**PLATTE RIVER RECOVERY IMPLEMENTATION PROGRAM (PRRIP -OR- Program)**

**Data Analysis Outline—Quantifying Effects of Predation on Piping Plover Productivity and Evaluating Effectiveness of Predator Management**

The Platte River Recovery Implementation Program’s (PRRIP or Program) management objective for the piping plover (*Charadrius melodus*; hereafter plover) is to improve plover productivity along the central Platte River. Plover fledge ratios (chicks fledged per estimated breeding pair) are highly variable among years. In 2018 and 2019, estimated plover fledge ratios reached the lowest values observed during 2010–2019. In response, Program stakeholders prioritized learning about the impact of predation and our ability to mitigate those impacts at off-channel sand and water (OCSW) nesting sites. Two of the Program Extension Science Plan’s (PRRIP 2022a) Big Questions involve the role of predation on plover productivity. Extension Big Question (EBQ) No. 8 asks: “how much of an effect does predation have on plover productivity?” (PRRIP 2022a). Associated learning objectives for EBQ No. 8 include: (1) quantifying the impact of predation on plover productivity; (2) identifying predator species responsible for losses; (3) determining when losses occur (i.e., incubation; brood rearing); and (4) using population models to predict the effect of decreasing fledge ratios due to predation (PRRIP 2022a). EBQ No. 9 queries: “how effective is Program management at mitigating losses of plover productivity due to predation?” (PRRIP 2022a). Associated learning objectives for EBQ No. 9 include: (1) evaluating the effectiveness of trapping, fencing, and deterrent lighting at reducing nest and brood failure due to predation; (2) developing predator management alternatives based on learning through remote camera monitoring; and (3) evaluating the necessity for additional predator management actions based on plover response to predation over time (PRRIP 2022a). Herein, we provide a summary of the data collected to answer these EBQs and an outline of data analysis approaches to quantifiably address the questions.

**Data Available**

Program biologists have monitored plovers and interior least terns (*Sternula antillarum athalassos*) on up to 10 Program-managed OCSW sites using a standardized monitoring protocol since 2010 (PRRIP 2024). The 10 sites had basic predator management actions implemented including: electrified fences across the peninsula land entrance to the site; fence panel wings extending into the water at the peninsula land entrance; removal of trees ≤492 ft from the site; placement of avian spikes on non-removable perches; and trapping of mammalian predator species (PRRIP 2024). Data collected on a twice monthly basis for each site includes the number of adults and number of nests. Once ≥1 nest is established on a site, the site is monitored twice weekly to determine nest fate (successful; failed), hatching dates (if successful), and brood fate, and enumerate the numbers of chicks, fledglings, and adults (PRRIP 2024).

Beginning in 2021, the Program implemented an intensive predator monitoring study on a sample of six of the OCSW sites. Predator monitoring efforts included: weekly surveys of the peninsula shoreline for tracks of potential predators; deployment of remote cameras at fixed points along the shoreline and on the site to document potential predator presence by species; and monitoring of a sample of plover and tern nests using remote cameras. At three of the OCSW sites (Kearney Broadfoot South; Leaman; Newark West; hereafter “treatment” sites), the Program implemented additional predator management actions beginning in 2021 including the use of lights with flashing and/or random patterns to deter potential predators. The Program also established and maintained permanent fences along the interior shoreline of the peninsula at Kearney Broadfoot South and around the water moat at Newark West. Therefore, we had seven OCSW sites as “controls” and three OCSW sites as “treatments” in terms of predator management with three of the “control” sites having the more intensive predator monitoring since 2021.

**Summary of Proposed Data Analyses**

We provide an outline summary of each of the proposed data analyses below. Each analysis will address one or more questions regarding the role of predation on plover productivity and the effectiveness of the predator management actions that the Program implemented beginning in 2021 ([Figure 1](#Figure1)). We provide a timeline of data analyses, presentation of results, required decision making, and implementation in [Figure 1](#Figure1). For a more detailed background on the statistical methodology and programs to be used for each analysis, please refer to the [Appendix](#Appendix).

**Analysis 1. Evaluating management effectiveness for improving fledge ratios with a Before-After-Control-Impact (BACI) paired series design.**

* **Response variables:** annual plover fledge ratios from the seven “control” and three “treatment” OCSW sites; mean difference between treatment and control sites after the treatment (2021–2023 period) minus the mean difference between treatment and control sites before the treatment (2010–2020 period).
* **Covariates:**
  + *For annual fledge ratio response variable***:** *treatment* (control; treatment); *time* (before treatment; after treatment). We will evaluate a “classic” BACI effect as *treatment* + *time* + *treatment* x *time*.
* **Analytical frameworks:** before-after-control-impact paired series (BACIPS) design (Stewart-Oaten et al. 1986); mixed-effects modeling; Mann-Whitney U-test.

