Appendix S2

Gerber and Kendall. Adaptive management of animal populations with significant unknowns and uncertainties: a case study. Ecological Applications.

Harvest Mortality Compensation

Under the Generating Model, harvest mortality is compensated up to natural mortality (i.e., non-harvest mortality). For a given stage k and year t, harvest mortality will only effect the number of individuals in the subsequent year ($N_{k,t}$) if harvest mortality exceeds natural mortality. We calculate this ($N2_{k,t+1} = Binom(N_{k,t}, S_k)$) as,

$$\text{f}(H_{k,t}, N_{k,t}) = \begin{cases} 0 & ,(N_{k,t} - N2_{k,t+1}) > H_{k,t} \\ N2_{k,t+1} - (N2_{k,t+1} - H_{k,t} + (N_{k,t} - N2_{k,t+1})) & ,\text{Otherwise} \end{cases}$$

In contrast, additive harvest mortality included in some population models (below) will always effect the population size in the following year, regardless of natural mortality. Such that, additive mortality is equal to $H_{k,t}$.

Carrying Capacity

To capture a wide range of conditions of density-dependence and thus population dynamics, we set the carrying capacity to be stable for the first 40 years at 20,000 cranes and then to stochastically increase for several decades before it declined back to 20,000. We calculated the stochastic carrying capacity using a simple sin function with the parameters A = 5000 (amplitude), B = 0.1 (cycles) from 0 to 2pi, C = 1500 (horizontal shift), and D = 25000 (vertical shift).

$$log(K_t) \sim \text{Normal}(log(\text{Kfunc}(5000, 0.1, 1500, 25000, t)), 0.05)$$

$$\text{Kfunc}(A, B, C, D, t) = \{A * sin(B \times (t - C)) + D\}$$

Stochastic Annual Survival

Juvenile survival is Beta distributed with a mean of 0.73 ($S_{1,\mu}$) and standard deviation of 0.07 ($S_{1,\sigma}$). We derive the α and β parameters of the Beta distribution as follows,

$$\begin{aligned}
\mu_{S_1} &= \text{JuvSDD}(S_{1,\mu} = 0.73, N_t, K_t). \\
\alpha_{S_1} &= -1 \times (\mu_{S_1} \times (S_{1,\sigma}^2 + \mu_{S_1}^2 - \mu_{S_1}))/S_{1,\sigma}^2 \\
\beta_{S_1} &= ((S_{1,\sigma}^2 + \mu_{S_1}^2 - \mu_{S_1}) \times (\mu_{S_1} - 1))/\sigma_{S_1}^2. \\
S_1 &\sim \text{Beta}(\alpha_{S_1}, \beta_{S_1})
\end{aligned}$$

Distributions are similarly derived for the adult survival parameters, but use the AdultSDD density-dependent function instead of JuvSDD.

Model 2

Model 2 is a discrete logistic growth model,

$$N_{t+1} \quad = N_t + r \times N_t \left(1 - \frac{N_t}{K_t}\right),$$

where K is unknown and not annually measured but is believed to be 30,000. The intrinsic growth rate (r) is defined based on juvenile recruitment (R_t), which is observed annually without error ($R = \frac{N_{juv}}{N_{juv}+N_{adults}}$) and differential survival of juveniles (S_1) and adults (S_2). N_{juv} and N_{adults} are the population size of juveniles (<1 year olds) and adults (> 1 year olds), respectively. $N_{juv} = \frac{R \times N_{adults}}{1-R}$. D are adult deaths, $D = N_t(1 - S_{adults})$.

$$\begin{aligned}
N_{t+1} &= N_t + r \times N_t \left(1 - \frac{N_t}{K}\right) \\
r \times N_t \left(1 - \frac{N_t}{K}\right) &= N_{t+1} - N_t \\
r &= \frac{N_{t+1} - N_t}{N_t(1 - \frac{N_t}{K})} \\
r &= \frac{N_t + N_{juv} - D - N_t}{N_t - \frac{N_t^2}{K}} \\
r &= \frac{N_{juv} - D}{N_t - N_t^2 \times K^{-1}} \\
r &= \frac{N_{juv} \times K - D \times K}{K \times N_t - N_t^2} \\
r &= \frac{K(N_{juv} - D)}{N_t(K - N_t)}
\end{aligned}$$

Need to replace N_{juv} and D, based on R and S_{juv} and S_{adults}....

