the Bering Sea, Aleutian Islands, and Gulf of Alaska ECOPATH models, P/B and Q/B values depend on available mortality rates, which were taken from estimates or literature values used in single-species models of the region. It is noted that the single-species model assumptions of constant natural mortality are violated by definition in multispecies modeling; therefore, these estimates should be seen as "priors" to be input into the ECOPATH balancing procedures or other parameter-fitting (e.g. Bayesian) techniques.

Several methods were used to calculate P/B, depending on the level of data available. Proceeding from most data to least data, the following methods were used:

1. If a population is not in equilibrium, total production P for a given age class over the course of a year can be approximated as $(N_{at} \cdot \Delta W_{at})$, where N_{at} is the number of fish of a given age class in a given year, exponentially averaged to account for mortality throughout the year, and ΔW_{at} is the change in body weight of that age class over that year. For a particular stock, if weight-at-age data existed for multiple years, and stock-assessment reconstructed numbers-at-age were also available, production was calculated by summing this equation over all assessed age classes. Walleye pollock P/B for both the EBS and GOA were calculated using this method: examining the components of this sum over the years showed that numbers-at-age variation was responsible for considerably more variability in overall P/B than was weight-at-age variation.

2. If stock assessment numbers-at-age were available, but a time series of weight-at-age was not available and some weight-at-age data was available, the equation in (1), above, was used, however, the change in body weight over time was estimated using fits to the generalized Von Bertalanffy equations described in the consumption section, above.

3. If no stock assessment of numbers-at-age was available, the population was assumed to be in equilibrium, so that P/B was taken to equal Z. In cases for many nontarget species, estimates of Z were not available so estimates of M were taken from conspecifics with little assumed fishing mortality for this particular calculation.

7. Guild definition

We divided the entire food web into groups (guilds) which shared common prey (Table 2). Therefore, trends for a guild may indicate the overall pressure on or condition of its prey base. Guild definitions were based on a cluster analysis classifying predators together by shared prey (20% similarity).

PRELIMINARY RESULTS

For the EBS and GOA, all species included in food web models (Aydin et al. 2007) were aggregated into 12 guilds by trophic role. The guilds span the trophic levels between phytoplankton and apex predators and include a separate pathway for pelagic and benthic components of the ecosystem (Table 2). For each guild, time trends of biomass are presented for 1977-2009. Catch and exploitation rate (catch/biomass) are presented for guilds with exploitation rates exceeding 0.0001. Differences in time series data availability led to different methods for EBS and GOA ecosystem guild analysis. EBS biomass trends are summed stock assessment model estimates or scaled survey data, where available, for each species within the guild. If neither time series are available, the species is assumed to have a constant biomass equal to the mid-1990s mass balance level estimated in Aydin et al. (2007). Inconsistencies in the GOA trawl survey time series in depth and area surveyed made ecosystem model fits to trends more reasonable than summing scaled survey data. The GOA ecosystem model was forced by stock assessment model estimates where available for each species within the guild, and fit to survey time series, catch data, groundfish diet data, and the mid-1990's mass balance for all other species. In both regions, catch data was directly taken from the Catch Accounting System and/or stock assessments for historical reconstructions. Pie charts indicate the relative contribution of each data type to the average biomass within each guild (Figs. 1, 2, 3). For 2010-2011 projections, the stock assessment authors' recommended catch and estimated biomass time series were used in both regions.

EBS status and trends: Current (2004-2009) mean biomass, catch, and exploitation rates have been within +/- one standard deviation of 1977-2009 levels for all guilds except pelagic foragers (biomass below mean, exploitation rate above mean) and structural epifauna (biomass above mean). Apex predators and

pelagic foragers have decreasing trends in biomass, catch, and exploitation rates, while benthic foragers have increasing catch and exploitation rate trends. The apex predator trends are driven largely by a decrease in Pacific cod biomass and catch. The pelagic foragers guild is dominated by walleye pollock (77% of guild biomass in 2009), whose decrease with general declines in other forage species has brought the biomass of this group to overall low levels. Exploitation rate was over one standard deviation above the mean from 2004-2007, however the decreased catches in 2008 and 2009 have decreased the pelagic foragers exploitation rate back towards its long-term mean. Increasing trends in benthic forager catch and exploitation rate reflect increased ABCs for flatfish species allowable under the 2 million metric ton OY cap with decreased pollock ABCs. Copepod trends through 2007 have been returning towards the mean from historically low levels observed between 2001-2004; no new data are available since 2007.