**Analysis 2. Quantifying the role of predation on and impact of other factors affecting daily nest and brood survival with a BACI paired series design.**

* **Response variable(s):** plover daily nest survival rate from the seven “control” and three “treatment” OCSW sites; plover daily brood survival rate from the seven “control” and three “treatment” OCSW sites.
* **Covariates:** 
  + *Predator management and monitoring factors:*presence of interior fence (yes; no); presence of exterior fence (yes; no); use of deterrent lighting (yes; no); nest monitored by camera (yes; no).
  + *Site and nest attribute factors:*area of potential nesting habitat; age of the OCSW site since construction or rehabilitation; nest initiation date.
  + *Random effects:*site; year.
* **Analytical frameworks:** Bayesian multinomial logistic exposure model (Darrah et al. 2018); Bayesian BACI ratio for a BACIPS design (Conner et al. 2016, Dudley et al. 2022); Bayesian Control-Impact assessments (Chevalier et al. 2019).

**Analysis 3. Quantifying factors affecting plover abundance, survival, and recruitment, and using a BACI effect to evaluate the effectiveness of predator management on these parameters.**

* **Response variable:** annual total number of adult plovers at the seven “control” and three “treatment” OCSW sites.
* **Additional model parameters:** initial abundance; apparent survival; recruitment; detection probability.
* **Covariates:**
  + *For initial abundance*: initial area of potential nesting habitat at site *i*.
  + *For apparent survival and/or recruitment*:
    - Site attributes and previous nesting: area of potential nesting habitat at site *i* in year *t*; age of site *i* since construction or rehabilitation; apparent nest success at the site the previous year; maximum number of breeding pairs at the site the previous year; number of fledglings at the site the previous year; and maximum and minimum water surface elevation at the site during year *t*.
    - Weather variability: total accumulated precipitation during May through July during year *t*; average maximum and minimum daily temperatures during May, June, and July during year *t*.
    - Temporal: the year for evaluation of different functional forms of a trend.
    - Predator management: presence of interior fence (yes; no); presence of exterior fence (yes; no); use of deterrent lighting (yes; no).
    - BACI: *treatment* (control; treatment); *time* (before treatment; after treatment). We will evaluate a “classic” BACI effect as *treatment* + *time* + *treatment* x *time*.
  + *For detection probability*: Julian date
* **Analytical framework:** *N*-mixture model (Dail and Madsen 2011).

**Analysis 4. Assessing predator communities and responses to management through evaluation of predator detections across sites and time with camera trap data.**

* **Response variable:** number of unique potential predator registers per total camera effort at three “control” and three “treatment” OCSW sites during 2021–2023.
* **Covariates:** year (2021; 2022; 2023); OCSW site (Cottonwood Ranch; Dyer; Kearney Broadfoot South; Leaman; Newark East; Newark West); use of deterrent lighting; presence of exterior fence; presence of interior fence; camera type (shoreline; site; nest); and group of species types (avian; mammalian; reptilian/amphibian).
* **Analytical framework:** mixed-effects regression.

**Analysis 5. Use of a Monte Carlo population projection model to predict impacts of predation on future plover abundance at OCSW sites through variations in adult breeding pairs and fledge ratios.**

* **Response variable(s):** annual total number of plover breeding pairs at OCSW sites; annual plover fledge ratio.
* **Covariates:** adult survival; juvenile survival; nesting density, adult immigration and emigration; juvenile immigration and emigration; available nesting habitat; nesting density.
* **Analytical framework:** Markov chain Monte Carlo simulation.

**Figure 1.** Tasks and associated timelines for data analyses (see corresponding numbers on pages 2 and 3), presentation of results, decision making, and implementation related to efforts of “Quantifying Effects of Predation on Piping Plover Productivity and Evaluating Effectiveness of Predator Management.”

