Octopus Updates for September 2016 Plan Teams

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Please note there are 3 sections to this document:

1) An excerpt from the BSAI stock assessment document describing results of an update to the Pacific cod consumption estimate with new stomach data. This estimate is used for setting the BSAI OFL/ABC, and we agreed in 2011 to update the estimate every 5 years. The new calculation shows an increase in the long-term average consumption rate. GOA plan teams may choose to skip this section.

2) A brief summary of recent octopus research that will be included in the full assessments as an appendix. This includes final results of discard mortality research, which is in press, and final results for the octopus tagging study.

3) A description of a theoretical population model for giant Pacific octopus *Enteroctopus dofleini*, which is in development. Note that this is not a stock assessment model and is not fitted to any data, but it allows simulation of an octopus population under different assumptions and may be useful for exploratory analysis, including which input data would be most useful in tracking changes in population biomass. Results to date will be presented to the teams, and feedback on areas for further exploration will be welcomed.

Updated Consumptions model estimates for BSAI octopus in 2016

Parameters Estimated Independently – Natural Mortality N

The 2011 BSAI octopus assessment introduced a new methodology for examining population trends in octopus. This approach used Tier 5 methodology, where MSY is obtained when fishing mortality equals the total natural mortality (in tons). For Tier 5 stocks, the total natural mortality is usually estimated as the product of biomass and an instantaneous mortality rate:

$OFL=N=MB$,

where N is the total natural mortality in tons and M is the continuous individual mortality rate widely used in other stock assessment models. The new method uses a different approach to estimate total natural mortality that does not rely on being able to estimate biomass. Rather, data from the AFSC's food habits database is used to estimate the total amount of octopus consumed by their main predator, Pacific cod. Because Pacific cod is an important commercial species, the AFSC food habits group collects a large number of Pacific cod stomachs for diet analysis. The amount of octopus consumed by Pacific cod likely lower than the true total natural mortality N for octopus, since it does not include mortality from other predators (*i.e*. marine mammals) or non-predation mortality. This approach has been reviewed by the Science and Statistical Committee, and has been selected by the Bering Sea plan team to set octopus catch limits for the BSAI fishery since 2012.

This analysis was originally performed in 2011 using stomach data through 2008 (Conners et al 2011). The consumption estimator has been updated this year after analysis of additional stomach samples through 2015 and additional samples from 2005 – 2007 (Table 22.6). The methodology used for this updated estimate is the same as used previously, with some minor changes to improve the way diets were binned into cod size strata. Details of the methodology are supplied in Appendix A1. This novel approach for setting annual catch limits for data-poor prey species has been presented at scientific conferences and is expected to be published next year.

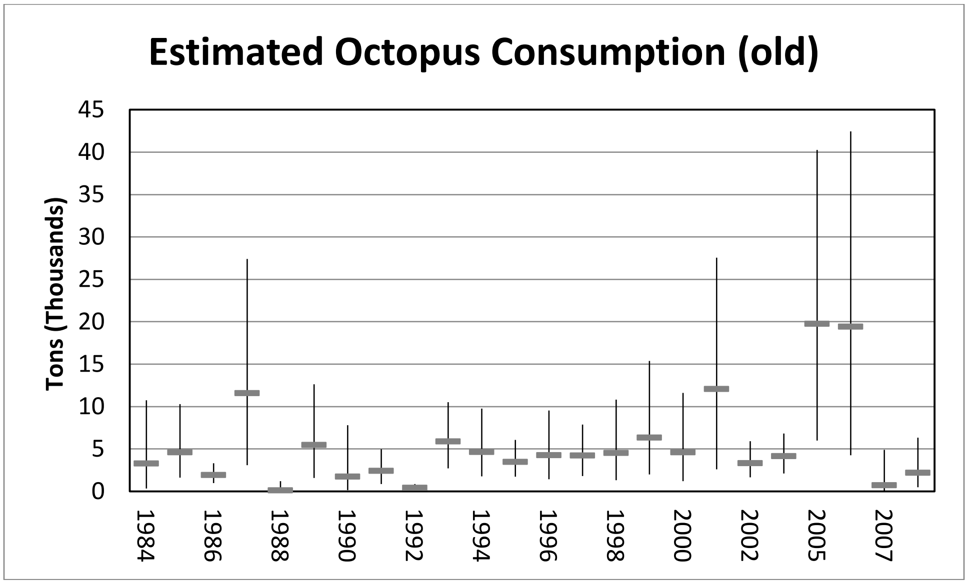
The **Total consumption of octopus by Pacific cod (t/year)** estimated for the EBS is shown in Figure 22.5 (both old and new consumption calculations). In both calculations, we used the geometric mean of the posterior distribution to estimate annual predation for each year in the time series. The geometric mean is used rather than the arithmetic mean because the posterior distribution is right-skewed (higher values have higher uncertainty). Uncertainty of each annual estimate obtained by bootstrapping is also shown. Estimates of annual predation mortality by Bering Sea cod on octopus range from <200 to over 20,000 tons; the larger values have a higher level of uncertainty. The majority of the annual estimates prior to 2004 lie in the range of 3,000 to 6,000 tons. The estimates for 2005 – 2015, however, show much larger levels of consumption, with several years in the 10,000-20,000 t range. This upward trend was initially assumed to be due to increasing abundance of Pacific cod, but there has also been an increase in the proportion of octopus in the diet of cod (Figure 22.6). Over the entire time series, this proportion shows large year-to year variability and some periods of high consumption for several years followed by low consumption. Thus it is unclear whether the recent upward trend is a permanent change (perhaps due to climate factors) or the peak of a periodic cycle.

