

## Appendix 1. Additional details on methods

Additional details on Least Bell's Vireo population model used to develop the decision support tool for the Santa Clara River population.

### *Habitat Model*

There is uncertainty in both how many breeding pairs of Least Bell's Vireo the river can currently support as well as the maximum carrying capacity in the future under the most optimistic scenario of habitat restoration. The initial carrying capacity was, therefore, sampled from a uniform distribution ranging from 1.0 to 2.0 times the initial abundance. We selected this range to represent uncertainty around whether the current abundance is already near the total carrying capacity that the river could support or whether there is an appreciable amount of suitable, but unoccupied, habitat. We set the initial abundance to sample from a uniform distribution ranging from 100 to 700 pairs. The maximum carrying capacity, assuming full habitat restoration is achieved, was sampled from a uniform distribution ranging from 1,400 to 2,000 pairs. We established this range through discussion with the expert working group to reach consensus on mean density of 1 pair per 2.0 acres and analysis of areas of current potential suitable habitat on the river in each management unit given active management (Table A1.1).

The population model did not explicitly account for the spatial configuration of the properties or attempt to model dispersal of birds between properties; the management units were simply to estimate the current and potential carrying capacity of the system under different potential management scenarios.

**Table A1.1.** Estimated number of current territories of Least Bell's Vireo and future potential carrying capacity (as number of breeding pairs) if land within management units with potential to be suitable for vireo nesting was actively and successfully restored.

management unit	estimated current territories	potential carrying capacity	data references for current territories
1	71	113	(Griffith Wildlife Biology 2014, Hall 2014, 2017a, Hall and Alvarado 2018)
2	42	144	(Hall 2014, 2017a, Alvarado and Hall 2016, 2017)
3	39	107	(Hall 2017b)
4	3	25	(Hall 2017a)
5	25	134	(Hall 2011, 2017a, Werner 2015)
6	57	300	(Woodstar Biological LLC 2017)
unmanaged	267	267	

### ***Population Model***

We modeled density dependence as a simple ceiling type model where the number of pairs in each timestep would be either the predicted number of pairs from the population model, or the carrying capacity at that timestep, whichever was lower. This type of density dependence assumes that any pairs in excess of the carrying capacity simply disperse out of the area without impacting the growth rate of the remaining population. This form of density dependence is straightforward to model and does not require additional parameters. There are many alternative models for density dependence, some of which are undoubtedly more biologically realistic for this subspecies; however, for the scope of this model and this iteration of the decision support tool, we felt the assumptions of the ceiling model of density dependence were acceptable. If a more detailed population projection model is constructed in the future, a deeper exploration of the density-dependent feedbacks (Dennis and Taper 1994, Sabo et al. 2004, Dennis et al. 2006) operating on this population would be warranted at that time.

We started with an estimate of maximum population growth rate so that we could systematically modify it to reflect specific management conditions. This required an estimate of the theoretical maximum population growth rate under ideal conditions ( $r_{max}$ ). However, life history parameters estimated from field studies naturally reflect the conditions under which they were estimated (Fagan et al. 2010), which for threatened and endangered species are unlikely to reflect the ideal conditions. Thus, we explored a wide range of theoretical conditions that would impact the growth rate (namely population growth under a range of cowbird control intensities).

Initial adult and juvenile annual survival were estimated from return rates of banded birds in long-term studies in San Diego County, California from 2007 to 2015 (Kus et al. 2010, Houston et al. 2017, Lynn et al. 2017). The mean adjusted annual adult survival rate was 0.65 +/- 0.03 (SE). The mean adjusted annual juvenile return rate was 0.15 +/- 0.02 (SE). Fecundity, measured as the number of fledglings per breeding adult, was measured from 1987 to 2015 and was estimated as 1.18 +/- 0.04 (SE); this would be equivalent to 2.36 fledglings per pair (Kus et al. 2010). We used these field-based observations to describe distributions from which we could draw random samples. We drew from beta distributions on the interval (0, 1) for the survival rates, and from gamma distributions for fecundity. From these random samples we assembled a set of proposal population matrices.

To estimate a theoretical maximum growth rate, we used an approach similar to Dillingham et al. (2016) to filter the proposal matrices to only those we might expect under ideal conditions. Niel and Lebreton (Niel and Lebreton 2005) demonstrated that most birds under optimal conditions (and regardless of body size) can achieve a maximum population growth rate that scales with generation length under optimal conditions such that  $r_{max} \times GT \sim 1$ , where  $GT$  is the generation time and  $r_{max}$  ( $\ln \lambda$ ) is the maximum intrinsic growth rate. Generation time was estimated as 4.1 years (BirdLife International 2018).

Each population matrix in the proposal set was retained or discarded proportional to the probability that the resulting product of  $r_{max} \times GT$  belonged to a distribution  $N(\mu = 1, \sigma = 0.25)$ .

During each replication loop we drew a sample of adult survival, juvenile survival, and fecundity from the retained set of population matrices. From this set of ‘ideal’ life-history parameters we retained the juvenile survival as is, adjusted adult survival by multiplying by an adjustment factor, and modified the fecundity by the Brown-headed Cowbird impact adjustment factor determined by the management loop. We added an adjustment factor to the annual adult survival rate to reflect the possibility that this rate may be depressed relative to the ideal due to conditions outside of the management options considered here (e.g., overwinter survival), and because the expert working group felt that rates measured in San Diego County were accurate and representative of the likely rates expected throughout the range. The adult survival adjustment factor was drawn from a uniform distribution,  $U(0.8, 1.0)$ , and was applied during the replication loop. The final population growth rate scalar for each replication during the management loop was estimated from the dominant eigenvalue of the two-stage matrix built using the modified life-history parameters.

## Literature Cited

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