$$
\begin{aligned}
R &= \frac{N_{juv}}{N_{juv}+N_{adults}} \\
R &= \frac{N_{juv}\times S_{juv}}{N_{juv}\times S_{juv}+N_t\times S_{adults}} \\
\frac{1}{R} &= \frac{N_{juv}\times S_{juv}+N_t\times S_{adults}}{N_{juv}\times S_{juv}} \\
\frac{N_{juv}\times S_{juv}}{R} &= N_{juv}\times S_{juv}+N_t\times S_{adults} \\
N_{juv}\times S_{juv} &= R\times N_{juv}\times S_{juv}+N_t\times S_{adults} \\
N_{juv} &= R\times N_{juv}+\frac{R\times N_t\times S_t}{S_{juv}} \\
N_{juv}-R\times N_{juv} &= R\times N_t\times S_{adults}\times S_{juv}^{-1} \\
N_{juv}(1-R) &= R\times N_t\times S_{adults}\times S_{juv}^{-1} \\
N_{juv} &= \frac{R\times N_t\times S_{adults}}{S_{juv}(1-R)}
\end{aligned}
$$

Now replace, N_{juv} (here) into the equation for r (above),

$$
\begin{aligned}
r &= \frac{\frac{K\times R\times N_t\times S_{adults}}{S_{juv}(1-R)}-K\times N_t(1-S_{adults})}{N_t(K-N_t)} \\
r &= \frac{K\times R\times S_{adults}}{S_{juv}(1-R)(K-N_t)}-\frac{K-K\times S_{adults}}{K-N_t}
\end{aligned}
$$

For each year, we observe the population (N_t) and fix K to an assumed value (30,000), fix juvenile and adult survival to an assumed value (S_{juv}, S_{adults}, respectively), and observe juvenile recruitment (R_t), we can then predict the population in the subsequent year ($\hat{N}_{t+1}$),

$$
\begin{aligned}
N_{t+1} &= N_t+\frac{K\times R\times S_{adults}}{S_{juv}(1-R)(K-N_t)}-\frac{K-K\times S_{adults}}{K-N_t}\times N_t\left(1-\frac{N_t}{K}\right) \\
S_{juv} &\sim Beta(\alpha_{S_{juv}},\beta_{S_{juv}}) \\
\alpha_{S_{juv}} &= -1\times(\mu_{S_{juv}}\times(\sigma^2_{S_{juv}}+\mu^2_{S_{juv}}-\mu_{S_{juv}}))/\sigma^2_{S_{juv}} \\
\beta_{S_{juv}} &= ((\sigma^2_{S_{juv}}+\mu^2_{S_{juv}}-\mu_{S_{juv}})\times(\mu_{S_{juv}}-1))/\sigma^2_{S_{juv}} \\
\mu_{S_{juv}} &= 0.81 \\
\sigma_{S_{juv}} &= 0.06 \\
\alpha_{S_{adults}} &= -1\times(\mu_{S_{adults}}\times(\sigma^2_{S_{adults}}+\mu^2_{S_{adults}}-\mu_{S_{adults}}))/\sigma^2_{S_{adults}} \\
\beta_{S_{adults}} &= ((\sigma^2_{S_{adults}}+\mu^2_{S_{adults}}-\mu_{adults})\times(\mu_{S_{adults}}-1))/\sigma^2_{S_{adults}}. \\
\mu_{S_{adults}} &= 0.956 \\
\sigma_{S_{adults}} &= 0.03
\end{aligned}
$$

Juvenile and adults survival are estimates from mark-resight and dead-recovery data (Drewien, R.C., unpublished data).

Model 3 and 4

Model 3 is a density-independent stochastic age-structured population model, where harvest mortality is additive, while Model 4 is the same population model but harvest is compensated up to natural mortality,

$$PPM1 = \begin{pmatrix} 0 & 0 & 0 & 0 & F \\ S_1 & 0 & 0 & 0 & 0 \\ 0 & S_2 & 0 & 0 & 0 \\ 0 & 0 & S_3 & 0 & 0 \\ 0 & 0 & 0 & S_4 & S_5 \end{pmatrix}$$

where S_i is the survival between ages i and $i+1$, and F is the per capita fecundity. The terminal column represents the dynamics of all individuals that live beyond the finite number of stages represented by each PPM. Survival is considered to be stochastic,

$$\begin{aligned}
S_i &\sim Beta(\alpha_{S_i}, \beta_{S_i}) \\
\alpha_{S_i} &= -1 \times (\mu_{S_i} \times (\sigma^2_{S_i} + \mu^2_{S_i} - \mu_{S_i}))/\sigma^2_{S_i} \\
\beta_{S_i} &= ((\sigma^2_{S_i} + \mu^2_{S_i} - \mu_i) \times (\mu_{S_i} - 1))/\sigma^2_{S_i} \\
\mu_{S_1} &= 0.85 \\
\sigma_{S_1} &= 0.06 \\
\mu_{S_2} &= 0.95 \\
\sigma_{S_2} &= 0.02 \\
\mu_{S_{3-5}} &= 0.96 \\
\sigma_{S_{3-5}} &= 0.03
\end{aligned}$$