We use a geometric mean of all the annual values to calculate a conservative long-term average predation rate over the 30 years of annual estimates. **The geometric mean of all of the annual estimates in the updated data set is 4,770 tons, a substantial increase over the old estimate of 3,452 tons.** Both estimates are a full order of magnitude higher than the current rate of fishery catch of octopus.

Table 22.6. Numbers of Pacific cod stomach samples analyzed for octopus consumption estimates. New data for the current update of consumptions calculations are highlighted.

Year	No. Stomach Samples
1984	636
1985	952
1986	1,338
1987	747
1988	551
1989	1,662
1990	1,121
1991	1,546
1992	1,876
1993	2,303
1994	2,381
1995	2,395
1996	1,314
1997	1,155
1998	1,262
1999	1,049
2000	1,101
2001	1,304
2002	1,334
2003	1,770
2005	408
2006	671
2007	578
2008	1,204
2009	1,312
2010	1,169
2011	1,511
2014	1,617

Figure 22.5. Estimated consumption of octopus by Bering Sea Pacific cod, 1984-2008. Error bars show 95% confidence intervals of the posterior distribution; solid bars are annual hyperbolic means. The top chart shows estimates made in 2011, the bottom chart shows new estimates from updated data set.



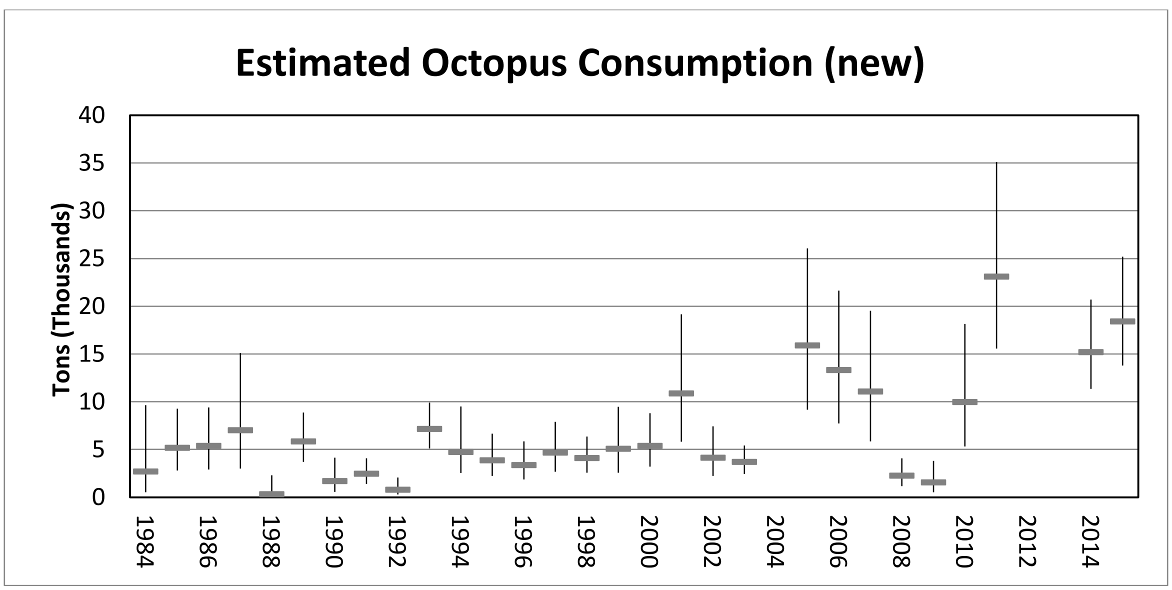
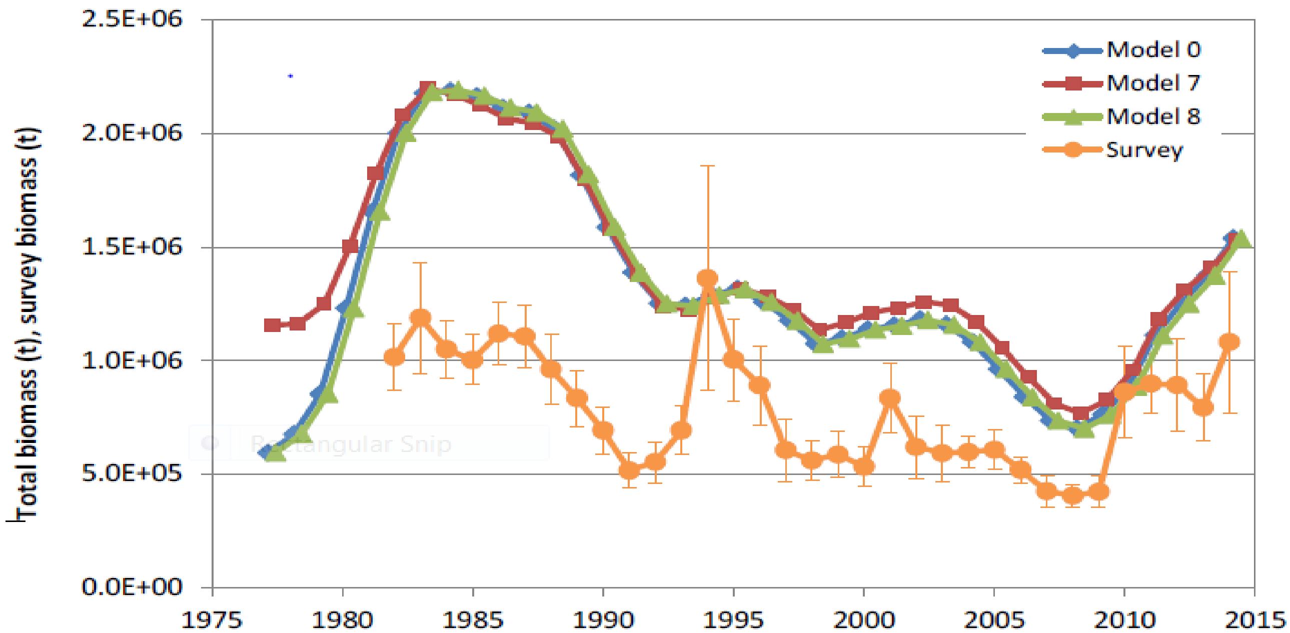
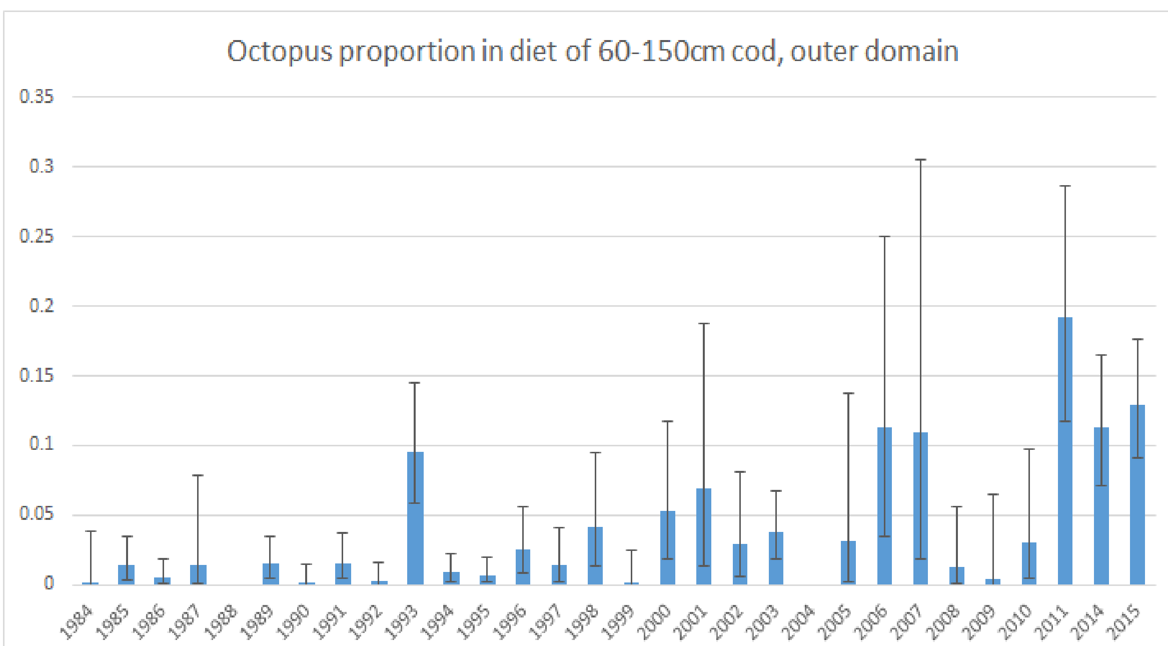


Figure 22.6 Time series trends in a) the biomass of Bering Sea Pacific cod (from Thompson, Dec 2015 SAFE) and in b) the proportion of octopus in cod diets.





