6. STOCK SYNTHESIS MODEL

6.1 Model description: We used the size- and age-structured version of the "Stock Synthesis" program, hereafter referred to as Synthesis, (Methot 1990; Methot 1998; Methot 2000) to model the population dynamics of the California Sheephead stock. Synthesis is an age and size-structured model that projects the survival, growth and reproduction of individual age classes. Synthesis can incorporate ageing errors and individual variation in growth. Synthesis has three main components: First, the population model is used to project the size and age structure. Second, an observation model uses data inputs (in our case landings, CPUE data, survey information and length compositions, see Section 4) and selectivity functions (logistic functions with potentially both ascending and descending components) to relate the simulated population to the data. Third, a statistical model uses a likelihood approach to estimate the best-fit parameters for the model. Synthesis allows a variety of data types to be combined and used to estimate parameters in one formulation. A single log-likelihood function is used to calculate the total log-likelihood value associated with the model and allows emphasis factors to control the weight of each type of data and parameter in influencing the total likelihood. The likelihood calculation of our model assumed a multinomial error structure for the length compositions and log-normal error for the surveys. For more details see Methot (2000).

The preexisting version of Synthesis was not able to incorporate the sex-changing life history of Sheephead. As described above, the population dynamics of Sheephead can be approximated by a combined-sex model with a double logistic maturity function (where only individuals that are mature and female produce eggs, see Section 5). We therefore used a version of Synthesis modified by Rick Methot to allow the maturity function to have both ascending and descending portions of the equation (synl32r.exe, 1251 KB in size, compiled April 5, 2004). There were 4 parameters associated with the maturity function (see Table 3.1); these gave the probability of being mature and being female (i.e. the probability of producing eggs). We assumed that spawning occurs in June for the model, the maximum age class in the model is 20 years of age (an accumulation ages, accounting for all older fish), and mortality rates are time- and age- independent. For the original runs of the model we assumed equal likelihood weights (of 1.0) for all data sources (landings of the four fisheries, length compositions of the four fisheries, three CPUE indices and the CalCOFI survey). We used a convergence criterion of 0.001 log-likelihood units for all runs of the model.

Because CPUE data were only available starting in 1947, the landings data described above were used to generate a landings record from 1947-2003, as well as to estimate historical catch prior to 1947 (see Section 4 for details). Therefore, we used the model to project the population size structure and abundance during these years. The landings data were used within the model to estimate fishing mortality and the model assumed that mortality is independent between the four fisheries (hook and line, setnet, trap and recreational). As a result, the fishing mortality for fishery i for an age (a) and size (l) class $F_{a,l}(i,t)$ is given as the product of the selectivity of the fishery for that size and age class $(s_{a,l}(i,t))$ and the total instantaneous fishing mortality of that fishery $F(i,t)$

$$F_{a,l}(i,t) = s_{a,l}(i,t)\ F(i,t) \tag{6.1}$$

Synthesis estimated the selectivity function associated with each of these fisheries based on length composition data associated with each fishery (the available length composition data are described in Section 4) and the statistical model found the parameters for the ascending and where applicable the descending portions of the selectivity functions that best fit the data and population projections.

Since no age data associated with the fisheries or surveys were available, the selectivities were fit as only size-dependent and we explored the possibility of both descending and ascending portions of the functions (option 8 within Synthesis). The ascending function includes three parameters: an initial selectivity, a slope, and an inflection point. Including the descending portion of the function adds four parameters: a size at which the transition from ascending to descending occurs, a slope, a final selectivity, and an inflection point for the descending portion of the function.

The three CPUE indices were based on recreational landings and effort data and were therefore assumed to exhibit the same selectivity as the recreational fishery. The CalCOFI survey was fit as a spawning biomass index and the maturity and fecundity schedules serve as the selectivity curve (see below).