GOA status and trends: Current (2004-2009) mean biomass is more than one standard deviation above 1977-2009 mean levels for apex predators and benthic foragers, and trends for catch and exploitation rate are also increasing for these guilds. The apex predator guild is driven by the stock assessment-estimated increase in arrowtooth flounder, and to a lesser extent in Pacific halibut and Pacific cod, while the benthic forager guild is driven by a stock assessment-estimated increase in flathead sole and survey trends for increasing skates and flatfish. In contrast, pelagic foragers recent mean biomass is one standard deviation below the long term mean, driven by the stock assessment estimated decline in pollock. Catch and exploitation rates for pelagic foragers remain within one standard deviation of the long term mean. GOA shrimp are above long term mean biomass, a trend which agrees with trawl survey results. Based on assessment and survey results for the data rich guilds, current status of infauna is estimated to be below long term average; structural epifauna, mesozooplankton, and copepods are predicted to be above long term average; and pelagic primary production remains close to the long term average.

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Table 1. Objectives, drivers, pressures and effects, significance thresholds and indicators for fishery and climate induced effects on ecosystem attributes.

Objective	Drivers	Pressures/Effects	Significance Threshold	Indicators
Maintain predator-prey relationships and Energy flow	Need for fishing; per captia seafood demand	Availability, removal, or shift in ratio between critical functional guilds (combines: Pelagic forage availability, removal of top predatyors, and energy removal)	Fishery induced changes outside the natural level of abundance or variability, taking into account ecosystem services and system-level characteristics (e.g. predator demands, respiration), and catch levels high enough to cause the biomass of one or more guilds to fall below minimum biologically acceptable limits.	Trophic level of the catch Trends in catch and bycatch, by guild and for entire ecosystem Sensitive species catch levels Population status and trends of each guild and within each guild Production rates and between-guild production ratios ("balance")
		Spatial and temporal concentration of fishery impact on forage	Fishery concentration levels high enough to impair long term viability of ecologically important, nonresource species such as marine mammals & birds	Degree of spatial/temporal concentration of fishery on pollock, Atka mackerel, herring, squid and forage species (qualitative)
		Introduction of nonnative species	Fishery vessel ballast water and hull fouling organism exchange levels high enough to cause viable introduction of one or more nonnative species, invasive species	Total catch levels Invasive species observations
		Energy re-direction	Long-term changes in system biomass, respiration, production or energy cycling that are outside the range of natural variability due to fishery discarding and offal production practices	Trends in discard and offal production levels (quantitative for discards) Scavenger population trends relative to discard and offal production levels (qualitative) Bottom gear effort (qualitative measure of unobserved gear mortality particularly on bottom organisms)
Maintain diversity	Need for fishing; per captia seafood demand	Effects on species diversity	Catch removals high enough to cause the biomass of one or more species (target, nontarget) to fall below or to be kept from recovering from levels below minimum biologically acceptable limits	Species richness and diversity Population levels of target, nontarget species relative to MSST or ESA listing thresholds, linked to fishing removals (qualitative) Number of ESA listed marine species Steller sea lion population trends (pup and non-pup counts) Northern fur seal pup production
		Effects on functional (trophic, structural habitat) diversity	Catch removals high enough to cause a change in functional diversity outside the range of natural variability observed for the system	Guild diversity or size diversity changes linked to fishing removals (qualitative) Bottom gear effort (measure of benthic guild disturbance) HAPC biota bycatch
		Effects on genetic diversity	Catch removals high enough to cause a loss or change in one or more genetic components of a stock that would cause the stock biomass to fall below minimum biologically acceptable limits	Community size diversity Degree of fishing on spawning aggregations or larger fish (qualitative) Older age group abundances of target groundfish stocks

| Maintain habitat | Need for fishing; per captia seafood demand | Habitat loss/degradation due to fishing gear effects on benthic habitat, HAPC biota, and other species | Catch removals high enough or damage caused by fishing gear high enough to cause a loss or change in HAPC biota that would cause a stock biomass to fall below minimum biologically acceptable limits. | Areas closed to bottom trawling