Appendix 22.A2 Summary of Octopus Research

A number of research projects have been completed in the last 5-7 years and are published or nearing publication. Areas of research, publications, and major results are summarized below.

Reproductive Cycle and Life History of E. dofleini

GOA: NPRB Project 906 included development of maturity indices for *E. dofleini* and collection of octopus specimens for dissection.

- Sexually mature octopus of both sexes were present in all seasons, suggesting spawning is not fully synchronous for this species in the GOA. GSI of females was highest in late winter to early spring, however, suggesting a high proportion of egg laying in early spring.
- In the Gulf of Alaska, this species was found to mature between 10-20 kg with size at 50% maturity values of 13.7 kg (95% CI 12.5-15.5 kg) for females and 14.5 kg (95% CI = 12.5-16.3 kg) for males. Size at maturity was highly variable for this species, particularly for male octopus.
- Fecundity for this species in the Gulf of Alaska was found to range from 41,600 to 239,000 with an average fecundity of 106,800 eggs/female. Fecundity was significantly and positively related to the weight of the female (n = 33, P < 0.001).

Conners, M. E., C. L. Conrath, and R. Brewer. 2012. Field studies in support of stock assessment for the giant Pacific octopus *Enteroctopus dofleini*. NPRB Project 906 Final Report. North Pacific Research Board, Anchorage, AK.

