

# **Trend Analysis for National Park Service Prairie Falcon Data from 1989 to 2013**

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October 2013

U.S. Department of the Interior  
National Park Service  
Natural Resource Stewardship and Science  
Fort Collins, Colorado

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## **INTRODUCTION**

Annual prairie falcon monitoring at Pinnacles National Park (PINN) has been conducted annually for over 25 years. Prairie falcon surveys have been conducted most consistently since 1989, and the data collected from 1989 through 2013 are analyzed here. Trends in occupancy, productivity, and phenology are estimated and tested to determine if the prairie falcon population has changed significantly during the past 25 years.

## **SURVEY DESIGN**

The current population consists of a total of 45 territories, defined as areas occupied, defended, and used for nesting by a pair of prairie falcons. These 45 territories have been identified over years of sampling, and the original sampling frame of prairie falcon territories from the beginning of the monitoring period was likely smaller given the smaller sample sizes from the earlier years (Table 1).

The territories are divided into areas called "Core" and "Non-Core" areas. Core areas are those occurring in habitat with steep walls that are often used by humans for climbing. PINN personnel often monitor these areas closely to ensure that climbing activity does not adversely impact prairie falcon breeding, and those areas are closed to climbing if human impacts become a concern. The Core territories are nearly censused each year due to this additional monitoring. The remaining territories are considered Non-Core territories and nearly censused in recent years.

Note that classic randomized sampling has not been applied in obtaining annual samples. The Core sites have always been nearly censused and the Non-Core territories were visited on a roughly alternating schedule so that each would be visited regularly if not annually. Model-based statistical analysis requires the assumption that territories visited each year were not chosen based on the outcomes of interest, which include measures of occupancy, productivity, and phenology (Schreuder et al. 1999). Because Core areas providing excellent climbing opportunities may also serve as good prairie falcon nesting sites, the classification of Core vs. Non-Core is used as a stratification variable. The Core stratum is censused (or nearly so), so bias due to inference outside of the stratum is not of concern.

Table 1: Number of Core and Non-Core Territories Sampled by Year

| <b>Year</b> | <b>Non-Core Territories Sampled</b> | <b>Core Territories Sampled</b> |
|-------------|-------------------------------------|---------------------------------|
| 1989        | 7                                   | 10                              |
| 1990        | 7                                   | 10                              |
| 1991        | 6                                   | 12                              |
| 1992        | 6                                   | 10                              |
| 1993        | 4                                   | 10                              |
| 1994        | 4                                   | 11                              |
| 1995        | 4                                   | 11                              |
| 1996        | 3                                   | 10                              |
| 1997        | 3                                   | 12                              |
| 1998        | 3                                   | 11                              |
| 1999        | 4                                   | 7                               |
| 2000        | 7                                   | 11                              |
| 2001        | 7                                   | 12                              |
| 2002        | 8                                   | 12                              |
| 2003        | 11                                  | 12                              |
| 2004        | 11                                  | 12                              |
| 2005        | 10                                  | 12                              |
| 2006        | 12                                  | 14                              |
| 2007        | 18                                  | 13                              |
| 2008        | 14                                  | 16                              |
| 2009        | 18                                  | 17                              |
| 2010        | 25                                  | 18                              |
| 2011        | 25                                  | 17                              |
| 2012        | 27                                  | 18                              |
| 2013        | 26                                  | 18                              |

## DATA ANALYSIS

Occupancy is modeled with two approaches: the naïve estimator of occupancy that assumes perfect detection for the combined number of territory visits within a year and occupancy estimation assuming imperfect detection. Poisson hurdle models are used to describe trends in hatchlings and known fledglings and to account for the excess zeros in the metrics. Trends in phenology measured by minimum and maximum hatch dates are assessed with ordinary least squares regression. Modeling covariate data were obtained from the National Park Service Air Resources Division's (2013) database for gaseous pollutant and meteorological data. Covariates include measurements of temperature, solar radiation, and ozone. Relative humidity and wind speed metrics were incomplete for some years of the monitoring period, so these variables were not used in favor of modeling as complete a data set as possible.

## Occupancy Analysis

### *Naïve occupancy*

Naïve occupancy estimation involves the implicit assumption that, over several revisits to a site within a year, an accurate assessment of occupancy is obtained. In this case, no occupied territories are mistakenly categorized as unoccupied sites. The PINN prairie falcon monitoring protocol was developed to meet this assumption as previous work determined that three revisits to a territory within a year was sufficient to make an accurate determination of occupancy. Therefore, assuming perfect detection over the combined within-year revisits, the final status of occupancy in each territory is used to obtain an estimate of annual occupancy calculated as the proportion of occupied territories by Core vs Non-Core stratum.

A linear mixed model of the occupancy rate is used to obtain a test of the fixed effect of trend and to account for serial correlation with the random effect of time. Linear trend is modeled with a numeric covariate ranging from 0 to 25 (WYear) and the random effect is modeled with a factor representing the 25 levels of the Year variable. An arc-sine square-root transformation was applied to the occupancy rate to meet the assumptions of linear modeling. No environmental covariates were found to be significant in modeling the occupancy rate. The modeling results are provided below. Satterthwaite degrees of freedom for the unbalanced data set (Piepho and Ogutu 2002) are used to test the null hypothesis of no trend against the two-sided alternative (t-statistic = -6.709, df = 19.66, p-value < 0.0001).