**Appendix. Details of Proposed Data Analyses**

**Analysis 1. Evaluating management effectiveness for improving fledge ratios with a Before-After-Control-Impact (BACI) paired series design.**

A before-after-control-impact paired series (BACIPS) design (Stewart-Oaten et al. 1986) uses paired datasets from before and after a treatment. Treatment effects may be evaluated using a *treatment* x *time* interaction in a generalized linear mixed-effects model with *treatment* categorized as control or treatment, and *time* classified as before or after the treatment (Zuur et al. 2009, Popescu et al. 2012). The paired design allows treatment effects to be distinguished from background temporal variability shared by all sites, and from background differences between treatment and control sites (Popescu et al. 2012). Additionally, treatment effects for a BACIPS can be estimated as the mean difference between treatment and control sites after the treatment (*f*treat-control,after; 2021–2023) minus the mean difference between treatment and control sites before the treatment (*f*treat-control,before; 2010–2020; Stewart-Oaten et al. 1986). Frequentist tests for statistically significant differences between the two means may be done through a parametric t-test or nonparametric Mann-Whitney U-test (Stewart-Oaten et al. 1986, Neter et al. 1996).

We will use annual plover and tern fledge ratios (i.e., chicks/breeding pair or chicks/nest; *f*prg) estimated from the seven “control” and three “treatment” OCSW sites during 2010–2023 to conduct two analyses for each species with *p* denoting the species, *r* the site number, and *g* the year. First, we will use mixed-effects modeling techniques in R (R Core Team 2023) to examine *treatment* and *time* effects on *f*prg. Second, we will use a Mann-Whitney U-test to determine whether a significant difference exists in *f*p,treat-control,after – *f*p,treat-control,before for each species. Despite not being the species of interest in the EBQs, we will also use data from terns due to their greater abundance and number of nests established on most OCSW sites compared to plovers. The larger sample size of terns on OCSW sites may provide additional insights into predator management effectiveness.

**Analysis 2. Quantifying the role of predation on and impact of other factors affecting daily nest and brood survival with a BACI paired series design.**

We will use our twice weekly nest and brood monitoring data from the 10 OCSW sites to separately fit models for daily nest survival (*n*) and daily brood survival (*b*) for each species (Dinsmore et al. 2002, Shaffer 2004). Darrah et al. (2018) developed a Bayesian multinomial extension of the logistic exposure model to incorporate: (1) multiple causes of nest loss to assess competing probabilities of nest failure; (2) random effects to account for a lack of independence of fate probabilities within sites; and (3) annual and site-specific covariates. Including causes of nest failure in the model affords estimation of the proportion of nest losses to different causes, which then may be used for implementing tailored management actions (Darrah et al. 2018). The model has the form *yij* ~ multinomial([*Ps*(*tj*)*ij*, *Pd*(*tj*)*ij*, *Po*(*tj*)*ij*, *Pw*(*tj*)*ij*, *Pa*(*tj*)*ij*, *Pu*(*tj*)*ij*],1], where *yij* are the observed fates of nest *i* at nest-specific interval *j*, where each interval is *t* days long (Darrah et al. 2018). Observed nest fates are survival (*s*), failed-predation (*d*), failed-flooding (*o*), failed-weather (*w*), failed-abandonment (*a*), or failed-unknown (*u*), and *PF,ij* are the probabilities of the nest being at fate *F* (*F* = {*s*,*d*,*o*,*w*,*a*,*u*}) by the end of a check interval *j*, given the interval length *t* (Darrah et al. 2018).

Effects of covariates on nest loss probability during interval *j* are modeled as linear predictors of the form: *ηlij* = β*lcXij* + γ*lr*, where β*lc* is a matrix of regression coefficients for each covariate *c* associated with nest loss type *l*; *Xij* is the design matrix with nest- and interval-specific covariates values; and γ*lr* represents random effects of site *r* for loss type *l* (Darrah et al. 2018). We will define binary covariates for predation management actions at the site as: presence of interior fence; presence of exterior fence; and use of deterrent lighting. We will also define a binary covariate denoting whether the nest was monitored by a camera. We will define continuous covariates for: site area; age of the site since construction or rehabilitation; and nest initiation date. We will define year and site as random effects. We will use the model of Darrah et al. (2018) to analyze plover and tern nest and brood survival data from the seven “control” and three “treatment” OCSW sites. We will analyze data for the periods 2010–2020 (i.e., before treatment) and 2021–2023 (i.e., after treatment) separately to evaluate treatment effects as part of a BACIPS design (see description below). We will fit models with Bayesian techniques using Program JAGS (Plummer 2017) interfaced in Program R (R Core Team 2023). We will evaluate model goodness-of-fit (GOF) using techniques for multinomial models as described in Darrah et al. (2018).