Conrath, C.A. and M.E. Conners. 2014. Aspects of the reproductive biology of the giant Pacific octopus (Enteroctopus dofleini) in the Gulf of Alaska. Fishery Bulletin, U.S. 112(4):253-260.

BSAI: NPRB Projects 906 and 1005 also included collection of octopus specimens and examination of gonad maturity.

- In the southern Bering Sea, *E. dofleini* were reproductively active in the fall with peak denning occurring in the winter to early spring months.
- *E. dofleini* in the Bering Sea were found to have size at 50% maturity values of 12.8 kg for females and 10.8 kg for males. Animals smaller than 10 kg tended to be immature but male and female octopus in the size range between 10 – 20 kg were found to be immature, maturing, and mature.

Brewer, R.S. and B.L. Norcross. (in Review) 2016. Seasonal changes in the sexual maturity and body condition of the North Pacific giant octopus (Enteroctopus dofleini).

Brewer, R.S. 2016. Population biology and ecology of the North Pacific Giant Octopus in the eastern Bering Sea. PhD thesis, Univ. Alaska Fairbanks.

Octopus Tagging Study

Reid S. Brewer conducted a three-year, five season tagging study on Giant Pacific Octopus captured with commercial cod pots. The study was conducted in a 25 km^2 area north of Unalaska Island in depths ranging from 50 to 200m. A total of 1,714 E. dofleini were tagged and 246 were recaptured. While most of the recaptures occurred within a few weeks after tagging (same season), 32 octopus were recaptured between seasons after 60 days. Cormack-Jolly-Seber models were used to estimate survival and study-area abundance for *E. dofleini* in the size range vulnerable to commercial pot bycatch.

- The tagging method using Visual Implant Elastomers (VIE tags) was feasible. Tags were readily visible in recaptured animals and had no associated tissue damage
- In autumn when temperatures were warmest, *E. dofleini* had higher growth rates, moved more and both sexes were predominantly mature when compared to colder winter months.
- Size and water temperature also played a role in growth of tagged *E. dofleini*. The mean SGR for short-term recaptures was 0.75% d-1 ± 0.09, SGR was positively related to temperature and negatively related to size at initial capture. The mean SGR for long-term recaptures was 0.20% d-1 ± 0.03 and SGR was negatively related to size at initial capture
- Average annual survival rate of tagged octopus was estimated at 3.33% ± 2.69 SE. The survival for this population was modeled using recaptures of mostly mature individuals. Female survival estimates were lower than male survival due to sex-specific post-spawning reproductive activities.
- The abundance estimate for octopus in the study area was 3,180 octopus or 127 octopus per km^2. If this density is applied the three statistical areas in the southeast Bering Sea where most of the incident catch occurs (areas 509, 517, and 519) the estimate for octopus abundance in the 3,500 km^2 area was 1.47 million octopus.
- Mean size of octopus captured in this study was 14.1 kg, the estimated biomass estimate of octopus in the study area was 44.8 mt and in the three statistical areas was 20,697 mt, an order of magnitude larger than the current biomass estimate for the entire EBS

Brewer, R.S. and B.L. Norcross. 2012. Long-term retention of internal elastomer tags in a wild population of North Pacific giant octopus (Enteroctopus dofleini), Fisheries Research 134-136: 17-20.

Brewer, R.S. 2016. Population biology and ecology of the North Pacific Giant Octopus in the eastern Bering Sea. PhD thesis, Univ. Alaska Fairbanks.

Brewer, R.S. and B.L. Norcross. (in Review) 2016. Seasonal changes in the sexual maturity and body condition of the North Pacific giant octopus (Enteroctopus dofleini).

Brewer, R.S., B.L. Norcross, and E. Chenoweth (in press). Temperature and size-dependent growth and movement of the North Pacific giant octopus (Enteroctopus dofleini) in the Bering Sea. Marine Biology Research

Species of Octopus Bycatch

A NOAA Cooperative Research Program project was conducted in 2006 and 2007 by AFSC scientist Elaina Jorgensen. Species identification of 282 animals at Harbor Crown Seafoods in Dutch Harbor and 102 animals at Alaska Pacific Seafoods in Kodiak confirmed that all individuals were *E. dofleini*. All plant deliveries of octopus were from pot fishing vessels.

Octopus Discard Mortality

In 2006-2007 and 2010-2012, some fishery observers collected data for a special project on octopus size frequency and condition at discard. Data from this project allowed qualitative comparisons of size frequency by gear type and the immediate capture mortality of octopus from different gear types. Two follow-up studies were conducted to examine short-term and long-term delayed mortality for octopus captured with commercial pot gear.