Linear mixed model fit by REML

Formula: arcsinsqrt(Occ) ~ WYear + (1 | Year)

Random effects:

| Groups   | Name        | Variance  | Std.Dev. |
|----------|-------------|-----------|----------|
| Year     | (Intercept) | 0.0013683 | 0.03699  |
| Residual |             | 0.0888103 | 0.29801  |

Number of obs: 58, groups: Year, 25

Fixed effects:

|              | Estimate         | Std. Error      | t value       |
|--------------|------------------|-----------------|---------------|
| (Intercept)  | 1.343198         | 0.081119        | 16.558        |
| <b>WYear</b> | <b>-0.036119</b> | <b>0.005384</b> | <b>-6.709</b> |

A similar analysis was conducted using the binary indicators of occupancy (0 for unoccupied or 1 for occupied) at the territory and year level in a binomial generalized linear model (GLM). As in the prior naïve occupancy analysis, no environmental covariates were found to be significant predictors. The trend test for the binomial GLM also indicates a significant trend (z-statistic = -0.1215, p-value < 0.0001) that is also negative (output below). A "rug" plot, which plots the frequency of the binary occupancy indicators with the predicted occupancy rate in the [0,1] interval is provided in Figure 1.

Formula:  $PA \sim WYear + (1 \mid Year)$

Random effects:

| Groups Name      | Variance | Std.Dev. |
|------------------|----------|----------|
| Year (Intercept) | 0.11377  | 0.33729  |

Number of obs: 586, groups: Year, 25

Fixed effects:

|              | Estimate        | Std. Error     | z value       | Pr(> z )            |
|--------------|-----------------|----------------|---------------|---------------------|
| (Intercept)  | -239.49898      | 33.17146       | -7.220        | 5.20e-13 ***        |
| <b>WYear</b> | <b>-0.12145</b> | <b>0.01681</b> | <b>-7.226</b> | <b>4.98e-13 ***</b> |

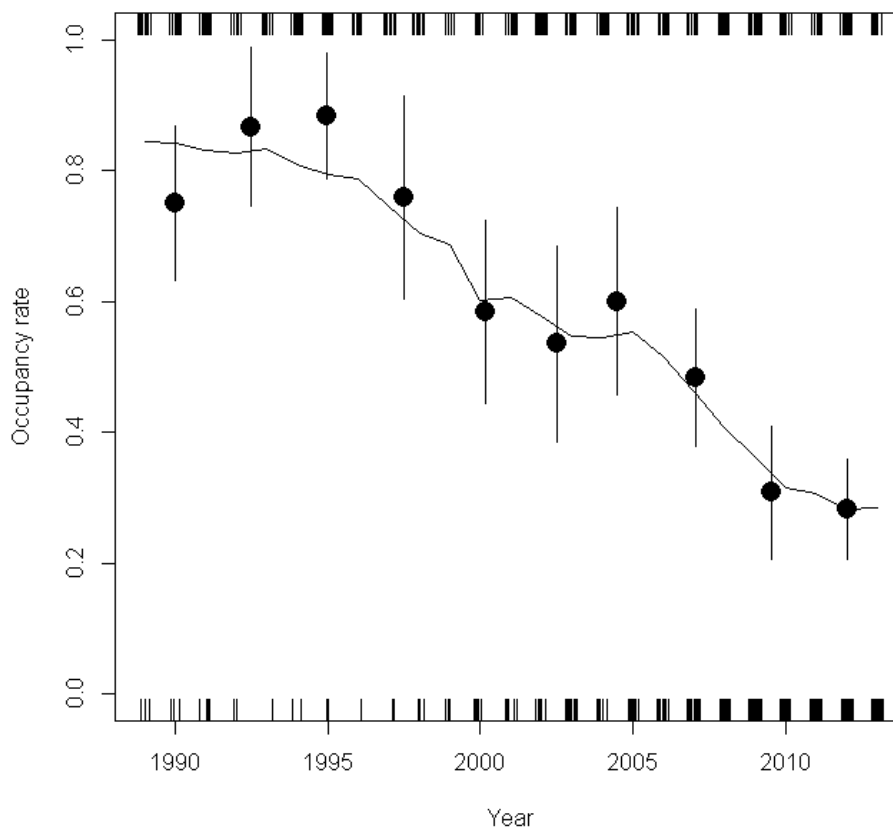


Figure 1: "Rug" plot of occupancy with binomial GLM regression line for the complete sample of territories

A concern is that the sites initially visited in the 1980's and 1990's were sites that are more consistently occupied. If this is true, then the trends observed in this analysis may detect a trend toward more accurate occupancy estimation for the entire population of territories rather than a trend in the occupancy parameter. A trend analysis was conducted for the subset of 18 sites that were visited during at least 15 of the 25-year monitoring period. The trend analysis for this subpopulation indicated a declining trend (see results below) but one that is not as severe as measured for the entire population of sites with the binomial GLM (z-statistic = -0.0835, p-value < 0.0001). The slope of the trend in the rug plot for the subset of sites indicates a trend line with a less-severe downward slope (Figure 2).

Formula:  $PA \sim WYear + (1 | Year)$

Random effects:

| Groups Name      | Variance | Std.Dev. |
|------------------|----------|----------|
| Year (Intercept) | 0.16708  | 0.40876  |

Number of obs: 399, groups: Year, 25

Fixed effects:

|              | Estimate        | Std. Error     | z value       | Pr(> z )        |            |
|--------------|-----------------|----------------|---------------|-----------------|------------|
| (Intercept)  | -164.23085      | 38.29175       | -4.289        | 1.80e-05        | ***        |
| <b>WYear</b> | <b>-0.08347</b> | <b>0.01939</b> | <b>-4.305</b> | <b>1.67e-05</b> | <b>***</b> |

