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Don McIvor

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Population Viability Analysis of Ferruginous Hawk (*Buteo regalis*) in Eastern Washington

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WEST

EXECUTIVE SUMMARY

Horse Heaven Wind Farm, LLC (Horse Heaven) is proposing development of the Horse Heaven Clean Energy Center (Project) in Benton County, Washington. The breeding range of the state-endangered ferruginous hawk (*Buteo regalis*) overlaps the Project. Although the Washington nesting population size has historically been low compared to populations in surrounding states, the decline in the Washington breeding population over the past half century was a factor considered in the recent decision to uplist the species to state endangered. Due to the species vulnerability to the effects of wind energy development, Western EcoSystems Technology, Inc. (WEST) analyzed how ferruginous hawk populations might be impacted by hypothetical impact scenarios and how the population might respond to potential mitigation measures.

We used a population viability analysis (PVA) to model projected outcomes and sensitivities to various levels of impacts from wind energy development and proposed mitigation measures. Our study objectives were to: 1) use a stochastic growth model to generate a baseline population growth rate based on published vital rates, 2) simulate how biologically realistic levels of direct and indirect effects influence nesting population trends, 3) identify sensitive life-history stages to guide future conservation management actions, and 4) simulate how conservation efforts from the construction and use of artificial nest platforms (nest platforms) might affect population trends.

Using a range of scenarios, ferruginous hawk PVA simulations resulted in the following key points:

- Declining baseline population growth rates (λ) of 0.97 reduced the number of occupied nesting territories (territory) by 49% from 47 to 24 nesting territories over a 30-year period.
- The low levels of direct effects simulating loss of six adults over 30 years due to wind energy reduced the number of nesting territories by 50% over a 30-year period; however, indirect effects from the loss of one territory resulted in a 57% a reduction in nesting territories. Thus, population trajectories showed a comparatively greater response to the loss of nesting territories than collisions (the loss of individual birds). Combined, these scenarios magnified the effects on population trend, depending on the intensity of the effect.
- The average number of nesting territories were largely unaffected by variable survival rates of adults and juveniles.
- Construction of artificial nest platforms in suitable areas lacking natural nest substrates can effectively maintain or increase nesting territory occupancy. Assuming an average annual occupancy rate of 36%, increases of three to 10 nesting territories can positively affect ferruginous hawk population trends.

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1 INTRODUCTION

Horse Heaven Wind Farm, LLC (Horse Heaven) is proposing development of the Horse Heaven Clean Energy Center (Project) in Benton County, Washington. The breeding range of the state-endangered ferruginous hawk (*Buteo regalis*) overlaps the Project and historical nests are located within 2.0 miles (mi; 3.2 kilometers [km]) of Project facilities. Decline in the Washington breeding population over the past half-century was a factor considered in the recent decision to uplist the species to state endangered. Mortality from turbine collisions and reduced territory occupancy resulting from wind energy development both have the potential to affect population trends, particularly in populations with few individuals (Squires et al. 2020, Diffendorfer et al. 2021, Watson et al. 2021). Due to the species vulnerability to the effects of wind energy development, Western EcoSystems Technology, Inc. (WEST) analyzed how ferruginous hawk populations might be impacted by hypothetical impact scenarios and how the population might respond to potential mitigation measures.

We used a population viability analysis (PVA) that incorporated ferruginous hawk population demographics to model projected outcomes and sensitivities to various levels of Project impacts and proposed mitigation measures (Reed et al. 2002, Saeher and Engen 2002). PVA models have been used in a wide variety of applications to model extinction probabilities, identify sensitivities in demographic or genetic parameters, or simulate the outcome of different management scenarios (Beissinger and McCullough 2002). Specifically for ferruginous hawk, PVA models have been used to examine how changes in demographic vital rate parameters affect population growth in US Forest Service Region 2 (Collins and Reynolds 2005), and to simulate how collisions with wind turbines could affect population growth rates throughout the species' range in the US (Diffendorfer et al. 2021). In this study, our overall objective was to compare effects of management actions and vital rate sensitivities following Reed et al. (2002), who provided guidance on the application of demographic matrix models. This study does not attempt to predict the probability of extinction due to the small population size (e.g., < 200 individuals) and uncertainty of survival rates and long-term territory occupancy in Washington. To our knowledge, this is the first PVA of ferruginous hawk in Washington applied to a proposed wind energy development scenario.

We considered a range of model scenarios to account for uncertainty in demographic vital rates, direct and indirect effects, conservation efforts, and how Project impacts could affect the population. We used vital rate parameters (e.g., survival, nesting success) typically used in population modeling to determine how direct effects (wind turbine mortality), indirect effects (nest occupancy), and conservation effects (artificial nest platforms) influenced population trends. Specifically, our study objectives were to: 1) use a stochastic growth model to generate a baseline population growth rate based on published vital rates, 2) simulate how biologically realistic levels of direct and indirect effects influence nesting population trends, 3) identify sensitive life-history stages to guide future conservation management actions, and 4) simulate how conservation efforts from the construction and use of artificial nest platforms affected nesting population trends.

2 ANALYSIS AREA

The Analysis Area consisted of two areas. We considered a Study Area that included the entire breeding range of the ferruginous hawk in Washington; and a comparatively smaller Project Area where wind energy development is proposed and potential Project impacts to the population were evaluated.

2.1 Study Area

The Study Area occurs in the Level III Columbia Plateau Ecoregion (CPE) in eastern Washington (Clarke and Bryce 1997). The CPE includes the shrub-steppe and grassland nesting habitat that encompasses the northwestern extent of ferruginous hawk nesting in the US. As part of the larger Great Basin Bird Conservation Region (BCR 9), approximately 74% of the CPE is located within Washington (Bird Studies Canada and US North American Bird Conservation Initiative 2014). We used the CPE in Washington as the Study Area because its inclusion of suitable nesting habitat, including all publicly available records of ferruginous hawk nests in Washington, as well as it being a focal area for renewable energy development in the region (Hayes and Watson 2021, Washington Department of Fish and Wildlife [WDFW] 2021, Renewable Northwest 2022).

Using Breeding Bird Survey (BBS) data collected from 2006−2015, Partners in Flight (2020) estimated 130 ferruginous hawk (95% confidence intervals [CI]: 0–370) within the Washington portion of the Great Basin BCR. Population trends corresponded with -1.59% annual change (97.5% CI: -7.01−3.66) in Washington based on BBS data, 1999−2019 (Sauer et al. 2019). The last WDFW statewide-population surveys conducted in 2016 documented 32 breeding pairs and 47 occupied nests at 263 known territories (Hayes and Watson 2021).

2.2 Project Area

The Project Area consisted of a 113 mi^2 (293 km^2) Project Lease Boundary, of which approximately 35 mi^2 (91 km^2; 31%) consists of micrositing corridors[1] where 244 wind turbines, three areas of solar array and related infrastructure are proposed in a maximum build scenario (Horse Heaven Wind Farm, LLC 2021). The Project Area is located adjacent to the Tri-cities urban areas of Kennewick, Richland, and Pasco. The majority of native land cover (e.g., shrub-steppe and grassland) within and surrounding the Project Area has been converted to dryland and irrigated wheat (*Triticum aestivum*) cropland (Horse Heaven Wind Farm, LLC 2021). Portions of the 63-wind turbine generator Nine Canyon Wind Project were located within or adjacent to the Project Area.