- The size frequency of octopus taken by different fishing gears was very distinct, with pot gear capturing almost exclusively large octopus (>10kg). Pelagic trawl and longline gear captured mostly small octopus (<2 kg), and bottom trawl gear captured a range of sizes. Patterns in size distribution for the different gear types were similar for all three ecosystems (BS, GOA, and AI).
- Pot gear in all regions caught a much higher proportion of males than trawl and longline gears. There was also seasonal difference in sex ratios in both BS and GOA, with a higher proportion of males caught during the fall fishing season than during the winter. Males were generally slightly larger than females.
- Initial condition at capture was best in pot gear, with over 90% of octopus discarded from pot vessels alive in excellent condition. Octopus taken in trawl gear had the highest immediate mortality rate, with 68-94% dead or injured at discard.
- Octopus captured during Pacific cod fishing in the southeast Bering Sea in winter 2013 were held for 24 to 60 hours in circulating seawater tanks. Octopus captured ranged in size from 5.5 kg to 22.0 kg. Of the 36 octopus held, none showed any delayed mortality or decline in condition. Statistical power analysis showed that the probability of the observed result of no mortality out of 36 trials would be very small ($p < 0.05$) unless the true underlying mortality rate was larger than 8%.
- Separate long-term delayed mortality studies collected octopus on commercial pot vessels in Kodiak, Alaska and held individuals for 21 days in a running seawater laboratory. This study showed no long-term delayed mortality of uninjured octopus, and a 50% delayed mortality rate for visibly injured octopus.
- The current catch accounting for octopus assumes 100% mortality for all catch, but studies show that the discard mortality rates for octopus from pot gear are much lower. The studies discussed above provide quantitative estimates of immediate and delayed mortality rates that could be used to conduct gear-specific accounting of octopus discard mortality.

Conners, M. E. and M. Levine. 2016 (in press). Characteristics and discard mortality of octopus bycatch in Alaska groundfish fisheries. Fishery Bulletin

Conrath, C.A. and N. B. Sisson. 2016 (in press). Delayed discard mortality of the giant Pacific octopus in pot fisheries in the Gulf of Alaska. Fishery Bulletin

Habitat Pot Gear for Directed Octopus Survey & Research

NPRB Project 906 and an NMFS Cooperative Research Project included testing and developing a specialized gear for octopus fishing. The gear consists of small "habitat pots" that act as artificial den space for octopus. A large number of these pots can be longlined as a clip-on gear.

- A variety of pot designs and materials were tested for use in Alaska. In the NPRB study, plywood box pots and scrap ATV tires captured octopus much more effectively than pots made of various plastic materials. One vessel in the CR study also caught octopus using plastic pots purchased from Korea, at similar rates to plywood box pots.
- Bycatch of crabs and other species in plywood box pots was close to zero. Starfish were occasionally seen.
- Habitat pots were successfully deployed on longlines fished as tub gear, off a longline reel, and using a commercial crab hauling block. Experimentation is still needed to determine optimal pot spacing and soak times
- Octopus captured in habitat pots ranged in size from smaller than 2 kg to over 20 kg, giving a broader and more consistent size distribution than fishing and survey gears.
- Overall capture rates varied widely between seasons and locations, ranging from less than ten percent to over 50% occupancy. More development is needed to determine most productive places and seasons for fishing.
- The gear is suitable for comparative scientific studies and may be suitable for index surveys at fixed locations. Suitability of the habitat pot gear for directed commercial fishing will depend on ex-vessel prices and catch rates.

Age Determination in Giant Pacific Octopus

Collections of octopus beaks, stylets and statoliths were made during NPRB projects and from AFSC surveys. Preliminary analyses have been conducted, but a funded research project would be needed to determine if accurate methods for age determination can be developed.

- Hood length of both upper and lower octopus beaks is strongly correlated with octopus weight and can be measured on beaks in stomach contents.
- Statoliths of *E. dofleini* are too soft and chalky for age reading, but beaks and stylets both show banding patterns in cross section that may be correlated with age.
- Translating beak or statolith bands to age will require a validation study using octopus marked with radioisotopes or chemicals and held for known time periods.

Appendix 22.A3. Theoretical Octopus Population Model (new for 2016)

General Model Formulation

The base model is a stage-based model based on total weight and reproductive status of the octopus. Computer code is designed to allow the number of stages and the size range of each stage to be changed as needed. Initial inputs include the number of stages and the average weight of each stage. The final stage always represents reproductive adults: sexually mature animals that will mate, lay eggs, and die within the next time step. The remaining stages represent various sizes of immature animals. The model is not age-based because there is as yet no established method for aging *E. dofleini*. If the growth parameters are set so that each immature stage grows to the next size stage in each time step, with none remaining in the current stage, then the stage model is identical to an age-based model. There is an additional important life stage that is not explicitly included in the model. The planktonic paralarval stage is not modeled, but is considered to be a major source of early natural mortality and recruitment variability. The first size stage of the model represents small octopus after they have settled from the paralarvae to a fully benthic habitat, approximately one year after mating of mature octopus.

The transition matrix for the model is determined by parameters for growth and maturation. In this formulation, the survivors of each immature size stage are presumed to either grow to the next size stage, stay in the same size stage, or mature into reproductive adults. Immature octopus were assumed to not grow more than one size stage in each time step, and individual weight loss to a smaller size step was assumed not to occur. The larger size stages may also mature into reproductive adults (stage 6). The transition probabilities, conditioned on survival, are thus made up of three input vectors: the probability of staying in the same size range (g0, failing to grow enough to reach the next stage), the probability of maturing into reproductive adults (mat), and the probability of growing to the next size class (g1). This last vector is calculated to ensure that the conditional transition probabilities sum to one. The transition matrix (conditional probability of growth or maturity given survival) has the vector g0 along the diagonal, g1 above the diagonal, and mat in the final column.