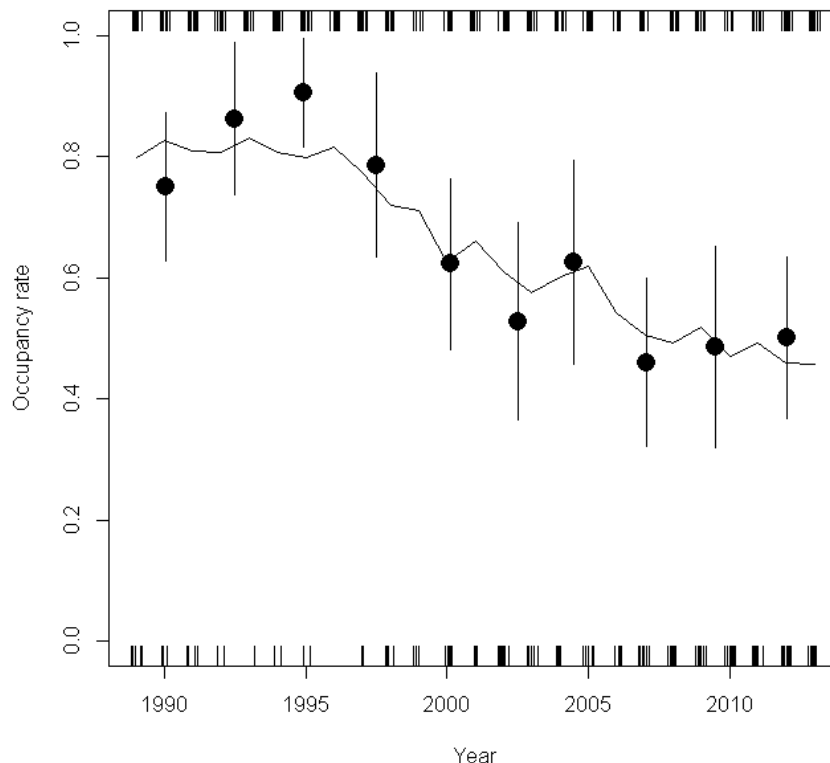


Figure 2: "Rug" plot of occupancy with binomial GLM regression line for the subset of 18 territories visited at least 15 of the 25 years in the monitoring period

### *Occupancy assuming imperfect detection*

Occupancy analysis assuming that the detection probability is less than one is conducted as outlined in SOP 5. The number of detections is modeled as a zero-inflated binomial random variable. The implicit occupancy model, in which the net effect of extinction and colonization rates on occupancy is modeled, is applied (MacKenzie et al. 2006). Both the occupancy rate and the detection rate are modeled solely as a function of time. Due to excessive time required for convergence to maximum likelihood solutions, time is the only covariate included in the occupancy and detection models. The estimates of occupancy and detection rates are provided in Table 2 and plotted in Figure 3. Tests of trend are conducted with the The occupancy rate exhibits a significant decreasing trend over time (Chi-squared statistic = 142.41, df = 1, p-value < 0.0001) and the detection probability significantly increases over time (Chi-squared statistic = 70.82, df = 1, p-value < 0.0001).

Table 2: Estimated occupancy and detection rates with 90%-confidence intervals

| <b>Year</b> | <b>Est.<br/>Occupancy<br/>Rate</b> | <b>90%-CI<br/>Low</b> | <b>90%-CI<br/>High</b> | <b>Est.<br/>Detection<br/>Rate</b> | <b>90%-CI<br/>Low</b> | <b>90%-CI<br/>High</b> |
|-------------|------------------------------------|-----------------------|------------------------|------------------------------------|-----------------------|------------------------|
| 1989        | 0.9998                             | 0.9991                | 0.9999                 | 0.0077                             | 0.0010                | 0.0549                 |
| 1990        | 0.9997                             | 0.9988                | 0.9999                 | 0.0119                             | 0.0018                | 0.0729                 |
| 1991        | 0.9995                             | 0.9984                | 0.9999                 | 0.0182                             | 0.0032                | 0.0961                 |
| 1992        | 0.9993                             | 0.9979                | 0.9998                 | 0.0277                             | 0.0056                | 0.1259                 |
| 1993        | 0.9991                             | 0.9972                | 0.9997                 | 0.0419                             | 0.0097                | 0.1632                 |
| 1996        | 0.9973                             | 0.9932                | 0.9989                 | 0.1375                             | 0.0496                | 0.3272                 |
| 1999        | 0.9922                             | 0.9837                | 0.9963                 | 0.3672                             | 0.2149                | 0.5517                 |
| 2000        | 0.9890                             | 0.9783                | 0.9944                 | 0.4717                             | 0.3206                | 0.6282                 |
| 2001        | 0.9843                             | 0.9711                | 0.9916                 | 0.5787                             | 0.4467                | 0.7004                 |
| 2002        | 0.9778                             | 0.9615                | 0.9873                 | 0.6788                             | 0.5768                | 0.7662                 |
| 2003        | 0.9687                             | 0.9490                | 0.9809                 | 0.7648                             | 0.6920                | 0.8248                 |
| 2004        | 0.9560                             | 0.9327                | 0.9714                 | 0.8334                             | 0.7808                | 0.8754                 |
| 2005        | 0.9384                             | 0.9117                | 0.9574                 | 0.8850                             | 0.8434                | 0.9167                 |
| 2006        | 0.9144                             | 0.8848                | 0.9370                 | 0.9221                             | 0.8863                | 0.9473                 |
| 2007        | 0.8824                             | 0.8508                | 0.9080                 | 0.9480                             | 0.9166                | 0.9679                 |
| 2008        | 0.8404                             | 0.8087                | 0.8676                 | 0.9656                             | 0.9385                | 0.9810                 |
| 2009        | 0.7870                             | 0.7574                | 0.8138                 | 0.9773                             | 0.9545                | 0.9888                 |
| 2010        | 0.7216                             | 0.6954                | 0.7464                 | 0.9852                             | 0.9663                | 0.9935                 |
| 2011        | 0.6453                             | 0.6206                | 0.6692                 | 0.9903                             | 0.9751                | 0.9963                 |
| 2012        | 0.5607                             | 0.5315                | 0.5895                 | 0.9937                             | 0.9815                | 0.9978                 |
| 2013        | 0.4725                             | 0.4342                | 0.5111                 | 0.9959                             | 0.9863                | 0.9988                 |