We derived F based on the average number of young per pair observed in the SLV on fall migration over a 40 year period (*brood*, mean = 1.23, range = 1.13-1.39; Drewien 2011) and the proportion of breeders, which is believed to be $\approx 20\%$ (*PropBreeders*, Drewien, R.C., pers. comm., Case and Sanders 2009). The fecundity per individual is thus calculated as, $F = PropBreeders \times \frac{brood}{2}$. In order to project the population, a stage structure has to be assumed (*StageStructure*), which is also used to distribute harvest (a single annual population-level value) across each stage,

$$\hat{N}_{t+1} = PPM1 \cdot N_t \times StageStructure - f(harvest_t) \times StageStructure$$

Model 5

Model 5 is the generating model, as presented in the manuscript, but harvest mortality is assumed to be strictly additive.

Model 6

Model 6 is a moving three-year average (MTYA) estimator, $\hat{N}_{t+1} = \frac{N_{T-2}+N_{T-1}+N_T}{3}$, where T is the most current year. This estimator is often used to smooth counts in population monitoring of harvested species, including several species of geese (U.S. Fish and Wildlife Service 2014b), tundra swans, (Pacific Flyway Council 2001), and sandhill cranes, (Kruse and Dubovsky 2015).

Partial Controllability

To better understand the relationship between Rocky Mountain Population (RMP) annual harvest allocation and the estimated annual harvest, we estimated the rate of permit allocation success by state (Wyoming, Utah, Arizona, Montana, New Mexico, Idaho) using a Bayesian Poisson regression where state was treated as a random effect. The allocated permits by state was used as an offset, while the data were the annual sandhill crane harvest from each state, as estimated by hunter surveys (Kruse and Dubovsky 2015).

We found significant variation in the success of each state in fulfilling their annual permit allocation (Figure S1). Most important is that Wyoming is often near their allocation and in a few years, exceeding it. In contrast, Arizona only harvests near half their annual allocation. The reasons for these differences are many, including the number of crane hunters and hunter effort, but also the number permits each state chooses to sell in each year. States are allowed to sell more permits than their annual allocated harvest, as it creates revenue for the state, allows additional hunters to participate, and recognizes that not all permitted hunters will be successful.

References

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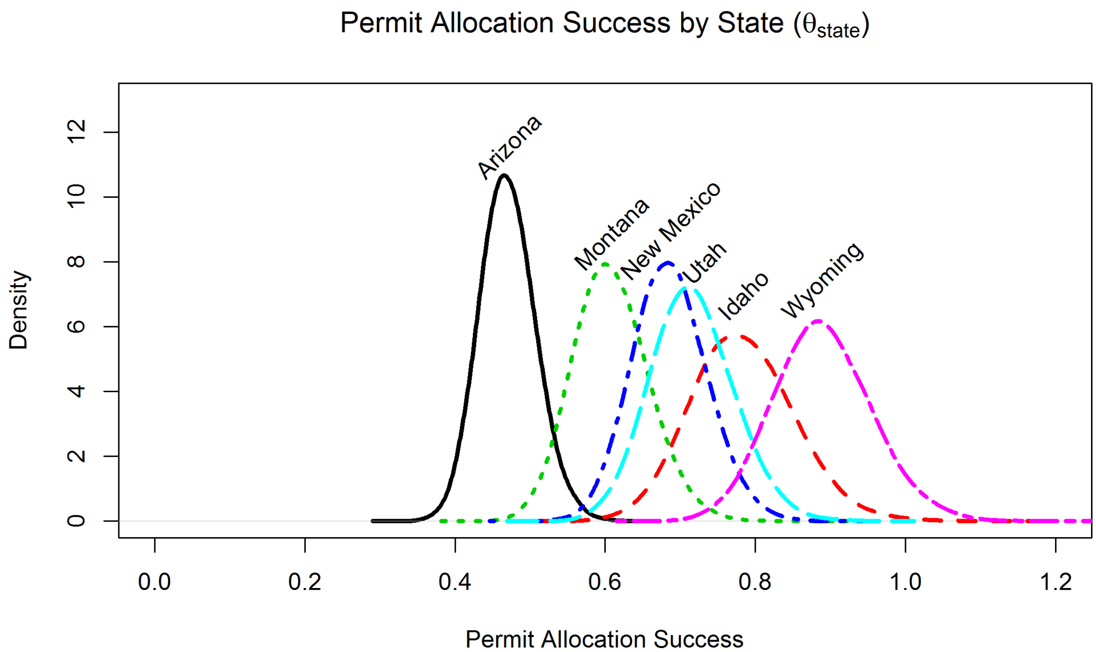

Figure S1: The estimated success rate of states that harvest sandhill cranes from the Rocky Mountain Population in fulfilling their annual allocated harvest from a Bayesian Poisson regression model.