The mortality matrix is composed of natural mortality and the sum of any fishery and survey mortalities. Natural mortality is a parameter that is input as a vector of stage-based natural mortalities. The natural mortality for the reproductive adult stage is set high to produce 100% post-spawning mortality of this size class. Fishery mortality from each source is the product of an overall fishing rate (*Ff*) and a vector representing size selectivity for the fishery for each size stage. The overall fishing rate is assumed to be proportional to abundance, with an unknown capture efficiency (*q*). Total mortality is calculated as the sum of natural and fishery mortality. Numbers of individuals in the successive time step is the product of instantaneous mortality and the conditional transition probabilities.

Recruitment is initially assumed constant, then is treated as a random variable with a mean recruitment level and recruitment variance as input parameters. There is also an option to use a general Beverton-Holt stock-recruitment function to model recruitment by specifying steepness as an input parameter. The random model is probably most representative of recruitment in *E. dofleini*; the population is largely unfished and there is strong and interannually variable mortality in the planktonic paralarval stage. Given the high fecundity of *E. dofleini* (90,000 egg/female in the GOA, Conrath and Conners 2014) effects of reduced spawning biomass on recruitment are not likely to be seen unless fishing pressure is extremely heavy.

The model simulates population dynamics from input parameters and starting conditions. As with any steady-stage model, if parameters are constant then the population converges to a stable stage distribution which is determined by the growth and maturity parameters. The simulation code tracks numbers and biomass is each stage in each simulated year, and calculates catch-at-stage vectors and total yield for each fishery or survey. Output statistics include the mean, variance, minimum, and maximum of population numbers over the simulation period, after allowing an initial period for burn-in. These statistics are also calculated for the recruitment, biomass, spawning biomass, and fishery yield time series.

Equations for the model are as follows:

For years t (1:nyr) and size stage a (1:nclass)

N[t,1] = R[t] R(t) is generated ~ Normal (Rbar, sigmaR) for all t
N[1,a] = N0 Initial population size, input vector

$N[t+1,a] = N[t,a]*G0_a*S_a + N[t,(a-1)]*G1_{(a-1)}*S_a$ a = 2,3,…,(nclass-1)
$N[t+1,nclass]$ = Sum (a = 1,2,….,(nclass-1)) of $(N[t,a] * S_a * mat_a)$
where S_a = exp(-Za) and Za = NatM + FishM

Octopus Population Simulations
The model explored for the octopus assessment is defined as having 6 stages: 5 immature stages and one stage for reproductive adults (Figure 22.A3.1). The five immature stages are selected to represent the range of octopus sizes seen in fishery and research data, and to roughly correspond to the presumed maximum lifespan of *E. dofleini*. The first size stage consists of newly settled octopus weighing < 3kg, the remaining stages are 6 kg intervals. The growth parameters are set so that the immature stages may either grow one size step with Pr(g1) or stay in the same size class with Pr(g0). Stages 2-5 also have a fixed probability of maturing (transitioning to stage 6) in each time interval. Natural mortality is presumed to decrease with increasing size for immature octopus as the number of predators decreases. The natural mortality of the final stage is set very high so that there is virtually 100% mortality. The fishery is modeled to represent the Pacific cod pot fishery, with maximum selectivity on the largest animals. There is also a simulation of the AFSC Bottom Trawl survey, which selects for small octopus but catches some larger octopus, and Pacific cod predation, which selects exclusively for small-medium octopus.

The model and some typical outputs are shown graphically below. This simulation model was run for a variety of input parameters and fishing scenarios; the results of these simulations will be demonstrated to the Plan Teams at the September 2016 meetings and will eventually be presented in a scientific publication. The population model will also be used to generate a range of simulated data sets with different levels of variance in the population parameters; these simulated data sets can then be submitted to a quantitative catch-at-age model to see how accurately it estimates the true population parameters. The Teams are encouraged to suggest additional scenarios for simulation.

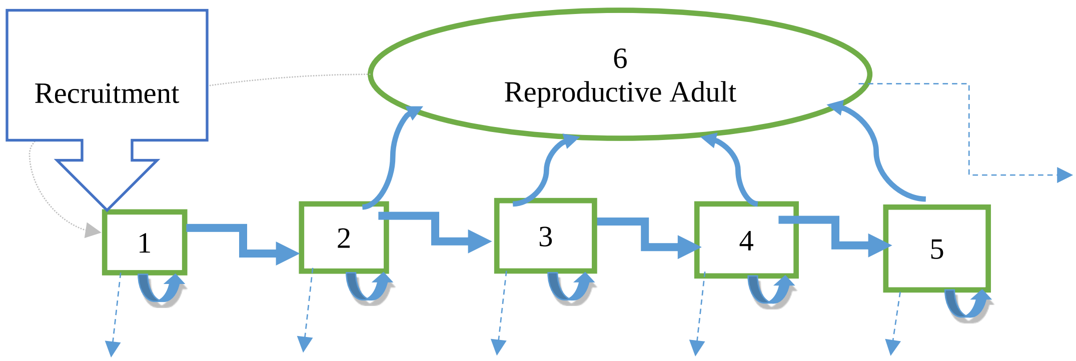
Simulation Models run as of 9/1/16:

Model 0 – fully deterministic (all input parameters constant), constant recruitment, no fishing
Sensitivity analysis

Model 1 – fully deterministic model, constant recruitment, fishing effects
Model 0 with FPot ranging from 0.01 to 0.6 – Yield, population effects
Cordue model – age based (g)=0 with same parameters from CIE review