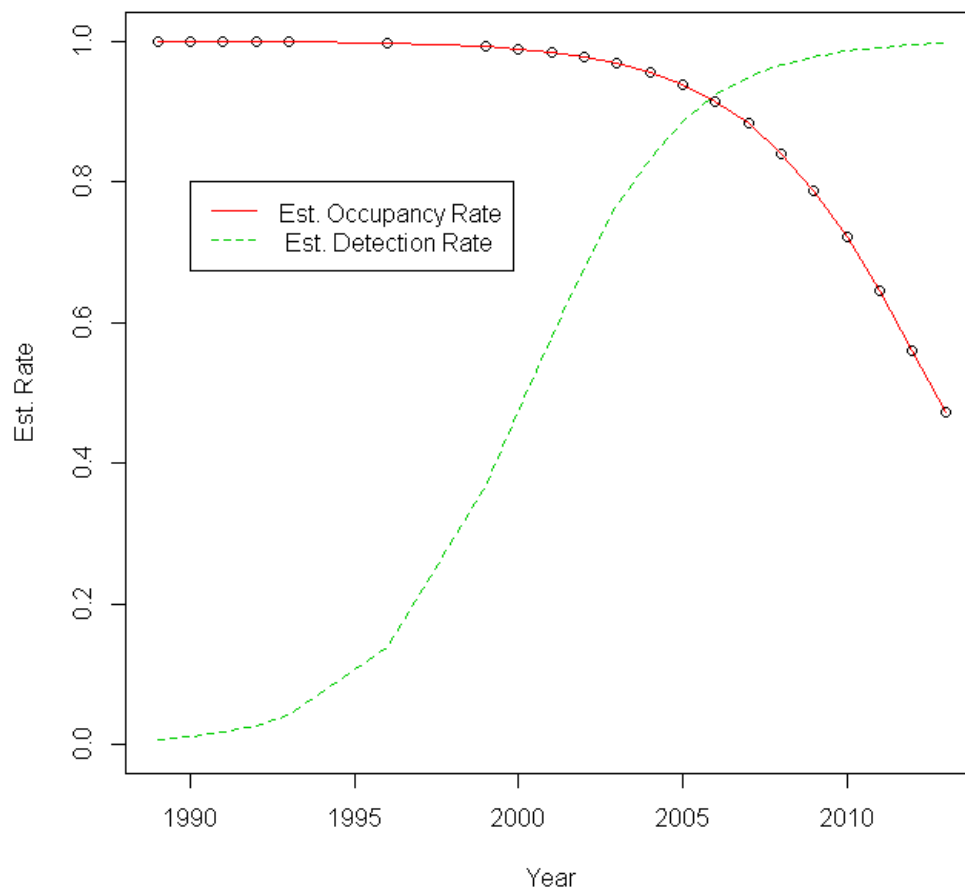


Figure 3: Estimated occupancy and detection rates from the occupancy analysis assuming imperfect detection

The estimated detection rates are very low for early years. More accurate detection estimates may be obtained from a model containing environmental covariates related to detection probabilities. Similarly, the occupancy rates from the early years are much higher than those obtained from the naïve analysis and are probably influenced by the low detection probability estimates. The estimated detection probabilities for recent years are very high, likely a function of consistent within-year monitoring as outlined by the protocol. The naïve analysis may provide the more reasonable estimates of occupancy for the entire monitoring period.

## Fecundity Analysis

### Hatchlings

A trend analysis of hatchlings was conducted to determine if numbers of fledglings in occupied territories were changing since 1989. Numbers of hatchlings per Territory range from 0 to 5 (Figure 4) with evidence of excessive zeros as compared to a standard Poisson count (Figure 5). Several possible models were examined, including a Poisson generalized linear model, a zero-inflated Poisson model, a Poisson hurdle model, and a negative binomial hurdle model. A zero-inflated model would model the zeros as partially explained by the Poisson process and partially by another process such as imperfect detectability or a mechanism that would impact successful hatching. The zeros in a hurdle model are treated as outcomes of a single mechanism that accounts for the extra zeros only when the expected number of zeros exceeds those of a Poisson distribution. Using AIC as the basis for model selection, the Poisson hurdle model was selected for the trend analysis. Covariates for temperature, relative humidity, wind speed, solar radiation, and ozone were considered, but stepwise variable selection based on AIC did not indicate that any were effective predictors of the number of hatchlings. The hurdle and zero-inflated models were computed with the *pscl* package (Zeileis et al. 2008) in R (2013).