We calculated expected growth from the von Bertalanffy growth equation as parameterized by Schnute (1981) using the growth parameters described in Section 3. Growth was assumed to depend on age but be independent of time, sex, or maturity. We used Synthesis to calculate the annual production of eggs from the predicted abundance of individuals at each length, the proportion of individuals predicted to be mature and female at that length and the expected individual egg production of a fish of that length. Synthesis was used to calculate individual fecundity from the expected weight $W(L)$ of a fish at a given length L (determined by the allometric relationship described in Equation 3.3) and a linear relationship between mass-specific egg production and total body weight. For most years (1947-2000), we allowed recruitment to be freely estimated within Synthesis. However for the most recent years (2001-2003), we set recruitment to the model-estimated background recruitment level since the length compositions from the fisheries would not reflect abundance in these age classes because it takes a fish 3-4 years to be large enough to recruit to the fishery. We allowed the model to fit a Beverton-Holt stock recruitment curve, but we only used this curve to estimate recruitment in sensitivity analyses of the baseline model. As part of our sensitivity analyses, we also explored the possibility of other recent years or the first decade of the model being set at the estimated background recruitment level.

There were 14 likelihood components: Eight associated with the landings and length compositions for each fishery, four associated with the CPUE indices and CalCOFI survey and two associated with the recruitment function. However for all baseline runs of the model the recruitment model was fit but not used and therefore their likelihood weights were set to zero.

6.2 Model selection: Initial runs of the model focused on finding starting values for the selectivity parameters and recruitment. We started by allowing the selectivities to only fit the ascending portion of the selectivity functions. Once the model was stabilized we also explored the possibility of allowing both ascending and descending portions of the selectivity function. The trap fishery was the only one for which the model ever fit a descending limb. However, in later runs of the model the descending limb did not improve the fit of the model. Therefore in the final baseline model, all selectivities were fit as ascending only.

In initial runs of the model, the coefficient of variation in growth parameters (CV_1 and CV_2) were fixed and were later allowed to be estimated with an upper bound of 0.29. We also conducted a sensitivity analysis on CV as described below. During model selection, we also explored the possibility of allowing recruitment to be freely estimated for all years as well as increasing the likelihood weight of the estimated stock recruitment curve. This did not affect the historical situation but may influence the forward projections and interpretation of the current status of the stock. The freely estimated recruitment values more closely reflected the trends in the CalCOFI larval abundance index and therefore we used the freely estimate values that are not fit to a stock recruitment curve for the baseline model. However, extensive sensitivity analyses explored the influence of varying all of these assumptions (see below).

Because Synthesis was constrained by the age and length structure, estimates of precision that are externally estimated (e.g. jack knife estimates of standard error for abundance indices) often lead to values that are more precise than Synthesis is capable of fitting to the data. In initial runs of the model, the standard error portion of the surveys was not used. In later runs of the model, we used the internally estimated root mean square error (RMSE) of the deviates to estimate the standard error value for all four abundance indices. These standard error values were updated in the data file whenever the results of the model run lead to a different estimated standard error (when rounded to the nearest tenth). In the final runs of the model the standard error of each survey stabilized so that they did not require updating.

The original runs of the model used the actual sample sizes of the length compositions (with a maximum of 200). However, we also adjusted the length composition standard sizes to an estimated effective sample size. Synthesis provides an empirical estimate of the effective sample size for each length composition used in the model. Rather than use these effective sample sizes directly, we used these values to estimate the relationship between the true and empirical effective sample size as suggested by MacCall (1999). For the hook and line and trap fisheries, the relationship between true sample size and the empirically estimated effective sample size did not have a significant slope. We therefore replaced the true sample size with the mean of the effective sample sizes calculated by Synthesis for that fishery. For the recreational and setnet fisheries, the relationship between the true sample size and the effective sample size calculated by Synthesis exhibited a significant slope (but negative intercept). We therefore fit the slope only (the intercept was set at zero) between the true and Synthesis generated effective sample sizes. We then used this slope to generate estimated effective samples sizes and replaced the

true sample size with the externally estimated sample sizes for these two fisheries. The maximum value of 200 was retained but only influenced the values for the recreational fishery. Effective sample sizes were updated between model runs and the relationship between true sample sizes and final externally estimated sample sizes are given in Figure 6.1. The data file and parameter file used the in the final version of the baseline model are given in Appendix 1 and 2.

6.3 Characteristics of the baseline model:
1) The model considered the years from 1947 through 2003 and assumed that June was the month in which spawning occurred. 2) The selectivities for the three commercial (hook and line, setnet and traps) and one recreational fishery were fit as ascending only. The three CPUE indices were treated as surveys and linked to the selectivity of the recreational fishery. The CalCOFI survey was fit as a spawning biomass selectivity. 3) Natural mortality, growth, fecundity and maturity parameters were estimated outside of Synthesis and fixed for all runs of the model as described in Section 3. The coefficient of variation of growth at age 1 and 2 were fit with an upper bound of 0.29. 4) Recruitment was freely estimated based on the age and length compositions in all but the three most recent years where recruitment was set at the model-estimated background recruitment. The stock recruitment curve was estimated but not used in the baseline version of the model (with likelihood weights of zero for the stock recruitment function). 5) All data sources (landings, length compositions, and surveys) had equal likelihood weights within the model.