Historical ferruginous hawk nest sites occurred within 2.0 mi of the proposed infrastructure, primarily at a relatively broad ridge along the northern perimeter of the Project Area. Four years of surveys during the nesting season resulted in low historical nest occupancy[2]. Nest surveys conducted for the Project during 2017–2019 and 2022 resulted in two occupied nests, one of

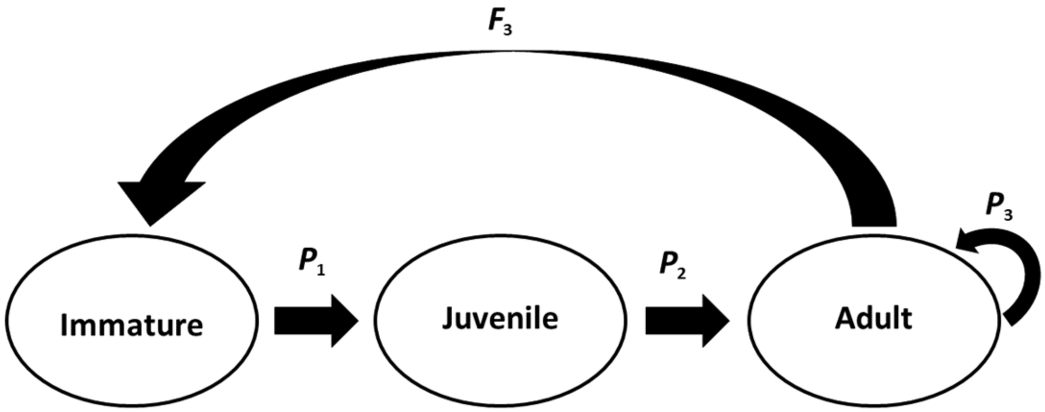
[1] Micositing corridors consisted of an 18.5 mi^2 (47.9 km^2) Wind Energy Micrositing Corridor and 16.8 mi^2 (43.5 km^2) of a Solar Siting Area (Horse Heaven Wind Farm, LLC 2021).

[2] As defined by Steenhof and Newton 2007 and USFWS 2013

which had an adult incubating during the 2017−2019 nesting seasons and the other nesting attempt was abandoned in 2017, and then was gone in subsequent nesting seasons (Jansen 2022).

3 METHODS

In this study, we used a 3-stage population projection matrix with three life history stages to estimate population growth rate (λ) and simulate population trends under potential model scenarios (Figure 1). The three life history stages followed Lande (1988) and incorporated a 1-year projection interval.



$$\begin{pmatrix} 0 & 0 & F_3 \\ P_1 & 0 & 0 \\ 0 & P_2 & P_3 \end{pmatrix}$$

Figure 1. Life cycle diagram and corresponding structure of the 3×3 projection matrix used in the ferruginous hawk population trend analysis in Washington. The probability (*P*) of survival from each stage to the next stage is represented by the subscript value. Fecundity (*F*) demonstrates biological productivity from adults back into the immature stage.

The first stage, immature, included individuals that survived from fledgling to dispersal, the second stage represented non-reproductive juveniles, and the third stage represented reproductively mature adults (Lande et al. 1988). Ferruginous hawk reach reproductive maturity between the ages of two and three (Wheeler 2003, Ng et al. 2020); thus, the projection matrix assumed reproduction after year two and continues indefinitely as birds age. Natural mortality due to age was implicit in the adult survival parameter. We selected vital rates for each parameter from published literature (Table 1). Because of the geographically constrained breeding population in southeast Washington, we attempted to keep all parameter values as local as possible to avoid introducing regional or national vital rates that may not reflect the condition of the breeding population.

Baseline adult fecundity estimates were based on 38 years (1978−2016) of nesting and reproductive success data in Washington (Table 2; Hayes and Watson 2021). The adult fecundity parameter (*F*) was calculated by taking the average number of successful nestlings per pair (2.4) and multiplying it by the average proportion of known successful nests (0.81), the proportion of breeding pairs contributing to the breeding pool (0.68), and 0.5 to account for sex ratios in the adult breeding population (Table 1). Baseline survival estimates were taken from the literature directly for immature (Watson et al. 2019), juvenile (Collins and Reynolds 2005), and adult life stages (Table 1; Watson and Pierce 2003). We assumed 47 initial occupied nesting territories (nesting territories or territories) based on the 2016 reporting (Hayes and Watson 2021).

Table 1. Baseline vital rate parameter values for ferruginous hawk in Washington.

Life Stage	Parameter	Value	Source(s)
Immature	Fecundity	0.00	Wheeler 2003, Ng et al. 2020
	Survival	0.62[a]	Watson et al. 2019[b]
Juvenile	Fecundity	0.00	Wheeler 2003, Ng et al. 2020
	Survival (Dispersal to Year 2)	0.43	Collins and Reynolds 2005
Adult	Average Number of Nestlings	2.40	Hayes and Watson 2021
	Average Nest Success Rate	0.81	Hayes and Watson 2021
	Occupied Nesting Territories	0.68	Hayes and Watson 2021
	Fecundity	0.66[c]	Hayes and Watson 2021
	Survival	0.76	Watson and Pierce 2003
	Baseline # Occupied Nests (2016)	47	Hayes and Watson 2021
	Baseline # Breeding Pairs (2016)	32	Hayes and Watson 2021
	Average # Breeding Pairs (1978–2016)	54	Hayes and Watson 2021

[a] Range-wide estimate was used as it is more conservative than the Montana survival estimate of 0.86 (Zelenak et al. 1997)

[b] As reported in Hayes and Watson 2021

[c] Calculated from table 2 from Hayes and Watson 2021 (2.4 nestlings per nest × 0.81 success rate × 0.68 proportion breeding × 0.5 females)

We generated a 3×3 projection matrix from vital rate parameters to calculate baseline values for growth rate (λ) using eigenanalysis to identify the dominant eigenvalue following Caswell (2001) and Stevens (2009). Additionally, the stable stage distribution (Table 2), elasticity, and sensitivity (Table 3) were calculated following Stevens (2009). We used the proportions from the stable stage distribution to calculate the initial abundance for each age class based on the 47 nesting territories observed in 2016 (Hayes and Watson 2021). We calculated sensitivity and elasticity of the projection matrices to determine how λ varied by the transitions between life stages. Sensitivity represented the effect a small change to the projection matrix would have on λ for each transition stage (i.e. immature to juvenile, juvenile to adult, adult mortality, or births). Elasticity represented the relative magnitude of effect that each transition has on λ.

Table 2. Proportions and initial abundances of ferruginous hawk based on the stable-stage distribution calculated from the projection matrix, according to Caswell (2001).

Parameter	Immature	Juvenile	Adult
Proportion	0.32	0.21	0.47
Initial Abundance[a]	32	21	47

[a] adult column represents the number of occupied nesting territories

Table 3. Sensitivity and elasticity during life-stage transitions from eigenanalysis of the projection matrix.