Model 2 – deterministic growth, maturity, and mortality; random recruitment, fishing effects
Recruitment variance vs. Biomass and Yield variance
Model 2 with added directed fishery on sizes 2-3
Model 2 simulating catch-at-age data for fitting with SS3

Fig 22.A3.1 Size-Stage Octopus Population Model and Base Parameter Values



Population Structure and Growth Variables

	1	2	3	4	5	Adult
Size (kg)	< 3	3 < 9	9 < 15	15 < 21	21 +	
Mean Wt (kg)	0.5	6	12	18	24	22
Mnat	0.7	0.5	0.2	0.1	0.1	10
Pr(Mature)	0	0.1	0.5	0.75	1.0	
Pr(grow 0)	0	0	0	0	0	
Pr(grow 1)	1.0	0.9	0.5	0.25	0	
InitSize%	0.55	0.15	0.10	0.08	0.02	0.1
N0	5,500	1,500	1,000	800	200	1,000
Fsel – Pots	0	0.1	0.5	1.0	1.0	1.0
Fsel– BTsur	1.0	0.1	0.1	0.1	0.1	0.1
Fsel- Cod	1.0	0.5	0	0	0	0

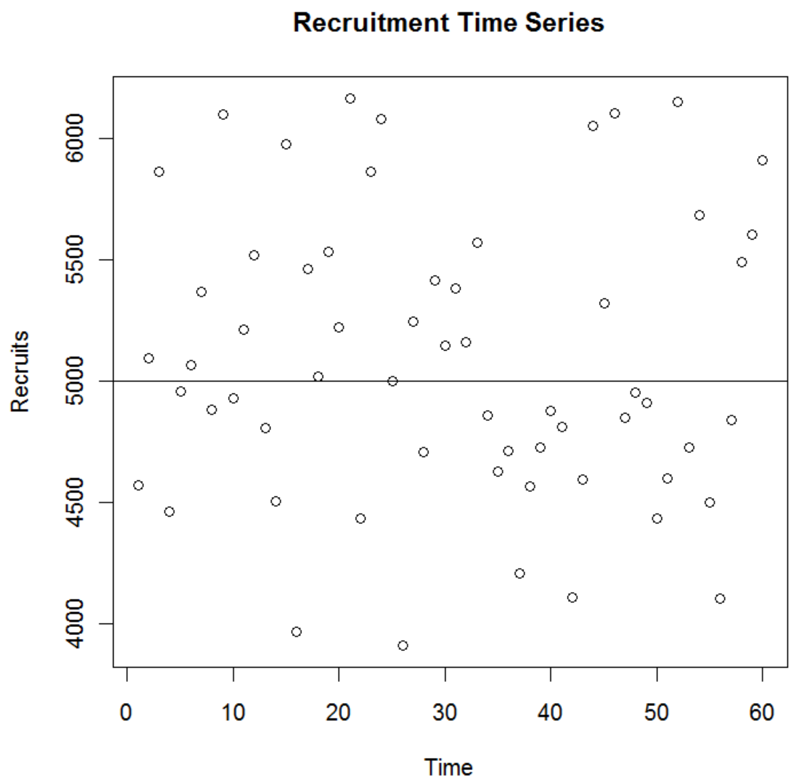
Run Variables

Nclass	6
Yrs, burn	60,10
N0_all	10,000
Rbar	5,000
sigmaR	0
Ftot - Pots	0
Ftot- BTsurv	0
Ftot- Cod	0

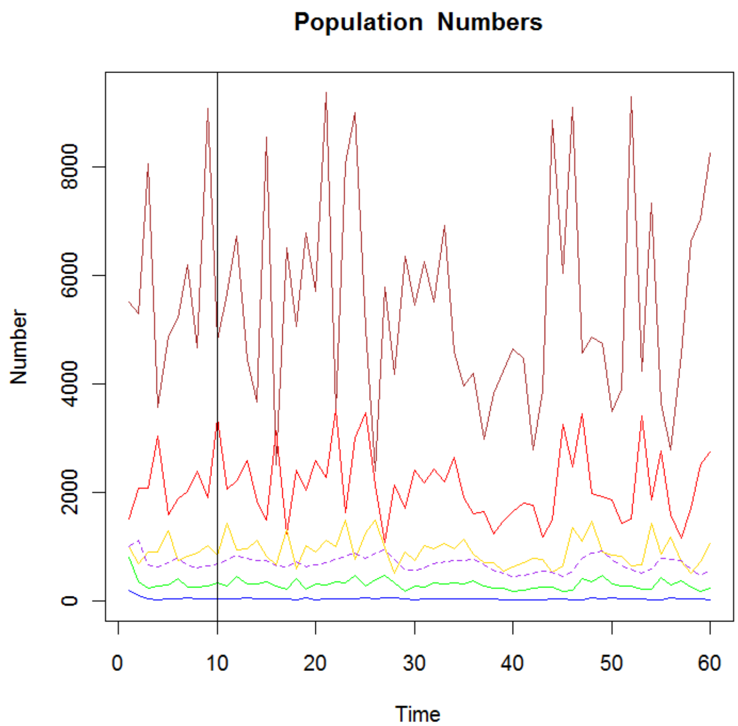
Calculated Variables / Outputs (units)