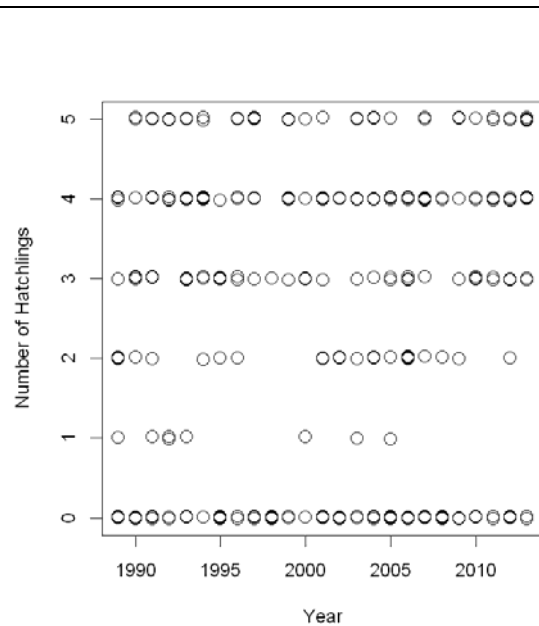


Figure 4: Number of Hatchlings by Year across Territories

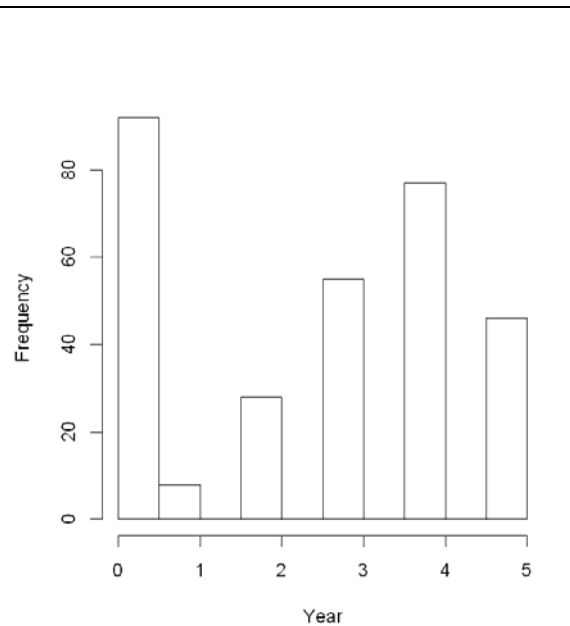


Figure 5: Frequency of Hatchlings across Years

Modeling both the zero hurdle model and the non-zero count model as functions of the location-shifted Year variable (shifted to range from 0 to 24) allowed model convergence and defined standard errors. Model selection was assisted by identifying covariates to model trends in the proportion of occupied territories with at least one hatchling (Figure 6). Covariates identified in this analysis were added to the zero portion of the hurdle

portion of the model and improved the fit based on AIC. The results of the analysis of the proportion of occupied territories with at least one hatchling are nearly identical to the results of the zero portion of the hurdle model and are not presented here.

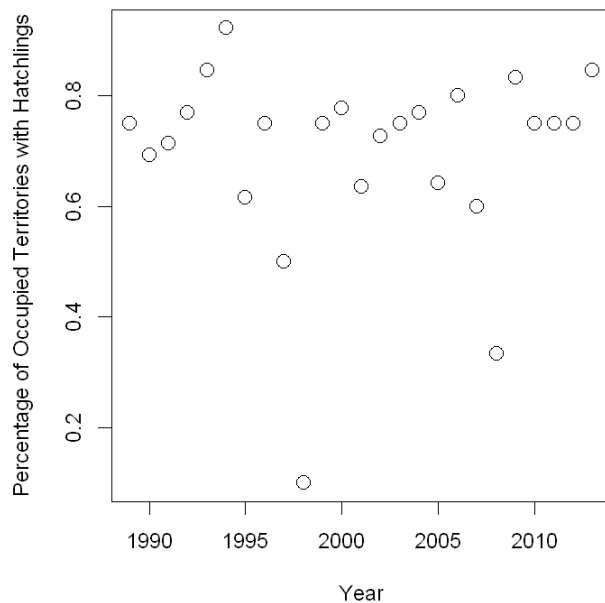


Figure 6: Proportion of Occupied Territories containing Hatchlings by Year

The results (given below from R output) indicate no significant trend in either the non-zero count data over time (Year coefficient for the truncated Poisson model with log link of 0.006076, SE = 0.005087, p-value = 0.2320) or the probability that the hurdle is cleared (*i.e.* that the number of hatchlings is non-zero; Year coefficient for the binomial model with logit link of 0.020352, SE = 0.018856, p-value = 0.2804). The zero portion of the model also contained several significant environmental covariates, including the indicator of a Core territory, April total precipitation, and the minimum April ozone level. Note the significant negative impacts of April total precipitation and minimum ozone levels and the on the probability that at least one hatchling is present in occupied territories. Also note that the positive coefficient of the Core stratum suggests that the probability of observing at least one hatchling in the core areas is greater than that found in the Non-Core stratum, although the p-value is not convincing. Autocorrelation plots revealed possible serial autocorrelation of lag 3, so the independence may not be met. Maximum likelihood methods are often insufficient to find solutions for nonlinear models that include random effects and complex correlation structure. Analysis in a Bayesian context may be useful in the future.

```
hurdle(formula = Hatchlings ~ WYear | WYear + Core + AprPrecip +
AprOzoneMin,
      data = PRFA.Occ, dist = "poisson", zero.dist = "binomial")
```

Count model coefficients (truncated poisson with log link):

|              | Estimate        | Std. Error      | z value      | Pr(> z )     |
|--------------|-----------------|-----------------|--------------|--------------|
| (Intercept)  | 1.170585        | 0.074038        | 15.811       | <2e-16 ***   |
| <b>WYear</b> | <b>0.006076</b> | <b>0.005087</b> | <b>1.194</b> | <b>0.232</b> |

Zero hurdle model coefficients (binomial with logit link):

|              | Estimate        | Std. Error      | z value      | Pr(> z )       |
|--------------|-----------------|-----------------|--------------|----------------|
| (Intercept)  | 1.294894        | 0.402786        | 3.215        | 0.00131 **     |
| <b>WYear</b> | <b>0.020352</b> | <b>0.018856</b> | <b>1.079</b> | <b>0.28044</b> |
| Core (TRUE)  | 0.509901        | 0.260665        | 1.956        | 0.05045 .      |
| AprPrecip    | -0.010020       | 0.006115        | -1.638       | 0.10134        |
| AprOzoneMin  | -0.240269       | 0.083906        | -2.864       | 0.00419 **     |