Fishing effort (bottom trawl, longline, pot)

HAPC biota catch

HAPC biota survey CPUE |
|---|---|---|---|---|
| **Incorporate/ Monitor effects of climate change** | Concern about climate change | Change in atmospheric forcing resulting in changes in the ocean temperatures, currents, ice extent and resulting effects on production and | Changes in climate that result in changes in productivity and/or recruitment of stocks | North Pacific climate and SST indices (PDO, AO, NPI, and NINO 3.4)

Combined standardized indices of groundfish recruitment and survival

Ice indices (retreat index, extent)

Volume of cold pool

Summer zooplankton biomass |

Table 2. The following guilds were defined based on diet data from each region, and groups are sorted from highest biomass (early 1990s baseline) to low biomass within each guild.

EBS Apex predators		GOA Apex predators	
Arrowtooth	31.49%	Arrowtooth	59.19%
P. Cod	29.67%	P. Cod	13.26%
Grenadiers	12.49%	P. Halibut	10.04%
Alaska skate	7.96%	Grenadiers	8.64%
Lg. Sculpins	6.26%	Sablefish	4.00%
P. Halibut	4.02%	Rougheye Rock	1.35%
Gr. Turbot	2.42%	Lg. Sculpins	0.82%
Other skates	1.29%	Dogfish	0.59%
Kamchatka fl.	1.16%	Sperm and Beaked Whales	0.36%
Sleeper shark	0.87%	Longnose skate	0.36%
N. Fur Seal	0.42%	Other skates	0.28%
Wintering seals	0.39%	Misc. fish deep	0.28%
Minke whales	0.31%	Salmon shark	0.21%
Sablefish	0.31%	Porpoises	0.14%
Sperm and Beaked Whales	0.23%	Sleeper shark	0.12%
Resident seals	0.17%	N. Fur Seal	0.08%
Belugas	0.16%	Steller Sea Lion	0.07%
Murres	0.11%	Puffins	0.05%
Misc. fish deep	0.11%	Murres	0.04%
Porpoises	0.05%	Sea Otters	0.03%
Rougheye Rock	0.03%	Resident seals	0.02%
Steller Sea Lion	0.02%	Minke whales	0.02%
Resident Killers	0.02%	Resident Killers	0.01%
Sea Otters	0.01%	Kittiwakes	0.01%
Kittiwakes	0.01%	Fulmars	0.01%
Fulmars	0.01%	Gulls	0.00%
Puffins	0.01%	Cormorants	0.00%
Shearwater	0.01%	N. Fur Seal_Juv	0.00%
Kamchatka fl._Juv	0.00%	Transient Killers	0.00%
N. Fur Seal_Juv	0.00%	Shearwater	0.00%
Cormorants	0.00%	Storm Petrels	0.00%
Transient Killers	0.00%	Albatross Jaeger	0.00%
Gulls	0.00%	Steller Sea Lion_Juv	0.00%
Albatross Jaeger	0.00%		
Steller Sea Lion_Juv	0.00%		
Storm Petrels	0.00%		

EBS Benthic foragers		GOA Benthic Foragers	
YF. Sole	26.22%	Other sculpins	23.75%
N. Rock sole	25.97%	FH. Sole	23.18%
AK Plaice	21.05%	Dover Sole	8.68%
FH. Sole	11.69%	S. Rock sole	7.63%
Other sculpins	3.98%	Rex Sole	7.53%
YF. Sole_Juv	3.04%	YF. Sole	5.37%
Misc. Flatfish	2.45%	N. Rock sole	4.31%
FH. Sole_Juv	1.72%	Misc. Flatfish	4.14%
P. Cod_Juv	1.17%	P. Cod_Juv	3.22%
N. Rock sole_Juv	1.16%	FH. Sole_Juv	2.69%
Walrus Bd Seals	0.83%	Big skate	2.58%
Rex Sole	0.37%	Arrowtooth_Juv	1.93%
Gray Whales	0.24%	Shortraker Rock	1.78%
Shortraker Rock	0.07%	Gray Whales	1.30%
Shortspine Thorns	0.03%	Shortspine Thorns	1.16%
P. Halibut_Juv	0.00%	AK Plaice	0.33%
Greenlings	0.00%	Greenlings	0.30%
Dover Sole	0.00%	P. Halibut_Juv	0.10%
Arrowtooth_Juv	0.00%	Shortspine Thorns_Juv	0.00%