Parameter	Immature to Juvenile	Juvenile to Adult	Adult Mortality	Births
Sensitivity	0.27	0.39	0.67	0.17
Elasticity	0.12	0.12	0.36	0.12

3.1 Population Growth Model

This PVA incorporated demographic stochasticity to reflect the variation in vital rates caused by dynamics inherent to small populations, such as ferruginous hawk in Washington. Demographic stochasticity can have large impacts on population size estimates and are important to model for reliable population projections (Saeher and Engen 2002). Demographic stochasticity incorporated the fluctuating random probabilities that affect nest productivity, which included nest success, nest occupancy, and number of nestlings. To incorporate demographic stochasticity, we allowed all vital rates in the baseline projection matrix to vary from year to year. Vital rate variation was based on random sampling from a normal distribution based on the mean (μ) and standard deviation (σ). The σ for average nest success ($\mu = 0.81$, $\sigma = 0.138$) and average number of nestlings ($\mu = 2.4$, $\sigma = 0.446$) were calculated from Hayes and Watson (2021). Nest occupancy and survival rates lacked published σ, therefore, a σ of 0.1 was used for these parameters to reflect a high level of uncertainty. Vital rates from the normal distribution were restricted so reasonable biological levels (within σ) were not exceeded. The model assumes that the net influence of immigration or emigration was zero.

Although we do not explicitly incorporate environmental stochasticity into the PVA, we acknowledge the effect of extrinsic environmental factors on ferruginous hawk nesting populations. Annual fluctuations in climate (e.g., temperature, precipitation), habitat quality (e.g., prey availability), and catastrophic events (e.g., wildfire, disease) can all affect ferruginous hawk populations and the underlying vital rates (Wallace et al. 2016a, Shoemaker et al. 2019, Squires et al. 2021). For example, annual fluctuations in the spatial and temporal variability of prey abundance affects age-specific survival rates (Collins and Reynolds 2005, Hayes and Watson 2021). Environmental stochasticity was not directly modeled in this effort; however, the variation in occupancy and nestling counts from Hayes and Watson (2021) from 1978–2016 enabled us to vary fecundity in our model in a way that likely reflects the inherent environmental fluctuations that could impact this population.

3.2 Model Scenarios

Population models were simulated over 30 years based on the anticipated life expectancy of the Project. The average population sizes and λ were calculated across 10,000 model iterations for each model scenario. First, we modeled a baseline population trend for all model scenarios using the vital rates in the projection matrix, no annual take, and the initial abundance established from the stable stage distribution (Figure 2). To compare the mean baseline population trend with historical occupancy data, we graphed historical counts of occupied territories, occupied territories with known breeding outcomes, and successful territories reported in Hayes and Watson (2021) against the predicted territory occupancy trend (Figure 3). Historical occupancy data were unadjusted for inter-annual survey effort and survey areas, which were unavailable. The mean λ and final population sizes from the 10,000 iterations are reported with 90% CIs (Appendix A).

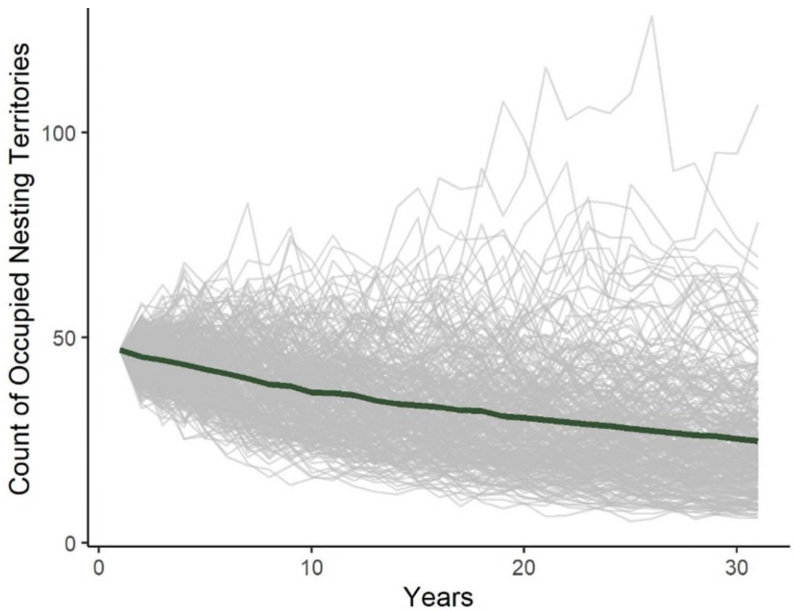


Figure 2. Baseline 30-year predicted trend for occupied nesting territories based on the projection matrix values derived from the literature. Each grey line represents one of the first 300 of 10,000 iterations to visualize variability.

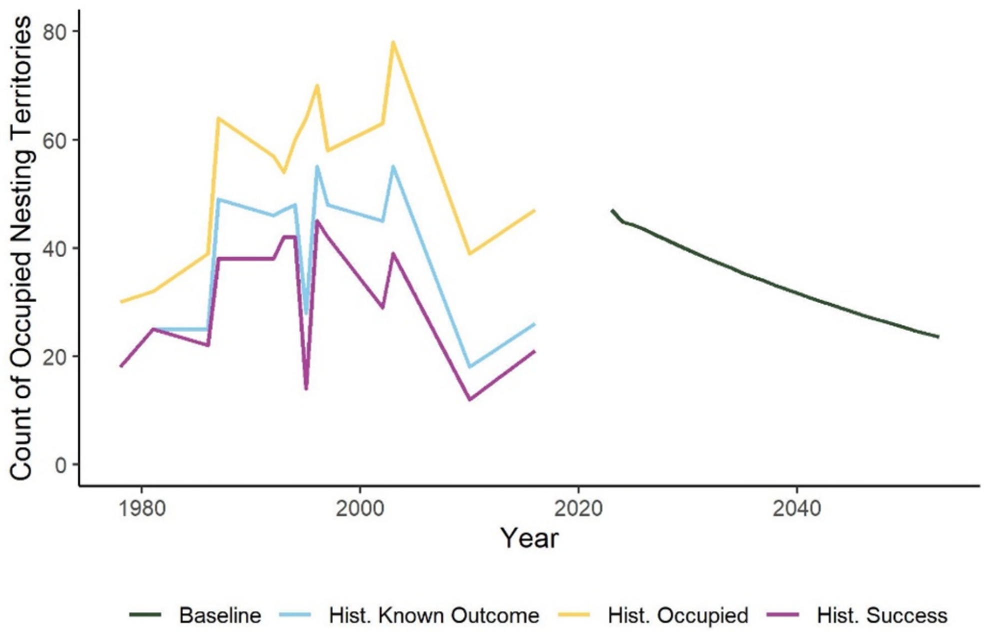


Figure 3. Comparison of historical occupied nesting territories, with the mean baseline predicted trend of occupied nesting territories from 10,000 iterations.

Direct and indirect effects were modeled separately and together to illustrate the relative effect on the population. We report decimals of territories instead of whole numbers to better illustrate the variation in the model results. Population benefits resulting from the construction and use of artificial nest platforms used the combined effects to simulate the biological response of increased nesting success. To simulate the effects on population trends from Project impacts and conservation efforts, we modeled the following scenarios:

- Direct effect from wind turbine collision considering low-, medium-, and high-effect scenarios (defined below);
- Indirect effect from loss of available nesting territories considering removal of one, two, or three territories;
- Direct and indirect effects from Project operations considering a combination of effects; and
- Artificial nest platform construction and use considering variable occupancy levels.