### *Known Fledglings*

A trend analysis of numbers of known fledglings from 1989 to 2013 (Figure 7) was conducted similarly to the hatchling analysis. The numbers of known fledglings also exhibited more zero counts than would be expected by a standard Poisson distribution (Figure 8). Four possible models were examined and included a Poisson generalized linear model, a zero-inflated Poisson model, a Poisson hurdle model, and a negative binomial hurdle model. As with the hatchling trend analysis, the number of known fledglings was best modeled with the Poisson hurdle model based on AIC as the model selection criterion.

As with the model of hatchlings, a trend analysis of the proportion of territories with at least one fledgling (Figure 9) helped in identifying model predictors. The non-zero count data area modeled as a function of time and the indicator of a Core territory, suggesting that the probability of at least one fledgling may be higher in Core territories than Non-Core territories. A significant trend in the non-zero counts of fledglings is found (Year coefficient for the truncated Poisson model with log link of 0.015372, SE = 0.005372, p-value = 0.0080). The probability of obtaining non-zero data is modeled as a function of the location-shifted Year and environmental covariates (R output given below), and no significant trend is observed in the probability of observing non-zero fledglings (Year coefficient for the binomial model with logit link of 0.0147, SE = 0.0175, p-value = 0.4015). The final model with the lowest AIC contained environmental covariates representing April precipitation and the minimum April ozone level. Autocorrelation plots revealed no significant serial autocorrelation, so independence is assumed.

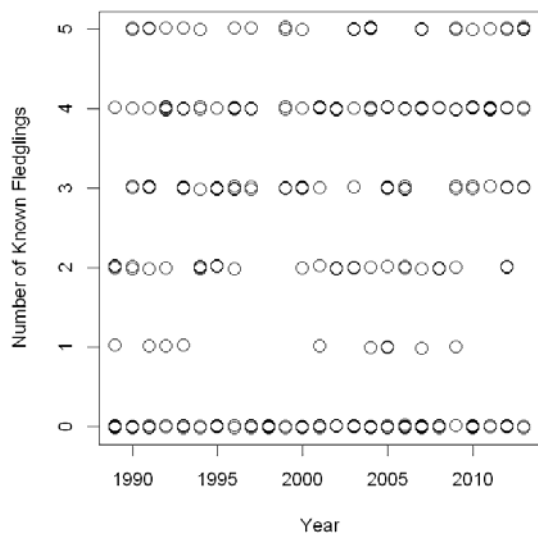


Figure 7: Number of Known Fledglings by Year across Territories

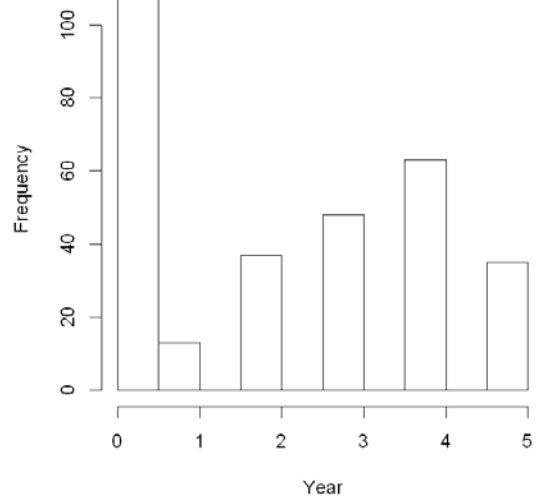


Figure 8: Frequency of Known Fledglings across Years

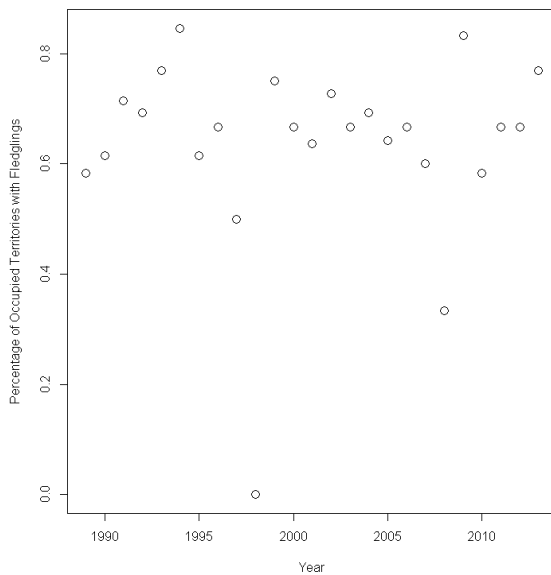


Figure 9: Proportion of Occupied Territories containing Known Fledglings by Year

```
hurdle(formula = Known_Fledglings ~ WYear + Core | WYear + AprPrecip +
AprOzoneMin, data = PRFA.Occ, dist = "poisson", zero.dist = "binomial",
link = "logit")
```

Count model coefficients (truncated poisson with log link):

|              | Estimate        | Std. Error      | z value      | Pr(> z )       |           |
|--------------|-----------------|-----------------|--------------|----------------|-----------|
| (Intercept)  | 0.887950        | 0.112586        | 7.887        | 3.1e-15        | ***       |
| <b>WYear</b> | <b>0.015372</b> | <b>0.005793</b> | <b>2.654</b> | <b>0.00796</b> | <b>**</b> |
| CoreTRUE     | 0.143310        | 0.089794        | 1.596        | 0.11049        |           |