EBS Pelagic foragers		GOA Pelagic Foragers	
W. Pollock	63.10%	Capelin	33.29%
W. Pollock_Juv	13.85%	Sandlance	11.61%
Herring	3.84%	Squids	6.84%
Myctophidae	3.38%	Oth. managed forage	6.43%
Misc. fish shallow	2.80%	Eulachon	5.09%
Sandlance	2.19%	POP	4.58%
Squids	2.18%	Misc. fish shallow	4.56%
Fin Whales	1.85%	W. Pollock	3.87%
Oth. managed forage	1.68%	Salmon returning	3.56%
Capelin	1.10%	Oth. pelagic smelt	2.74%
Scyphozoid Jellies	0.86%	Myctophidae	2.68%
Herring_Juv	0.71%	W. Pollock_Juv	2.28%
Bathylagidae	0.66%	Atka mackerel	1.96%
Atka mackerel	0.49%	Northern Rock	1.46%
Salmon returning	0.36%	Sharpchin Rock	1.41%
Eulachon	0.33%	Herring	1.28%
Atka mackerel_Juv	0.15%	Fin Whales	1.12%
Northern Rock	0.07%	Herring_Juv	0.96%
Oth. pelagic smelt	0.06%	Dusky Rock	0.94%
Salmon outgoing	0.06%	Humpbacks	0.85%
Humpbacks	0.05%	Atka mackerel_Juv	0.70%
Other Sebastes	0.05%	Scyphozoid Jellies	0.60%
POP	0.04%	Other Sebastes	0.48%
Bowhead Whales	0.03%	Bathylagidae	0.34%
Sei whales	0.03%	POP_Juv	0.12%
Gr. Turbot_Juv	0.02%	Sei whales	0.09%
Sablefish_Juv	0.02%	Salmon outgoing	0.08%
Right whales	0.01%	Sablefish_Juv	0.07%
Auklets	0.01%	Right whales	0.02%
Sharpchin Rock	0.01%	Auklets	0.00%
Dusky Rock	0.00%		

EBS Motile epifauna		GOA Motile epifauna	
Brittle stars	27.15%	Brittle stars	30.83%
Sea stars	19.11%	Hermit crabs	23.77%
Urchins dollars cucumbers	14.38%	Misc. crabs	11.37%
Hermit crabs	8.18%	Urchins dollars cucumbers	10.84%
Opilio	7.89%	Eelpouts	6.88%
Eelpouts	7.52%	Snails	5.61%
Snails	5.72%	Octopi	5.27%
Misc. crabs	4.97%	Bairdi	4.54%
Bairdi	2.89%	Sea stars	0.85%
King Crab	1.90%	King Crab	0.04%
Octopi	0.29%		

EBS Shrimp		GOA Shrimp	
Pandalidae	83.02%	NP shrimp	56.80%
NP shrimp	16.98%	Pandalidae	43.20%

EBS Infauna		GOA Infauna	
Bivalves	69.23%	Bivalves	45.60%
Polychaetes	11.15%	Benthic Amphipods	21.08%
Benthic Amphipods	9.35%	Polychaetes	13.54%
Misc. Crustacean	7.29%	Misc. worms	12.66%
Misc. worms	2.98%	Misc. Crustacean	7.13%

EBS Structural epifauna		GOA Structural epifauna	
Urochordata	45.42%	Urochordata	44.02%
Hydroids	19.84%	Hydroids	19.73%
Sea Pens	12.37%	Sponges	19.32%
Sponges	11.58%	Anemones	15.97%
Anemones	10.48%	Corals	0.86%
Corals	0.32%	Sea Pens	0.10%