3.2.1 Direct Effect Scenario

We simulated population trends that reflected variable levels of mortality from turbine collision to provide a range of possible population effects. We used fatality counts from publicly available post-construction fatality monitoring (PCFM) studies at multiple spatial scales to develop a biologically realistic range of mortality scenarios. Count data was used because many of the fatalities were found outside of standardized PCFM when the estimation process was not possible, species-specific fatality estimates were unavailable, or study designs lacked rigor in one or more areas. Because of the discrepancies, count data provided a larger sample size of studies conducted within a particular region and was used to standardize the enumeration of ferruginous hawk fatalities across regions. Fatality count data were unadjusted for searcher efficiency or carcass persistence; thus, the range of fatalities should be considered a conservative estimate within each region. We quantified the number of fatalities documented during PCFM in the US, the CPE, and Washington (Table 4).

- Within the US, there were 40 ferruginous hawk fatalities reported from 20 operational wind facilities, 1996−2021 (WEST 2022).
- Within the CPE, there were eight ferruginous hawk fatalities reported from six operational wind facilities, 1999−2020 (WEST 2022).
- Within Washington, there were four ferruginous hawk fatalities reported from two operational wind facilities, 1999−2020 (WEST 2022).

Table 4. Regional ferruginous hawk fatalities recorded during post-construction fatality monitoring studies at operational wind energy facilities, 1996−2021.

		Fatality Age Group			Total	Fatality
Region	**# Years**	**Adult**	**Juvenile**	**Unknown**	**Fatalities**	**Rate[a]**
United States	25	9	6	25	40	1.60
Columbia Plateau Ecoregion	21	5	1	2	8	0.38
Washington	21	3	1	0	4	0.19

[a] calculated as Total Fatalities ÷ # Years

To derive a range of fatality rates used to estimate direct effects, we used region-specific ferruginous hawk PCFM data divided by the total number of years of PCFM data available in the region to calculate a fatality rate, multiplied by 30 years, and rounded up to the nearest whole bird. The range of direct effect estimates were classified into three levels: low, intermediate and high. We used fatality rates from the CPE and Washington to calculate a high (12 fatalities/ 30 years) and low (six fatalities/30 years) level, respectively, and split the difference between estimates for the intermediate (nine fatalities/30 years) level. The US fatality rate was not used because it would exceed the entire size of the CPE breeding population.

Direct effects on ferruginous hawk populations were predicted by varying age specific survival in the projection matrix for low, intermediate, and high levels of fatalities. Because Hayes and Watson (2021) suggested a bottleneck exists for earlier life history stages, we implemented direct effects in age specific patterns. In one set of models, predicted fatalities were applied to just adults, whereas in another set of models, fatalities were split evenly between adult and juvenile age classes.

3.2.2 Indirect Effect Scenario

Indirect effect scenarios were evaluated by varying the fecundity parameter in the projection matrix to reflect biologically realistic reductions of nesting territories. The three scenarios reflect a permanent removal of one, two, or three nesting territories across the 30-year period. Removal of a nesting territory may result from the permanent abandonment due to disturbance or displacement or from land conversion to unsuitable habitat types that may cause territory loss.

3.2.3 Combined Direct and Indirect Effects Scenario

We simulated the combined impacts of direct and indirect effects by incorporating both into the models.

3.2.4 Artificial Nest Platform Scenario

Artificial nest platforms have been demonstrated as an effective mitigation and habitat-enhancement tool that provide supplemental nesting substrates in areas where nests have been destroyed or substrates were not available (Tigner et al. 1996, Wallace et al. 2016b). Artificial nest platform scenarios were incorporated into the modeling to determine population responses from the use of artificial nest platforms. These scenarios assume that direct and indirect effects occur as described above, but incorporate an increase in fecundity from artificial nest platform use and resulting nesting success. For an artificial nest platform to be successful in this scenario, it must be additive to the breeding population and increase breeding success, and not result in relocation of a presumably successful breeding pair to an artificial nest platform.

To determine anticipated platform occupancy for each scenario, we calculated the average annual artificial nest platform occupancy from a review of nine studies over 53 study years in the US and Canada, 1976−2019 (Table 5). Nest occupancy varied widely in the studies that cumulatively surveyed 1,155 nests with an average annual occupancy of 36% ± 24% (Table 5). We used this average annual occupancy value to model possible effects from the addition of three, seven, and 10 artificial nest platforms within the CPE.

Table 5. Annual ferruginous hawk nest occupancy of artificial nest platforms (ANP)

Survey Year	# ANP	# ANP Occupied	% Occupied	Location	Reference
1976-2004[a]	105	64	61	Wyoming, US	Neal 2007
1976	97	2	2	Alberta, Canada	Schmutz et al. 1984
1977	98	4	4	Alberta, Canada	Schmutz et al. 1984
1981	81	11	14	Alberta, Canada	Schmutz et al. 1984
1982	81	12	15	Alberta, Canada	Schmutz et al. 1984
1983	78	11	14	Alberta, Canada	Schmutz et al. 1984
1988	25	11	44	Wyoming, US	Tigner et al. 1996
1989	54	34	63	Wyoming, US	Tigner et al. 1996
1990	61	33	54	Wyoming, US	Tigner et al. 1996
1991	65	41	63	Wyoming, US	Tigner et al. 1996
1992	71	37	52	Wyoming, US	Tigner et al. 1996
1993	71	29	41	Wyoming, US	Tigner et al. 1996
2009	130	45	35	Alberta, Canada	Migaj et al. 2011
2013[b]	27	18	67	Wyoming, US	Wallace et al. 2016
2016	2	1	50	Alberta, Canada	Kemper et al. 2020
2017	3	2	67	Alberta, Canada	Kemper et al. 2020
2017-2018[c]	57	5	9	Utah, US	Hopkins 2019
2018	2	0	0	Alberta, Canada	Kemper et al. 2020
2019	2	1	50	Alberta, Canada	Kemper et al. 2020
2019	16	6	38	Alberta, Canada	Parayko et al. 2021
2019[d]	29	2	7	Washington, US	Hayes and Watson 2021
Total	**1155**	**369**	**32[e]**		
Mean	**55**	**18**	**36**		
St.Dev.	**38**	**18**	**24**		

[a] Annual occupancy ranged from 52.1–69.7% - median (60.9%) calculated for simplicity
[b] Re-occupancy = 0.66 (95% confidence interval = 0.10–0.97)
[c] 32 ANP in low predicted nesting likelihood, 25 ANP in medium to high
[d] Undetermined level of survey effort, construction and survey occurred same year
[e] Total # ANP occupied ÷ Total # ANP surveyed: 369 ÷ 1,155 = 32% overall

4 RESULTS

Based on eigenanalysis of the projection matrix, adult mortality was affected disproportionally more than other life stages by small shifts in vital rates with a value of 0.67 (Table 3). Fecundity or births demonstrated the lowest sensitivity (0.12) compared to other life stages; however, our effect scenarios did not reflect this pattern which showed more stable patterns when vital rates varied between age classes and fecundity.

