A (simplified) state-space multi-stage lifecycle model to evaluate population impacts in the presence of density dependence: illustrated with application to delta smelt

Multiple factors acting on different life stages influence population dynamics and complicate the assessment and management of natural populations. To provide appropriate management advice, the available data should be used to determine which factors are important and what life stages they impact. It is also important to consider density dependent processes because they can modify the impact of some factors and the strength of density dependence can vary among life stages.

Management can then better target limited resources to actions that are most effective. Unfortunately, the relationships among potential factors, the life stages that they influence, and density dependence are often difficult to piece together through standard correlation or linear regression analyses. Statespace multi-stage lifecycle models can be used to evaluate population impacts in the presence of density dependence. The framework is illustrated by application to delta smelt, a threatened species that is potentially impacted by multiple anthropogenic factors.

The model is fit to two survey based times series of relative abundance: Summer tow net (STN) and fall mid-water tow (FMWT), which roughly correspond to the life stages juveniles and adults, respectively. The population is modeled from 1972 to 2006. The STN abundance index is available for the whole time period. The FMWT abundance index is available for the whole time period except for 1974 and 1979.

The transition form one stage to the next is modeled using a Beverton-Holt stock-recruitment/survival relationship

$$f(N) = \frac{aN}{1 + bN} \exp\left[\sum \beta x\right]$$

$$N_{t,A} \sim \text{Lognormal}(f(N_{t,J}), \sigma_J^2)$$

$$N_{t,J} \sim \text{Lognormal}(f(N_{t-1,A}), \sigma_A^2)$$

$$I_{t,s} \sim \text{Normal}(qN_{t,s}, v_{t,s}^2)$$

The model parameters estimated include the initial abundance of the first stage $N_{1,1}$, the parameters of the stock-recruitment model for each stage \mathbf{a}, \mathbf{b} , the coefficients of the covariates $\boldsymbol{\beta}$, the standard deviation of the process variability for each stage $\boldsymbol{\sigma}$, and the standard deviation of the observation error

(used in defining the likelihood function) for each index of abundance ${\bf v}$. The scaling factor is completely confounded with the a parameter of the Beverton-Holt model and therefore the population is modeled in terms of relative abundance that is related to the scale of the abundance indices for each life stage and only makes sense in terms of total abundance if the abundance indices are also in terms of total abundance. Therefore, the proportionality constant (q) should be set to one.

Implementation in ADMB

$$N_{t,A} = f(N_{t,J}) \exp[\sigma_J \varepsilon_{t,J} - 0.5\sigma_J^2]$$

$$N_{t,J} = f(N_{t-1,A}) \exp[\sigma_A \varepsilon_{t-1,A} - 0.5\sigma_A^2]$$

$$\varepsilon_{t,s} \sim N(0,1)$$

A penalty is added to the objective function to implement the random effects,

$$\sum_{t,s} \mathcal{E}_{t,s}^2$$
.

The negative log-likelihood function for the abundance indices ignoring constants is

$$-\ln[L] = \sum_{t,s} \ln[v_{t,s}] + \frac{(I_{t,s} - qN_{t,s})^2}{2v_{t,s}^2}$$