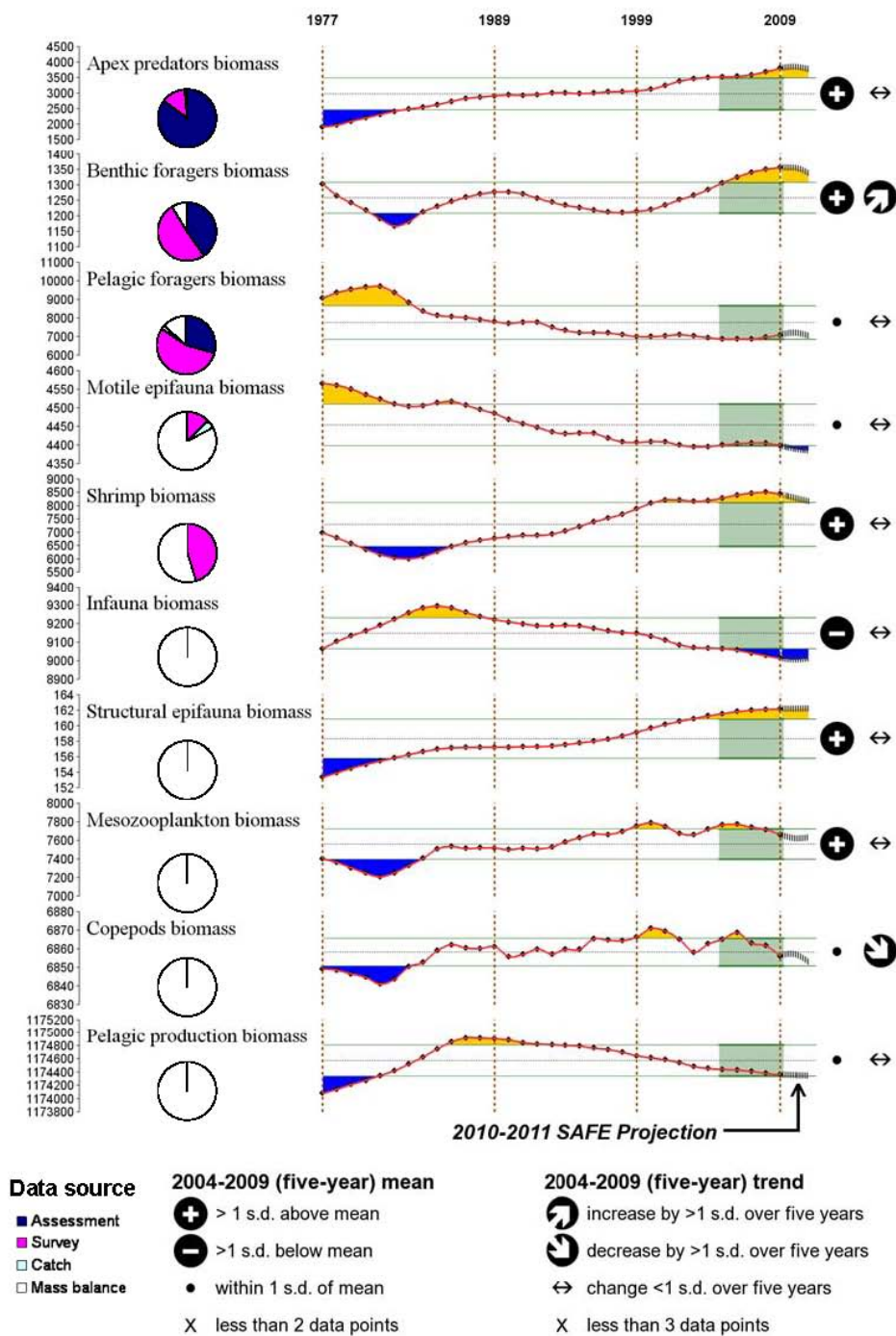| EBS Mesozooplankton		GOA Mesozooplankton	
Euphausiids	78.72%	Euphausiids	84.36%
Pelagic Amphipods	7.82%	Pelagic Amphipods	4.85%
Mysids	6.36%	Gelatinous filter feeders	4.37%
Chaetognaths	3.12%	Pteropods	2.30%
Gelatinous filter feeders	2.90%	Chaetognaths	2.24%
Pteropods	1.02%	Mysids	1.86%
Fish Larvae	0.05%	Fish Larvae	0.01%