Zero hurdle model coefficients (binomial with logit link):

|              | Estimate        | Std. Error      | z value      | Pr(> z )        |     |
|--------------|-----------------|-----------------|--------------|-----------------|-----|
| (Intercept)  | 1.192075        | 0.350658        | 3.400        | 0.000675        | *** |
| <b>WYear</b> | <b>0.014713</b> | <b>0.017538</b> | <b>0.839</b> | <b>0.401505</b> |     |
| AprPrecip    | -0.011102       | 0.005771        | -1.924       | 0.054388        | .   |
| AprOzoneMin  | -0.171092       | 0.079513        | -2.152       | 0.031417        | *   |

## Phenology Analysis

Trends in the first and last hatch dates are examined to determine if aspects of Prairie Falcon phenology are changing over time. The first and last hatch dates are interpreted as the integer day of the year, where January 1 is day of the year 1 and December 31 is day of year 365 in non-leap years. The minimum and maximum hatch days are calculated for each year across territories (Figures 10 and 11, respectively) and modeled as a function of time and environmental covariates.

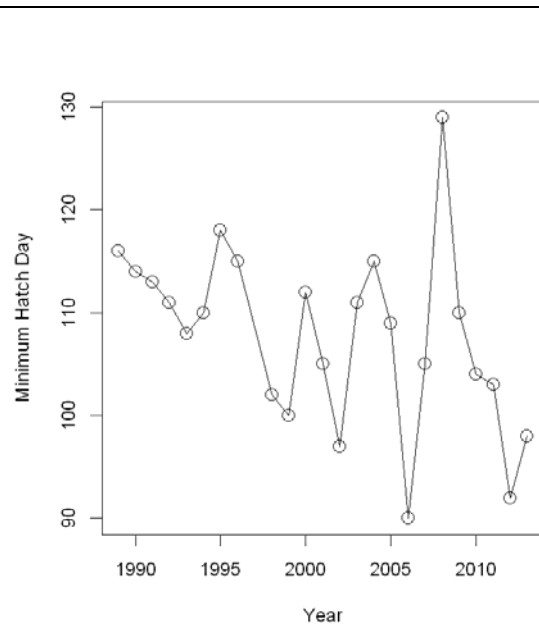


Figure 10: Minimum hatch day by Year

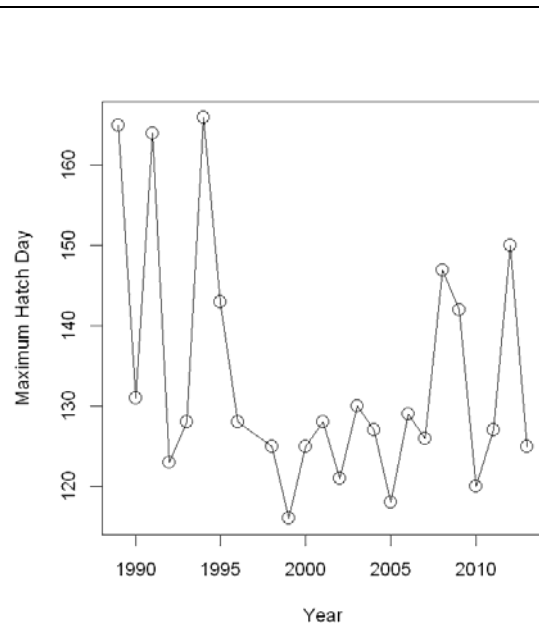


Figure 11: Maximum hatch day by Year

### *Minimum Hatch Day*

Model selection for ordinary least squares regression was conducted by stepwise regression with AIC as the selection criterion for the logarithmically-transformed first hatch days by Year. The final model (R output provided below) indicates a significant trend in the minimum hatch date of prairie falcons (Year coefficient = -0.0085, SE = 0.0022, t-statistic = -3.852, df = 18, p-value = 0.0012) and suggests that May temperatures and April ozone levels may influence the date of first hatch. Autocorrelation plots revealed no significant serial autocorrelation, so independence is assumed.

```
lm(formula = log(HatchMin) ~ Year + MarTempMean + AprOzoneMax +  
    AprOzoneMin + AprOzoneMean, data = Phen_Min)
```

|              | Estimate         | Std. Error      | t value       | Pr(> t )        |           |
|--------------|------------------|-----------------|---------------|-----------------|-----------|
| (Intercept)  | 21.224913        | 4.448828        | 4.771         | 0.000153        | ***       |
| <b>Year</b>  | <b>-0.008484</b> | <b>0.002203</b> | <b>-3.852</b> | <b>0.001168</b> | <b>**</b> |
| MarTempMean  | 0.020603         | 0.008381        | 2.458         | 0.024326        | *         |
| AprOzoneMax  | -0.004718        | 0.001905        | -2.477        | 0.023415        | *         |
| AprOzoneMin  | 0.012917         | 0.008475        | 1.524         | 0.144830        |           |
| AprOzoneMean | 0.014570         | 0.005913        | 2.464         | 0.024027        | *         |