6.4 Results of the model: The likelihood components of the baseline model associated with each data source are given in Table 6.1 and the parameter values of the baseline model (estimated and fixed) are given in Table 6.2. All selectivities increased with length and all selectivity parameters were freely estimated. Trap and recreational fisheries appear to select fish in smaller size classes than the setnet and hook and line commercial fisheries, which appear to select mainly larger fish (Figure 6.2). Although some of the fisheries might have been expected to exhibit a dome shaped selectivity, the fact that we did not have size at age data above 50 cm and hence binned the length compositions above this size may explain the absence of a descending limb in all cases.

The estimated historical total biomass and spawning stock biomass are shown in Figure 6.3a. Both total and spawning stock biomass were estimated to be lower in the 1950s than any time since, and current biomass is higher than this "initial" biomass but lower than estimated for 1960-1990. The lower biomass early in the model may correspond to lower water temperatures in the 1950s compared to the last 50 years. The spawning stock biomass and total biomass show similar trends although the spawning stock biomass shows larger relative variation through time than the total biomass. Historical recruitment is also estimated to have been highly variable through time with very low recruitment in the early years compared to the last 50 years. However recruitment was estimated to have been highest in the 1980s. The estimated relationship between spawning stock biomass and recruitment (SRR) is variable but relatively flat (Figure 6.3c) and the best-fit parameters of the stock recruitment curve reflect this basic pattern as well (Table 6.2, Appendix 1). The estimated historical spawning stock biomass per

recruit was also estimated to vary greatly through time with low values in the 1950s and recent years with peaks in the early 1960s and early 1970s (Figure 6.4). We found no evidence for a relationship between estimated recruitment and sea surface temperature (using the Scripps pier sea surface temperatures; linear regression where recruitment= temperature, $F<0.001$ and $p=0.99$).

In general the model fit the abundance indices relatively well (Figure 6.4). We estimated Sheephead abundance to be low early in the trajectory, increase from the 1960s until the mid 1980s and then decline from 1985 onward (Figure 6.3a). Recruit per spawning biomass is also estimated to be highly variable through time (Figure 6.3c). The estimated landings of the commercial hook and line and trap fisheries also reflected this pattern (Figures 6.6 and 6.7). The setnet fishery did not harvest much biomass compared to the other three fisheries (Figure 6.8). Finally, the recreational fishery estimated catches were highest in 1980s and lowest in the 1950s (Figure 6.9). The model was also able to fit the length composition relatively well given the small sample size and number of years represented in some cases (Figure 6.10). Exploitation rate is also estimated to have varied temporally. Exploitation rate was estimated to be high in the late 1940s and 1950s and again starting in 1990 (Figure 6.11).

6.5 Sensitivity analyses and uncertainty: All sensitivity analyses were made in comparison to the baseline model described above. Unless mentioned otherwise, only one aspect of the model was changed at a time.

Natural mortality: Because mortality is a very important parameter that influences estimates of abundance and is difficult to estimate precisely and may vary through time, we conducted a variety of sensitivity analyses on the mortality parameter M in the model. As described in Section 3, we allowed mortality to range from 0.05 to 0.5 based on observed maximum ages for Sheephead. Mortality had a clear effect on estimates of total (Figure 6.12) and spawning biomass as well as on recruitment . We also allowed the model to estimate mortality. When the model was started at the baseline value of M=0.35, the model estimated a mortality rate of 0.35 with the likelihood indicating no significant increase in the fit to the data (Model estimating mortality: log-likelihood -342.548; Baseline model with fixed mortality value: log-likelihood -342.573). However, a starting value of 0.05 led to a best-fit parameter estimate of 0.2 and the total likelihood as a function of natural mortality rate was relatively flat between M=0.2 and 0.4 (Figure 6.13). Because the model lacks data on actual age composition, it is unlikely that changes in the log-likelihood values for alternative values of natural mortality rate are a valid basis for identifying the best value of M.