Figure 1. Ecosystem trends – Gulf of Alaska guild analysis: biomass. Green shaded area shows +/- one standard deviation of time series over measured time period.
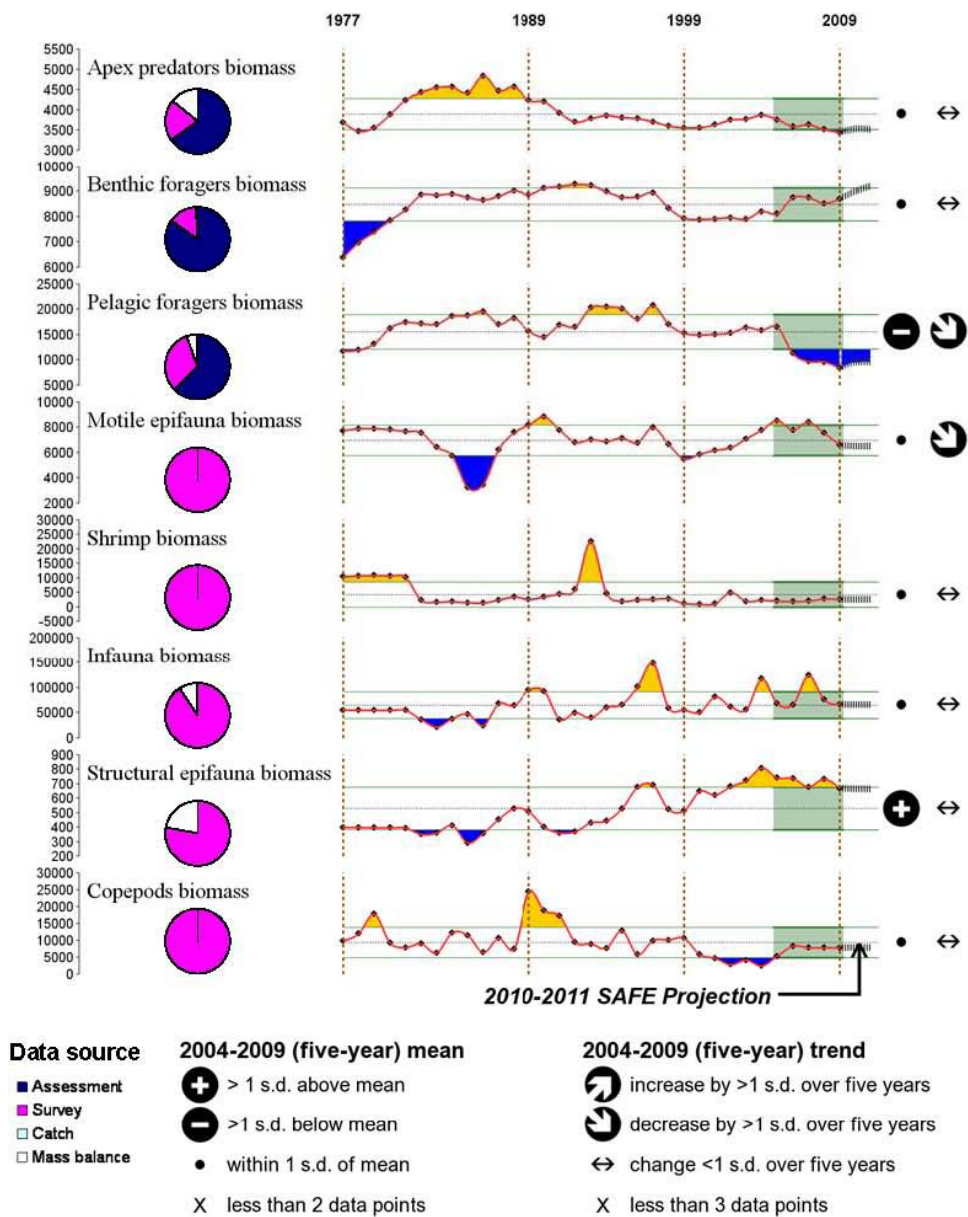
Figure 2. Ecosystem trends – Eastern Bering Sea biomass by guild. Green shaded area shows +/- one