We will use the methods described in Conner et al. (2016) and Dudley et al. (2022) for evaluating predation management effects on plover and tern nest and brood survival as part of a BACIPS design. Conner et al. (2016) developed a BACI ratio for paired designs based on Bayesian methods to estimate the probability of management action effectiveness. We will derive the posterior distributions of the cumulative probabilities of nest (θ*n,gp*) and brood survival (θ*b,gp*) to estimate the within year ratio of nest and brood survival probabilities from treatment and control sites as θ*n,gp,t|c* = θ*n,gp,treatment*/θ*n,gp,control* and θ*b,gp,t|c* = θ*b,gp,treatment*/θ*b,gp,control*, respectively. We will split nest and brood survival probability ratios into 2010–2020 and 2021–2023 periods denoting before and after predator management implementation, respectively. We will calculate an average ratio across all years within each period as θ*n,gp,t|c,before* and θ*n,gp,t|c,after* for nest survival, and θ*b,gp,t|c,before* and θ*b,gp,t|c,after* for brood survival. We will then calculate BACI ratios for nest survival as θ*n,BACI* = θ*n,gp,t|c,after*/θ*n,gp,t|c,before* and brood survival as θ*b,BACI* = θ*b,gp,t|c,after*/θ*b,gp,t|c,before* (Conner et al. 2016, Dudley et al. 2022). A BACI ratio of one may be interpreted as survival not changing at sites after predator management was implemented. A BACI ratio of 1.25, for example, may be interpreted as survival at predator management sites increasing 25% on average after implementation relative to control sites over the same period. In contrast, a BACI ratio of 0.75 may be interpreted as survival at predator management sites decreasing 25% relative to control sites over the same period.

We will use additional control-impact (CI) metrics defined by Chevalier et al. (2019) and applied by Dudley et al. (2022) to distinguish changes in nest and brood survival from management effectiveness compared to those from natural temporal changes. The CI-contribution measures the difference between the mean magnitude of effect over time in treatment sites and the mean magnitude of effect over time in the control sites and is defined for nest survival as *CIcontribution,n* = |θ*n,treatment,after* - θ*n,treatment,before*| - |θ*n,control,after* - θ*n,control,before*| (Chevalier et al. 2019, Dudley et al. 2022). The CI-divergence measures the change in the degree of dissimilarity between treatment and control areas over time and is defined as *CIdivergence,n* = |θ*n,treatment,after* - θ*n,control,after*| - |θ*n,treatment,before* - θ*n,control,before*| (Chevalier et al. 2019, Dudley et al. 2022). Comparable measures of CI-contribution and CI-divergence may be calculated for brood survival.

**Analysis 3. Quantifying factors affecting plover abundance, survival, and recruitment, and using a BACI effect to evaluate the effectiveness of predator management on these parameters.**

*N*-mixture models use repeated within year survey counts of unmarked individuals across multiple sites to make inference about abundance while accounting for detection probability (Kéry and Royle 2016). The *N*-mixture model combines one submodel for abundance with another submodel for the observation process (Kéry and Royle 2016). The dynamic *N*-mixture model of Dail and Madsen (2011) is applicable when the population is open to births, deaths, immigration, and emigration, and data is collected across years. The process model includes parameters for the: initial abundance at site *i* [*N*i,1 ~ Poisson(λ)]; survival process at site *i* from year *t* to *t*+1 [*S*i,t+1 ~ Binomial(*N*i,t,φ)]; and recruitment process at site *i* from year *t* to *t*+1 [*R*i,t+1 ~ Poisson(γ)] (Dail and Madsen 2011). Modeling the survival and recruitment processes provides estimates of apparent survival (true survival minus emigration) and gains (reproduction plus immigration), respectively (Dail and Madsen 2011). The process model describes dynamics by using the initial abundance and allowing transitions from *t* to *t*+1 using Markovian dynamics (Kéry and Royle 2021). The observation model includes a parameter for the detection probability based on a binomial distribution (Dail and Madsen 2011). Initial abundance may be related to temporally static covariates, whereas apparent survival and recruitment may be related to both static (i.e., temporally unchanging) and dynamic covariates (Dail and Madsen 2011).