The baseline scenario revealed that occupied nest outcomes can vary widely (Figure 2), likely due to the small population size and uncertainty in vital rates. However, even with this uncertainty the 90% CI for the average λ of 0.9776 (90% CI: 0.9774−0.9779) and the mean number of nesting territories after 30-years, 23.52 (90% CI: 23.31−23.74) resulted in narrow CI across all 10,000 iterations (Appendix A). Mean λ for the baseline scenario was an annual population decline of 2.2% (Appendix A).Effect scenarios are discussed in further detail, below.

4.1 Direct Effect Scenario

The low direct effect scenario simulating six adults over 30 years resulted in 52% fewer nesting territories (22.71; 90% CI: 22.5−22.93), than the starting number of territories (47). The difference in nesting territories between the low direct effect scenario and the baseline was 3.5% (difference of one nest), indicating a similar outcome after 30 years. Mean λ for the low direct effect scenario was 0.9764 (90% CI: 0.9761−0.9767), resulting in an average 2.4% annual population decline.

Low juvenile survival that reduced the number of birds reaching reproductive age has been suggested as a mortality bottleneck affecting population growth (Hayes and Watson 2021). However, our simulations did not result in a more rapid population decline when mortality rates were split evenly between adults and juveniles (Figure 4). Direct effect models focusing on only adult fatalities resulted in a range of 19.05−22.71 nesting territories after 30 years, whereas models that split fatalities between adult and juvenile age classes resulted in approximately one fewer nesting territories after 30 years (18.26−21.41 territories; Appendix A).

4.2 Indirect Effect Scenario

The removal of nesting territories resulted in more substantial declines in nesting territories (Figure 5) compared to variability in adult or juvenile survival (Figure 4). Reduction of one to three territories resulted in 19.34 to 12.73 (of 47) nesting territories remaining after 30 years, whereas low to high fatality rates (direct effects) resulted in 22.71 to 19.05 nesting territories. Compared to the baseline, removing one nesting territory across all years resulted in a 59% decline (from 47 to 19.34 territories [90% CI: 19.16−19.51]) in nesting territories after 30 years, and λ of 0.9708 (90% CI: 0.9705−0.971; Appendix A). Removal of three nesting territories decreased the predicted number of nesting territories nearly 73% from a starting baseline of 47 nesting territories to 12.73 territories after 30 years.

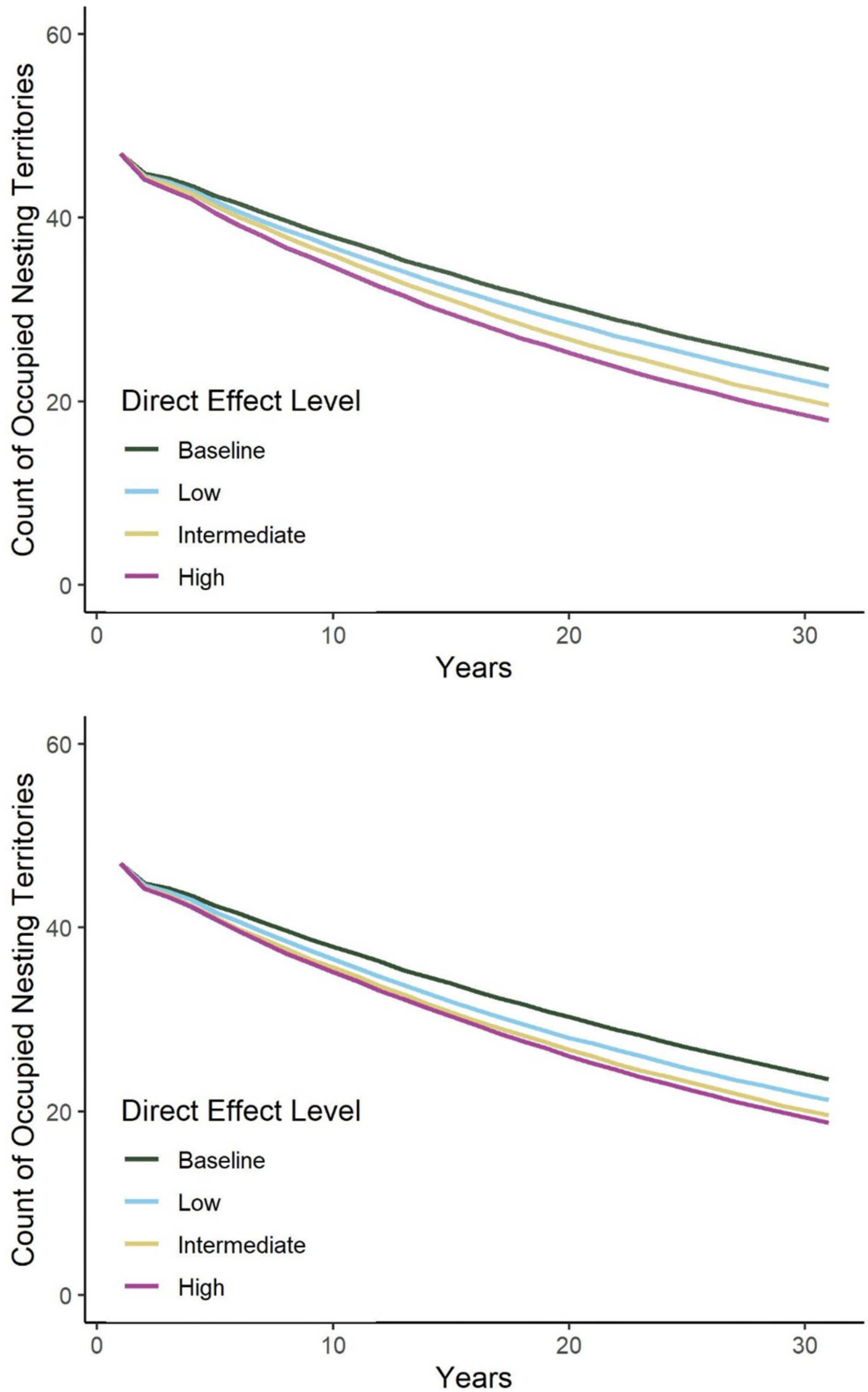


Figure 4. Predicted trend of occupied nesting territories accounting for direct effects to adults (top) and split evenly amongst adults and juveniles (bottom).