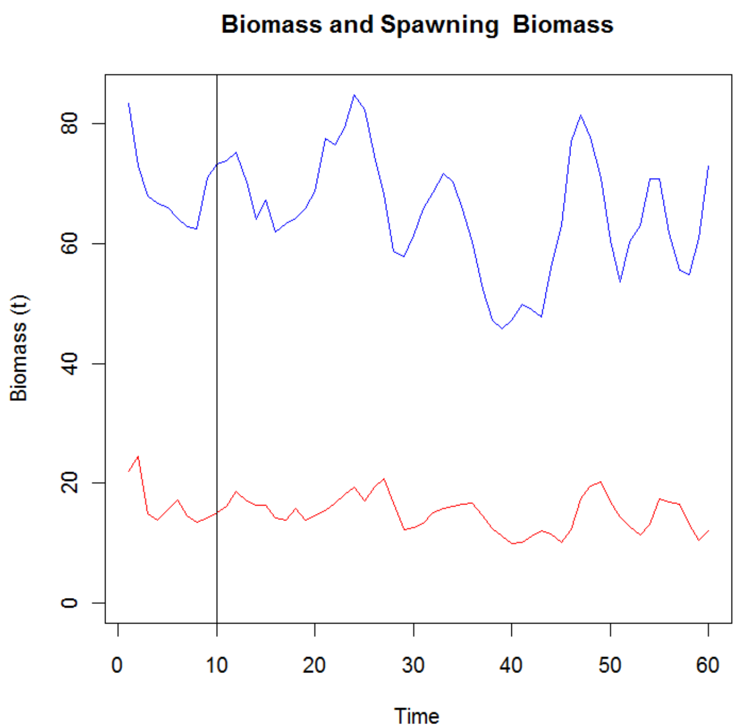
N(t,i) vector	Numbers at stage i	#	Matrix
N(t+1,i)	Numbers next year	#	
SF(t,i)	Size Frequency	%	Matrix
R(t)	Recruitment	#	Vector
B(t,i), B(t)	Biomass	mt	Vector
SpB(t,i), SpB(t)	Spawning Biomass	mt	Vector
CAAF(t,i)	Catch by stage	#/stage	Matrix
Yield (t)	Fishery Yield	mt	Vector

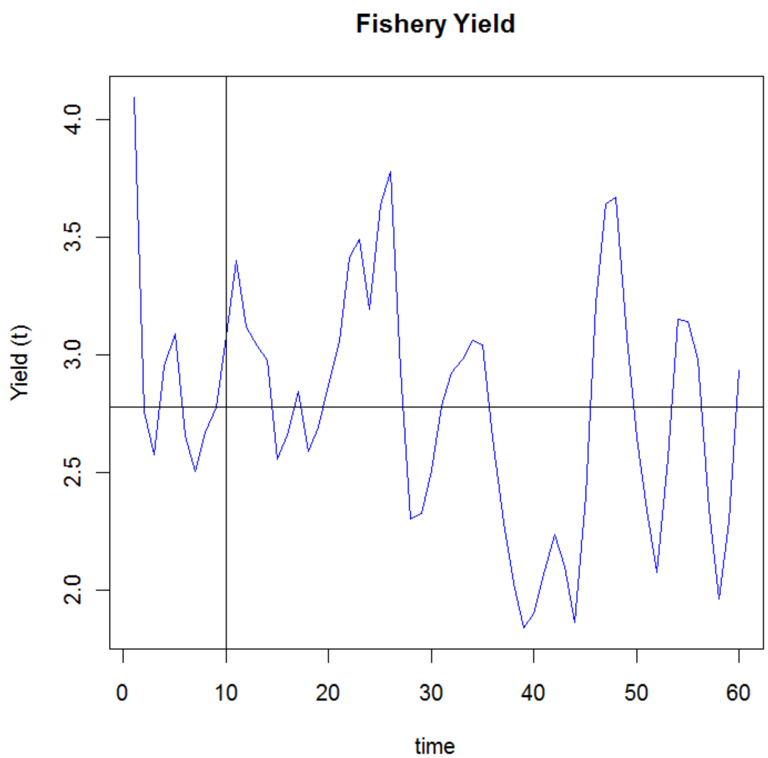
Fig 22.A3.2 Examples of Population Simulation – Model 2



Colors for population numbers plot: Stage1 brown, Stage2 red, Stage3 yellow, Stage4 green, Stage 5 blue, and Stages 6 dashed violet







R screen output:
Initial Biomass and Population Size = 83.4 10000
Final Biomass and Population Size = 64.19 12850
Average Fishery Yield = 2.77
Ending Size Frequency = 0.642 0.212 0.082 0.017 0.001 0.042

Mean, Stdev, Min, and Max of time series (after burn-in) for Nt[i] plus Rt, Bt, SBt, Yield

	Mean	StDev	Min	Max
N1	5439.621	1928.922	2396.300	9362.232
N2	2111.981	655.904	1080.014	3517.209
N3	926.392	273.844	508.435	1494.725
N4	297.731	82.156	173.443	475.272
N5	36.803	10.030	21.300	58.368
N6	678.445	129.686	452.450	946.847
Rt	5439.621	1928.922	2396.300	9362.232
Bt	64.956	10.011	45.855	84.812
SBt	14.926	2.853	9.954	20.831
Yield	2.752	0.515	1.840	3.776