We will use our adult count data from plover monitoring at the 10 OCSW sites during 2010–2023 to parameterize the Dail and Madsen (2011) model. Because our monitoring consists of multiple nested secondary sampling periods (*j*) within each year (*t*), our data is consistent with a “robust design” that assumes closure among secondary periods (Pollock 1982, Kéry and Royle 2021). We will define static covariates that characterize attributes of individual OCSW sites including the initial area of potential nesting habitat at site *i*. We will define dynamic covariates describing site attributes and previous nesting including the: area of potential nesting habitat at site *i* in year *t*; age of site *i* since construction or rehabilitation; apparent nest success at the site the previous year; maximum number of breeding pairs at the site the previous year; number of fledglings at the site the previous year; and maximum and minimum water surface elevation at the site during year *t*. We will define dynamic covariates describing weather variability including the: total accumulated precipitation during May through July during year *t* as determined from the weather station closest to the site; and average maximum and minimum daily temperatures during May, June, and July during year *t* as determined from the weather station closest to the site. We will define a covariate, *year*, to evaluate different functional forms of a temporal trend in apparent survival and recruitment. We will define binary covariates for predation management actions at the site as: presence of interior fence; presence of exterior fence; and use of deterrent lighting. We will also define a covariate denoting the Julian date of the survey for use in evaluating detection probability.

Popescu et al. (2012) evaluated a BACI design within a dynamic occupancy modeling framework. We will extend the approach of Popescu et al. (2012) to the Dail and Madsen (2011) model and apply it to our predator management efforts at OCSW sites. We will define binary covariates denoting whether the site had additional predator management (*treatment*) and whether the year *t* was before or after the implementation of additional predator management (*time*). We will evaluate a “classic” BACI effect term (*treatment* + *time* + *treatment* x *time*) for apparent survival and recruitment parameters. We will also define a continuous covariate denoting the number of years since implementation of additional predator management (*yearafter*).

We will use a stepwise approach to develop competing models consisting of biologically plausible combinations of covariates for initial abundance, apparent survival, and recruitment. We will fit models using package *unmarked* (Fiske and Chandler 2011, Kellner et al. 2023) in R (R Core Team 2023). We will calculate an AIC value for each model, and rank and select the best-approximating models using ΔAIC (Burnham and Anderson 2002).

**Analysis 4. Assessing predator communities and responses to management through evaluation of predator detections across sites and time with camera trap data.**

Our annual monitoring reports have provided yearly (2021, 2022, 2023) information on registers of potential predators per camera day for shoreline, site-level, and nest-level cameras by site and by species type (PRRIP 2022b, PRRIP 2023, PRRIP 2024). However, we have not analyzed all three years of data together. We will use data from our three years of remote camera monitoring efforts at the six OCSW sites to evaluate spatial, temporal, and site differences in avian, mammalian, and reptilian and amphibian predator communities, and the effectiveness of predator deterrents.

We will define a response variable *Trceg* as the number of unique registers per total camera effort for each site *r*, camera type *c* (shoreline; site; nest), and group of species types *e* (avian; mammalian; reptilian/amphibian) for each year *g*. We will calculate unique registers per total camera effort using the same methodology as that used in the annual monitoring reports (PRRIP 2022b, PRRIP 2023, PRRIP 2024). We will define categorical covariates as: year (2021; 2022; 2023); site (Cottonwood Ranch; Dyer; Kearney Broadfoot South; Leaman; Newark East; Newark West); use of deterrent lighting (yes; no); presence of exterior fence (yes; no); presence of interior fence (yes; no); camera type; and group of species types. We will use mixed-effects regression techniques in R (Pinheiro and Bates 2000, Pinheiro et al. 2023, R Core Team 2023) to fit models and estimate covariate coefficients. Models will consist of combinations of covariates to test hypotheses related to the effectiveness of predator deterrent actions on registers of potential predator species across years and sites. We will include the site as a random effect to account for repeated measurements over time. We note that this is a “naïve” approach that does not account for detection probability, the spatial coverage of the camera viewshed, and variability in spatial and temporal coverage of cameras across all scales due to any camera malfunctions that occurred.

**Analysis 5. Use of a Monte Carlo population projection model to predict impacts of predation on future plover abundance at OCSW sites through variations in adult breeding pairs and fledge ratios.**

We will use a Markov chain Monte Carlo (MCMC) population projection model (Oracle 2024) to examine how variability in plover demographic parameters (i.e., adult and juvenile survival), nesting density, adult and juvenile immigration, and adult and juvenile emigration affects predictions of future plover abundance and fledge ratios at OCSW sites. The model is parameterized using empirical data from our long-term monitoring including area of available OCSW habitat and estimates of adult breeding pairs and fledge ratios. We will use estimates of adult and juvenile survival, immigration, and emigration from the literature to inform prior estimates and distributions for the model. We will also use information gathered from analyses (1), (2), and (3) to evaluate biologically plausible effects of predator management on estimates and variability in plover breeding pairs and fledge ratios.

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