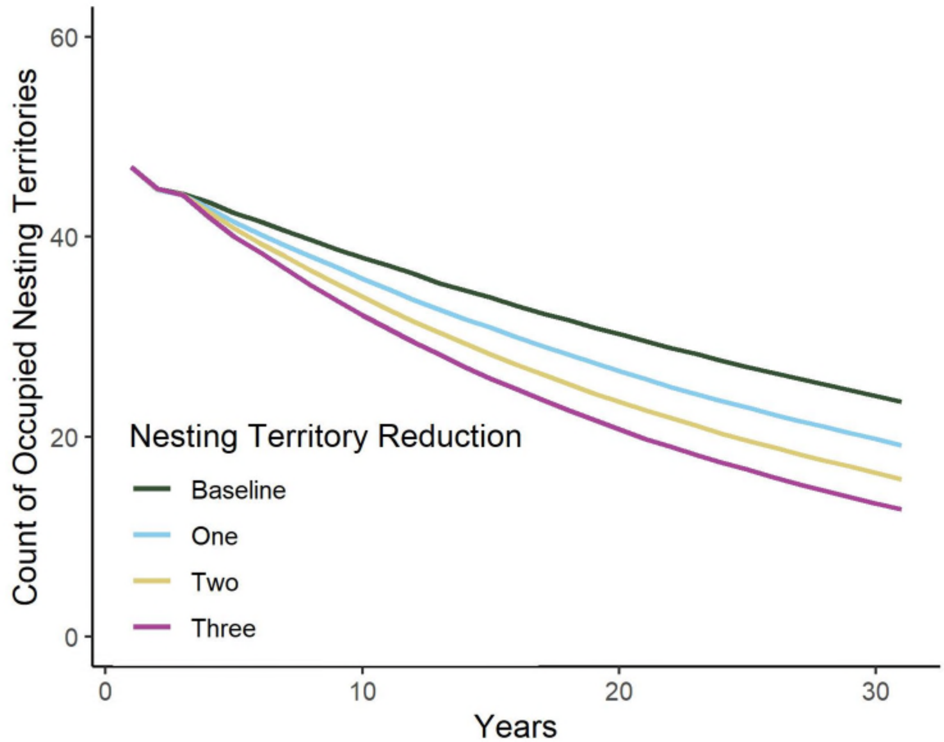


Figure 5. Predicted trend of occupied nesting territories accounting for indirect effects of nesting territory reduction.

4.3 Combined Direct and Indirect Effects Scenario

Population trends declined more substantially when the scenarios of reduced survival and declining territory occupancy were combined. Low direct effects and reduction of one nesting territory predicted 18.27 nesting territories remaining after 30 years, whereas high direct effects and reduction of three nesting territories predicted 10.12 territories after 30 years (Figure 6).

The difference in the magnitude of the effect is seen when compared with the baseline (Figure 6). The combined scenario of low fatality rates and reduction of one nesting territory resulted in a reduction of five nesting territories when compared to the baseline, and λ of 0.9694 (90% CI: 0.9691−0.9696; Figure 6; Appendix A). High direct effect levels and three removed territories resulted in 2.5 times fewer territories compared to baseline, and λ of 0.9495 (90% CI: 0.9492−0.9498; Figure 6; Appendix A). The corresponding average population decline was 2.2% for the baseline scenario compared with a 5.1% average annual decline for the combined high direct and indirect effect scenarios.

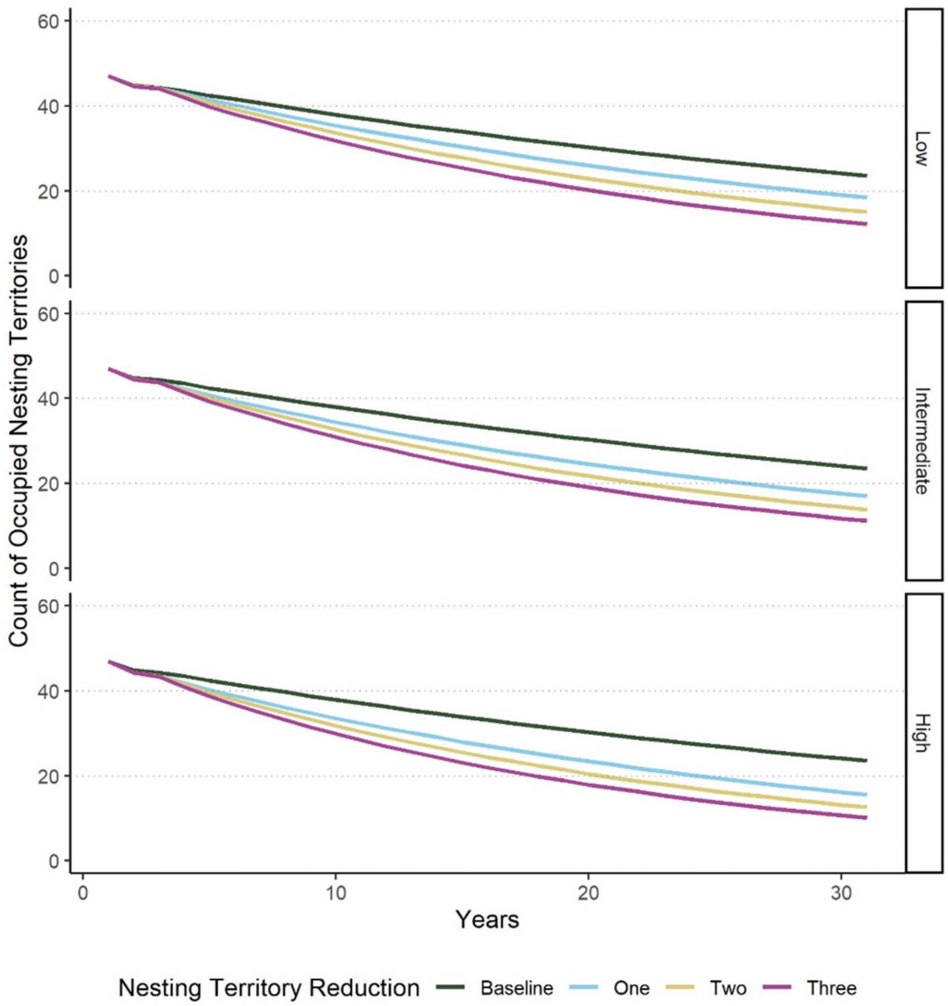


Figure 6. Predicted trend of occupied nesting territories accounting for direct effects (low, intermediate, and high) and indirect effects (reduction of one, two, or three nesting territories).

4.4 Artificial Nest Platform Scenario

Predicted λ for baseline, direct effect, indirect effect, and combined effects was always below 1.00, resulting in declining population trends across all scenarios (Appendix A). However, simulations incorporating artificial nest platforms resulted in a positive values of λ corresponding with an increase in successful breeding pairs in the population due to the construction and use of artificial nest platforms (Figure 7). Offsetting the effects of low or intermediate direct effects and the reduction of one occupied territory would require three artificial platforms to be constructed with an average annual occupancy of 36% (Appendix A). If high levels of direct effects occur, then seven artificial platforms are needed to return the number of nesting territories above baseline. Across all three levels of directs effects, 10 new territories are necessary to achieve a positive trend in nesting territories (Figure 7).