### *Maximum Hatch Day*

The logged maximum hatch days across territories within a year were modeled similarly to the minimum hatch days. The final model (R output provided below) included a non-significant trend (Year coefficient = -0.0040, SE = 0.0029, t-statistics = -1.408, df = 19, p-value = 0.1753) as well as covariates for temperature, precipitation, and wind speed. The model was selected with AIC, and none of the environmental covariates are convincing as predictors. The considerable variability in the maximum hatch date (Figure X) may be better explained by other covariates. Autocorrelation plots revealed no significant serial autocorrelation, so independence is assumed.

```
lm(formula = log(HatchMax) ~ Year + AprTempMax + MarPrecip +  
    AprWindSpdMin, data = Phen_Max)
```

|               | Estimate          | Std. Error       | t value       | Pr(> t )      |   |
|---------------|-------------------|------------------|---------------|---------------|---|
| (Intercept)   | 12.5108017        | 5.7382552        | 2.180         | 0.0420        | * |
| <b>Year</b>   | <b>-0.0040242</b> | <b>0.0028583</b> | <b>-1.408</b> | <b>0.1753</b> |   |
| AprTempMax    | 0.0136198         | 0.0067463        | 2.019         | 0.0578        | . |
| MarPrecip     | 0.0006277         | 0.0004258        | 1.474         | 0.1568        |   |
| AprWindSpdMin | -0.2913406        | 0.1955523        | -1.490        | 0.1527        |   |

## ESTIMATING THE ANNUAL POPULATION SIZE

The annual population of prairie falcons is estimated assuming a design-based inferential approach. Since 1989, a total of 45 territories have been identified as prairie falcon habitat. However, the earlier surveys had not identified all of these territories, and annual surveys of territories prior to 2000 included only 11 to 17 territories each year. The Core territories, which consist of sites that attract human climbing activity, have been surveyed more consistently in recent years to monitor impacts of climbers on the breeding season and to close those territories to climbers if needed. The difference in survey intensity between Core and Non-Core territories warrants treating these groups as strata. Since 1989, 18 territories were identified as Core stratum territories and 27 territories comprise the Non-Core stratum population. While explicit randomization is not employed to select territories for the sample each year, a representative sample is assumed within each stratum so that estimates of the total population and precision may be obtained. If a bias exists in the selection of territories visited annually, then the estimates of population size may be biased as well (e.g. if territories with consistent prairie falcon occupation and high productivity are visited more frequently, then estimates of the population size may be biased high).

For a design-based analysis, inclusion probabilities for each territory must be computed. Since Core territories are nearly censused each year, these inclusion probabilities will be closer to 1 than the inclusion probabilities calculated for the Non-Core stratum. Since previous years' populations consisted of fewer territories, population size is estimated only for the years since 2008 when the current prairie falcon protocol was implemented. For each stratum, the inclusion probability is calculated as the number of territories surveyed within that stratum divided by the total number of territories in the stratum. The outcome of interest is the number of prairie falcons in each territory each year. For unoccupied territories, the outcome of interest is zero. For occupied territories, the outcome is the sum of the two adults plus the reported number of known fledglings.

Design-based analysis is conducted with the *survey* package (Lumley 2012) in R (2013). Estimates of total population size across territories by Year with standard errors are provided in Table 3.

Table 3: Design-based estimates of prairie falcon population size, 2008-2013

| Year | Estimated Population Size | SE    |
|------|---------------------------|-------|
| 2008 | 55                        | 17.95 |
| 2009 | 77                        | 21.51 |
| 2010 | 53                        | 15.31 |
| 2011 | 61                        | 17.09 |
| 2012 | 52                        | 14.57 |
| 2013 | 72                        | 18.66 |

## DISCUSSION AND CONCLUSIONS

The PINN prairie falcon program demonstrates the benefits of consistent monitoring over time. The 25-year time series is a rarity in ecological surveys. For years in which the population of territories cannot be censused, the sampling design would benefit from randomization to panels so that inference to the entire population can be statistical justified.

Both the naïve occupancy analysis and the occupancy analysis that assumed imperfect detection indicate a significant decreasing trend in prairie falcon occupancy since 1989. The trend is only partially explained by the addition of more territories over time. High estimated detection probabilities since the establishment of the current protocol may justify estimation assuming perfect detection. Incorporating environmental covariates into both the occupancy and detection models for the imperfect-detection occupancy analysis may improve estimates of both rates.

The trend analysis of hatchlings and fledglings revealed negative effects of April precipitation and ozone levels on the probability of a non-zero hatchling or fledgling outcome in occupied nests. Zero-inflation in the hatchling and fledgling data may be better modeled in a Bayesian context so that serial correlation may be accounted for with the hurdle model. Incorporating random effects in a nonlinear model can difficult for likelihood estimation.

Trends in phenology were modeled with ordinary least squares regression on logged minimum and maximum hatch days quantified as the numeric day of the year. A significant trend in the minimum hatch date was measured and environmental covariates such as the March temperature and April ozone levels were found to be significant predictors. Maximum hatch date did not exhibit a significant trend over time and environmental covariates were not significant in explaining the variation in maximum hatch date over time. Additional covariates might be more successful in explaining the high variability over time. Neither metric exhibited significant serial autocorrelation.

## REFERENCES

Achim Zeileis, Christian Kleiber, Simon Jackman (2008). Regression Models for Count Data in R. Journal of Statistical Software 27(8). URL <http://www.jstatsoft.org/v27/i08/>.

Lumley, T. (2012) "survey: analysis of complex survey samples". R package version 3.28-2.

MacKenzie, D., J. Nichols, J. Royle, K. Pollack, L. Bailey, and J. Hines. (2006). *Occupancy Estimation and Modeling, 1st Edition*. Academic Press.

National Park Service Air Resources Division (2013). Gaseous Pollutant and Meteorological Data. <http://ard-request.air-resource.com/data.aspx>

Piepho, H.P. and J.O. Ogutu (2002). A simple mixed model for trend analysis in wildlife populations. *Journal of Agricultural, Biological, and Environmental Statistics* 7(3): 350-360.

R Core Team (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <http://www.R-project.org/>.

Schreuder, H.T., T.G. Gregoire, and J.P. Weyer (1999). For what applications can probability and non-probability sampling be used? *Environmental Monitoring and Assessment* 66: 281-291.