Life History Parameters: Because the life history parameters such as growth, maturity (and sex change) and fecundity also have important effects on the productivity of a stock, we performed sensitivity analyses on these parameters in the model. In the baseline model, we allowed the coefficient of variation on growth (CV_1 and CV_2) at t_1 and t_2 to be estimated but estimated the size at age 1 (L_1), size at age 13 (L_2), and growth rate k externally (as described in Section 3) and fixed them within Synthesis. As a sensitivity analysis, we allowed some of the growth parameters to be estimated by the model (L_2 and

k as well as CV_1 and CV_2). The starting values were the baseline case growth parameters. The model estimated a higher growth rate but similar size at age 13 (L_2) but this did not significantly improve the fit of the model (see Table 6.3).

Because the estimate of the coefficient of variation in growth was very high and higher than the estimated values of $CV_1=0.14$ and $CV_2=0.26$, we explored the effect of the two CV parameters on the predictions of the model. We only considered cases where $CV_1=CV_2$ since there was no biological reason to expect them to be different and examined the range from 0.10 to 0.29 in 0.01 increments. The coefficient of variation of growth had a strong effect on estimates of total biomass, recruitment and spawning stock biomass estimates and is a major source of uncertainty in this model (Figure 6.14).

As another sensitivity analysis, we ran otherwise identical versions of the model but varied the life history parameters (mortality, growth and maturity) in accordance with the estimates from the five different populations for which we had data (see Section 3 and Table 3.1). These life history parameters have a combined effect on the estimates of total biomass, recruitment and spawning biomass (Figures 6.15 and 6.16). However the two sets of parameters for Guadalupe Island did not fit the data (Figure 6.17) and lead to very different population estimates. In contrast, the parameters based on California populations all fit the data similarly well and led to the same general interpretation of the data (Figures 6.15-6.17).

We also ran a version of the model with a slope and significant intercept of the mass-specific fecundity relationship as described in Section 3 (where instead of an intercept of 129 the slope and intercept are 34.1 and 5.5; all fecundity parameters are scaled by 10,000 for computational efficiency). Although it led to a difference in individual fecundity, the same general patterns were predicted.

Clearly, the life history parameters determining mortality and growth had a strong effect on the interpretation of the available data. Therefore although we focused on the baseline case for making management recommendations we also examined a range of values of natural mortality and coefficient of variation in growth to determine how imprecision in these estimates would affect our recommendations. We also considered all four sets of life history parameters from California that fit the data well.

Recruitment: We varied the emphasis on the stock-recruitment relationship from 0 to 1 in 0.1 increments. Using the stock recruitment curve decreased the variability of the estimated recruitment through time (Figure 6.18) but not the overall trend. Changing whether recruitment early in the model (1947-1958) was set as the background level or freely estimated only affected predicted population trajectories in those years but all differences were completely gone by the 1960s. We also allowed the last three years to be read off the estimated stock-recruitment curve rather than set at the background level. This only affected the recruitment estimates in those years and values from the stock recruitment curve and freely estimated were at or near zero while the background recruitment level was higher.

Randomization of starting values: We also explored the effect of randomizing the initial values for all parameters. Starting values were sampled from a uniform distribution within ± 15% of the baseline value. This procedure was repeated twenty times and had no significant effect on either the log-likelihood (variation was at most 0.125 likelihood units), individual parameter values or predicted population trajectories.

Data: In our model we had four sources of abundance indices (three CPUEs from the recreational fishery and the CalCOFI survey) and length composition data for each of the four fisheries considered in our model (see Section 4). We explored the impact of individual data sources on the outcome of the model by increasing and decreasing their likelihood weights over the range 0.25, 0.50, 1.0, 2.0 and 4.0 while holding the likelihood weight of all other data sources at one (Figure 6.19-6.23). Only the CPFV logbook CPUE from 1980-2003 did not appear to be in agreement with the other data sources. We also explored the effect of decreasing or increasing the likelihood weight (using the same range) of all the surveys while holding all of the length composition sources at a constant likelihood weight of 1.0 as well as the reverse. This led to the same overall pattern.

Finally, we ran the model with the CPFV logbook based survey for 1947-1981 as one survey rather as two separate surveys by calibrating the effort units (see Section 4 for a complete description). This had very little effect on the fit to the survey data (Figure 6.24) or the outcome of the model (Figure 6.25).