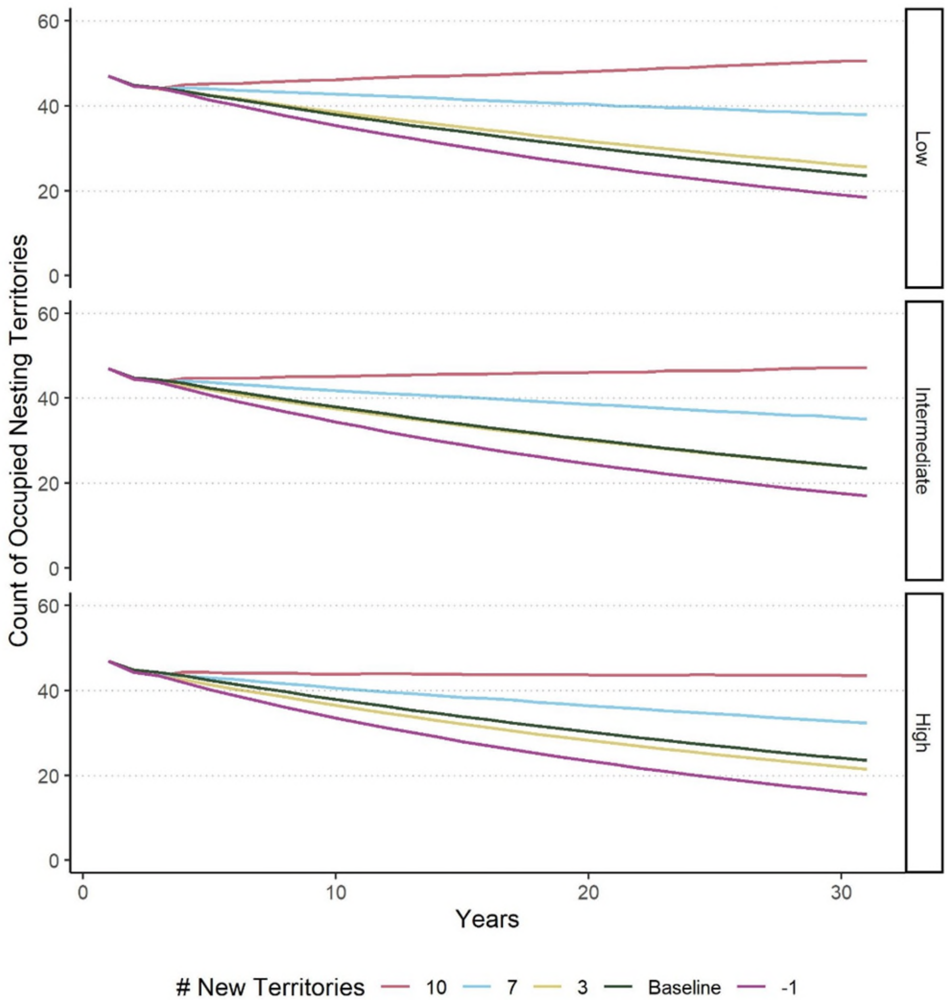


Figure 7. Predicted trend of occupied nesting territories accounting for direct effects (low, intermediate, high), indirect effects (reduction of one nesting territory), and construction of three, seven, and ten artificial nest platforms, assuming 36% occupancy.

5 DISCUSSION

Based on published vital rates and population estimates, our baseline model simulated a ferruginous hawk population with an annual average decline of approximately 2.4% over the next 30 years. By adjusting the simulated levels of turbine-related mortality and permanent loss of nesting territories, population trajectories showed a comparatively greater response to the loss of nesting territories than collisions (the loss of individual birds). Population trends did not respond to disproportionate effects to adult or juvenile age classes, suggesting age structure of turbine-related mortality has less of an affect than loss of a nesting territory or the removal of an individual from the population. When the effects of the scenarios were combined, the resulting influence to the population trends were magnified more than the influence of one effect alone. Our models simulated how the construction and use of artificial nest platforms, a common mitigation measure, could be used to mitigate the effects of Project operation.

As described above, simulations of the baseline population without the additive effects of increased mortality or loss of territories resulted in declining population trends for ferruginous hawk in Washington. Trend results corresponded with a -1.59% annual change (97.5% CI: -7.01−3.66) in Washington based on BBS data, from 1999−2019 (Sauer et al. 2019). Although statistically insignificant with credible intervals that included zero, BBS trend data in Washington reflected the patterns of declining nest occupancy, productivity, and nesting pairs observed over the last four decades (Hayes and Watson 2021). Despite the observed stability of ferruginous hawk populations across the US, Diffendorfer et al. (2021) modeled the vulnerability in maintaining a stable or positive λ from current (106 gigawatt [GW]) and future (241 GW) installed wind energy generation scenarios and found ferruginous hawk was comparatively more susceptible to changes in λ from turbine-related mortality compared to other species. In our study, localized effects on a small, declining population exposed to a myriad of existing environmental stressors unrelated to wind energy resulted in increased sensitivity to changes in demographic vital rates and λ.

In our PVA, there was no substantial change in population trends when the age structure of the survival parameter varied between adult and juvenile. Previous raptor research has shown adult survival can influence population viability (see Newton et al. 2016); however, the effect of low juvenile survival has been noted as a constraining factor in Washington populations of ferruginous hawks (Hayes and Watson 2021). The relatively equal effect of age class on population trends over a 30-year period perhaps underscores the demographic importance of all age classes, particularly for small populations. The reduced influence of adult survival on population trends compared to territory loss may suggest emigration of individuals into the breeding population during the non-breeding season or non-breeding “floaters” that replace breeding adults when densities decrease and breeding space becomes available (Watson and Keren 2019, Parayko et al. 2021).

Our scenarios show that the indirect loss of a nesting territory can have a greater affect than the direct loss of an individual and when combined, can substantially influence λ. Although nesting territories were not identified as a limiting factor in the Recovery Plan or status report

(Richardson 1996, Hayes and Watson 2021), loss of historical nesting territories and surrounding foraging habitat resulting from agricultural conversion, wildfire, reduced prey availability, urbanization and other anthropogenic sources have decreased or eliminated the suitability of nest sites over the ferruginous hawk breeding range in Washington. Efforts to increase availability of nesting territories through construction of artificial nest platforms in otherwise suitable areas lacking natural substrates can increase the number of nesting sites in a territory. Assuming an average annual occupancy rate of 36%, increases of three nesting territories may return the population trend to baseline conditions while 10 nesting territories may result in positive ferruginous hawk population trends.

Future PVAs could be refined to consider a range of probable fatalities based on annual fatality estimates from PCFM studies that adjust for searcher efficiency and carcass persistence. Count data excludes biases associated with carcass detection probabilities inherent with PCFM and thus is a coarse approximation we used to define a range of potential fatalities across spatial scales and not the biological reality that may occur. Despite the use of count data, we believe the relative magnitude in the effect of each scenario is representative of the biological response provided the same vital rates are considered. We want to acknowledge that the confidence intervals in Appendix A are narrower than we might expect for simulated ecological data suggesting that the data inputs are more precise than we might observe during the 30-year analysis period.

Our analysis scenarios demonstrate that reduced survival and territory occupancy can have synergistic effects on ferruginous hawk populations. Depending on the magnitude of the effects, the cumulative result of direct and indirect effects on small populations can substantially affect viability. The decrement in population growth from the loss of territories or individuals is not biologically restricted to wind energy development. As discussed in WDFW's Recovery Plan and Periodic Assessment, conversion and fragmentation of native habitats to agriculture and urbanization and the use of rodenticides and pesticides result in an increasingly human-disturbed landscape that affect ferruginous hawk populations (Richardson 1996, Hayes and Watson 2021). In addition to the installation of nesting platforms, WDFW discussed a range of conservation efforts including more comprehensive monitoring and research, increased funding and emphasis placed on habitat management and enhancement programs[3], reduced application of industrial chemicals, and strategic conservation planning that minimizes encroachment into unfragmented native habitats can result in incremental benefits (Richardson 1996, Hayes and Watson 2021). Mitigation of stressors that affect population trends should continue across the broad range of factors that impact ferruginous hawk nesting and foraging habitat in order to maintain viability of local populations over time.