standard deviation of time series over measured time period.
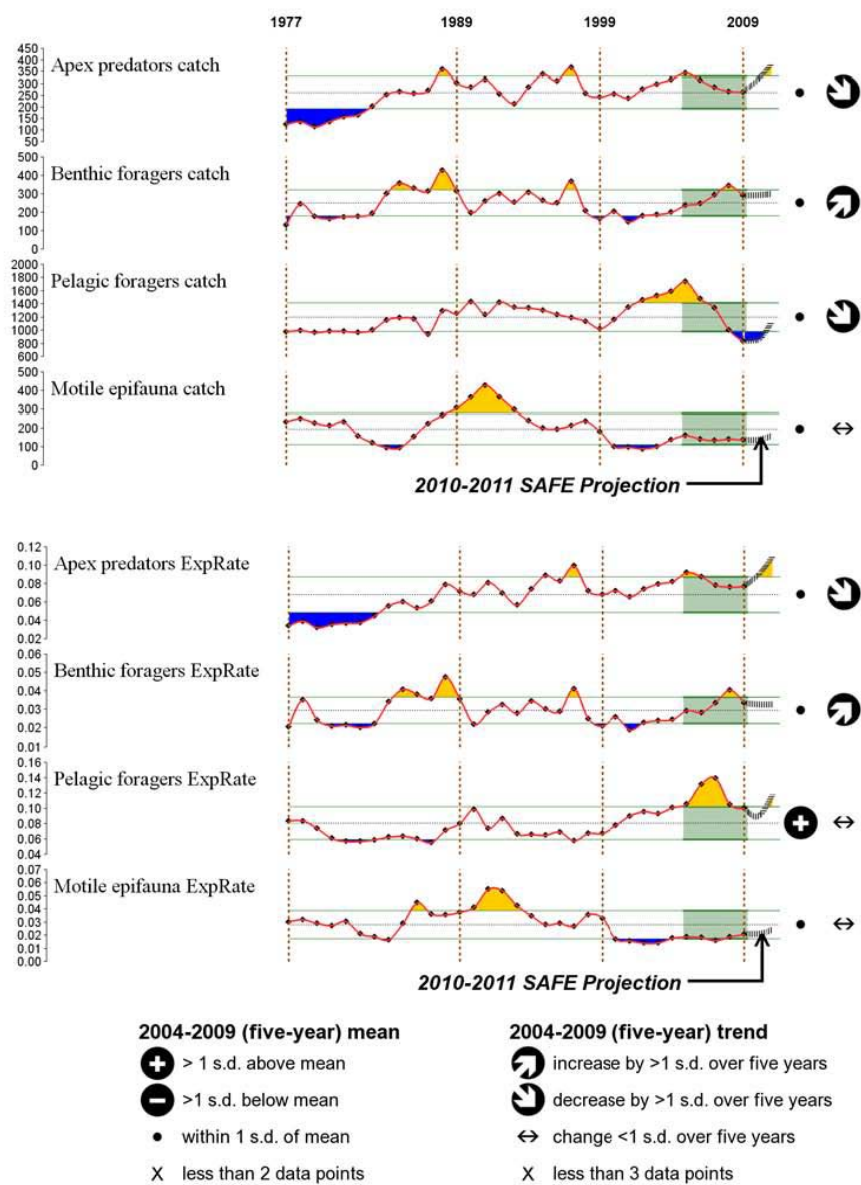
Figure 3. Fishing and fisheries -- Eastern Bering Sea fisheries catch and exploitation rate by guild. Green shaded area shows +/- one standard deviation of time series over measured time period.