[3] Examples of habitat management or enhancement programs include, but are not limited to, the US Department of Agriculture, Farm Service Agency's Conservation Reserve Program (CRP), Conservation Reserve Enhancement Program (CREP), State Acres for Wildlife Enhancement (SAFE), or the Washington Wildlife and Recreation Program (WWRP)

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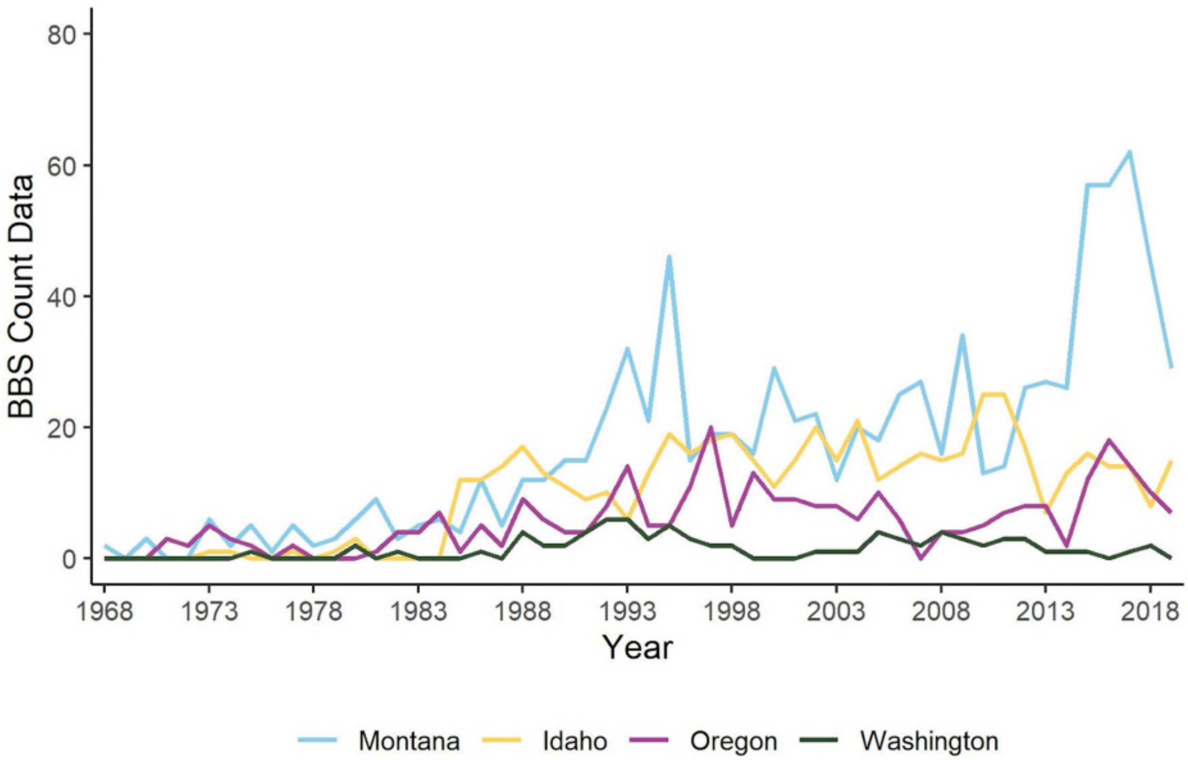
Appendix A1. Predicted λ and occupied nesting territories for each scenario after 30-years.

Scenario	Direct Effect Level	Indirect Effect Level	Added Nesting Territories	λ	λ 90% CI	# Territories	Territories 90% CI
Baseline	-	-	-	0.9776	0.9774−0.9779	23.52	23.31−23.74
Direct Effects	Low	-	-	0.9764	0.9761−0.9767	22.71	22.5−22.93
Direct Effects	Intermediate	-	-	0.9736	0.9733−0.9739	20.78	20.58−20.97
Direct Effects	High	-	-	0.9708	0.9705−0.971	19.05	18.87−19.23
Direct Effects (Adults and Juveniles)	Low	-	-	0.9746	0.9744−0.9749	21.41	21.22−21.61
Direct Effects (Adults and Juveniles)	Intermediate	-	-	0.9736	0.9734−0.9739	20.87	20.68−21.07
Direct Effects (Adults and Juveniles)	High	-	-	0.9694	0.9691−0.9696	18.26	18.09−18.43
Indirect Effects	-	1	-	0.9708	0.9705−0.9711	19.34	19.16−19.51
Indirect Effects	-	2	-	0.9639	0.9636−0.9641	15.68	15.54−15.83
Indirect Effects	-	3	-	0.9566	0.9564−0.9569	12.73	12.61−12.85
Combined Effects	Low	1	-	0.9694	0.9691−0.9696	18.44	18.27−18.6
Combined Effects	Intermediate	1	-	0.9667	0.9664−0.967	16.96	16.8−17.12
Combined Effects	High	1	-	0.964	0.9638−0.9643	15.6	15.46−15.75
Combined Effects	Low	2	-	0.9624	0.9621−0.9627	15.05	14.91−15.19
Combined Effects	Intermediate	2	-	0.9597	0.9595−0.96	13.79	13.66−13.92
Combined Effects	High	2	-	0.9569	0.9566−0.9571	12.6	12.48−12.71
Combined Effects	Low	3	-	0.9552	0.9549−0.9555	12.14	12.03−12.25
Combined Effects	Intermediate	3	-	0.9525	0.9522−0.9528	11.15	11.04−11.25
Combined Effects	High	3	-	0.9495	0.9492−0.9498	10.12	10.03−10.22
Artificial Nest Platform Credit	Low	1	3	0.9807	0.9804−0.9809	25.61	25.38−25.85
Artificial Nest Platform Credit	Low	1	7	0.994	0.9937−0.9943	37.87	37.51−38.22
Artificial Nest Platform Credit	Low	1	10	1.0044	1.0041−1.0046	50.68	50.22−51.15
Artificial Nest Platform Credit	Intermediate	1	3	0.9779	0.9776−0.9782	23.52	23.3−23.74
Artificial Nest Platform Credit	Intermediate	1	7	0.9917	0.9914−0.992	35.02	34.7−35.34
Artificial Nest Platform Credit	Intermediate	1	10	1.002	1.0017−1.0022	47.15	46.71−47.6
Artificial Nest Platform Credit	High	1	3	0.9749	0.9747−0.9752	21.48	21.28−21.68
Artificial Nest Platform Credit	High	1	7	0.989	0.9887−0.9893	32.35	32.04−32.65
Artificial Nest Platform Credit	High	1	10	0.9991	0.9989−0.9994	43.44	43.03−43.86

CI = confidence interval



Appendix A2. Breeding Bird Survey count data by state for the northwestern United States. Washington historically has had low numbers relative to other states. Interannual and interdecadal counts appears high, although differences were not quantified. The number of routes surveyed increased until the early 1990s before remaining relatively consistent. Therefore, any perceived population growth from 1968 through 1993 is likely the result of survey effort.