

A Population Study of Golden Eagles in the Altamont Pass Wind Resource Area:

Population Trend Analysis 1994–1997

Predatory Bird Research Group
Long Marine Laboratory
University of California
Santa Cruz, California



NREL

National Renewable Energy Laboratory

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Foreword

Although the use of wind energy as an alternative electric generation source is now a viable choice, concern is still raised over the possible impacts of wind farms on birds. The concern includes two primary areas: the effect of avian mortality on bird populations, and possible litigation over the killing of even one bird if it is protected by the Migratory Bird Treaty Act, the Endangered Species Act, or both.

The activities of the avian research program at the National Renewable Energy Laboratory (NREL) focuses on working towards minimizing the effects of wind turbines on birds and bird populations. NREL, funded by the U.S. Department of Energy, conducts research that (1) contributes to the refinement of the methods developed to assess impacts on the avian populations within wind farms, (2) seeks to understand how birds behave in and around wind turbines in different environments, (3) will try to identify how birds recognize wind turbines and develop recommendations for increasing the conspicuity of the turbines, and (4) will soon conduct acoustical research to develop acoustical deterrents where needed.

The habitat surrounding the Altamont Pass Wind Resource Area (WRA) supports a substantial resident population of golden eagles (*Aquila chrysaetos*), perhaps one of the most dense ever recorded. Each year, the wind industry reports 28–43 golden eagles killed by turbine blade strikes in the Altamont WRA.

NREL has supported the Santa Cruz Predatory Bird Research Group at the University of California, Santa Cruz, in conducting a golden eagle population study in the Altamont Pass WRA. The research, conducted over a four-year period, was designed to assess the impact of golden eagle deaths in the wind farm on the species' population survival and reproduction.

This research project, begun in 1994, included a preliminary field investigation of the ecology of the golden eagles in the vicinity of the Altamont Pass WRA. The first year report, *A Pilot Golden Eagle Population Study in the Altamont Pass Wind Resource Area California*, provides an extensive discussion of the natural history and ecology of the golden eagle in the Altamont Pass WRA.

A second report, *A Population Study of Golden Eagles in the Altamont Pass Wind Resource Area: Second-Year Progress Report*, provides an excellent discussion of how the population was sampled, the survival and distribution of the radio-tagged eagles through August 1996, and estimates of reproduction based on nesting surveys.

This final report provides a detailed discussion of the data and research findings. Much has been learned during the first four years of this study. However, because the golden eagle is a long-lived species, the findings contained in this document are considered preliminary. Additional data collection over the next few years should provide a better understanding of how the golden eagle population is being impacted in the Altamont Pass WRA.

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EXECUTIVE SUMMARY

The Predatory Bird Research Group (PBRG), University of California, Santa Cruz, is conducting a long-term field study of the ecology of golden eagles (*Aquila chrysaetos*) in the vicinity of the Altamont Pass Wind Resource Area (WRA). The facility lies just east of San Francisco Bay in California and contains about 6,500 wind turbines on 190 km² of rolling grassland. Each year, the wind industry reports 28–43 turbine blade strike casualties of golden eagles in the WRA, and many more carcasses doubtless go unnoticed. Because golden eagles are naturally slow to mature and reproduce, their populations are sensitive to changes in adult and subadult survival rates. The U.S. Fish and Wildlife Service and the California Department of Fish and Game have therefore expressed concern that the fatalities might have an adverse effect on the population. PBRG's four-year investigation of the population trend (January 1994 through December 1997) was supported for the first three months by the wind industry and thereafter by the National Renewable Energy Laboratory.

Annual nest surveys have revealed a substantial breeding population, the density of which is among the highest reported for the species. An 820-km² area near the town of Livermore held at least 44 pairs in 1997, a density of one pair per 19 km². PBRG has estimated that at least 70 active territories exist within 30 km of the WRA boundary. Territory occupancy from year to year has been 100%, and the reproductive rate, based on an annual sample of about 60 pairs, averaged 0.61 fledged young (~0.25 females) per occupied site.

To estimate survival rates, we tagged 179 eagles with radio transmitters equipped with mortality sensors and expected to function for at least four years. Population life stages represented in the tagged sample included 79 juveniles, 45 subadults, 17 floaters (non-territorial adults), and 38 breeders. Effective sample sizes in the older stages increased as eagles matured or became territorial. Thus, by the end of the study, we had obtained telemetry data on 106 subadults, 40 floaters, and 43 breeders, in addition to the 79 juveniles.

Weather permitting, we conducted weekly roll-call surveys by airplane to locate the radio-tagged eagles and to monitor their survival. The surveyed area, defined by the movements of tagged birds during the first few months of the study, extended from the Oakland Hills southeast through the Diablo Mountain Range to San Luis Reservoir about 75 km southeast of the WRA.

Of 61 recorded deaths of radio-tagged eagles during the four-year investigation, 33 (54%) resulted from electrical generation or transmission. Of these, 23 (38%) were caused by wind turbine blade strikes, and 10 (16%) by electrocutions on distribution lines, all outside the WRA. Additional fatalities went unrecorded because turbine blade strikes destroyed the transmitter in an estimated 30% of cases. The aerial surveys showed that breeding eagles rarely entered the WRA, whereas non-territorial eagles tended to move about freely throughout the study area, often visiting the WRA.

Computer analysis of survival data (Program MARK) by Alan Franklin, Tanya Shenk, and Ken Wilson (1998) from Colorado State University considered Kaplan-Meier survival estimates among the various groupings of life stages and sexes. Their most parsimonious solution was a pooling of data from juveniles, subadults, and floaters of both sexes to produce a single estimate of annual

survival for non-territorial eagles at 0.7867 (SE=0.0263). The estimate for the annual survival of territorial eagles (breeders) was 0.8964 (SE=0.0371).

Franklin, Wilson, and Shenk (1998) developed two Leslie matrix models to estimate the trend of the population. The first, which incorporates the rate at which non-territorial eagles become breeders, estimated the annual rate of population change (λ) at 0.9068 (SE=0.03). The 95% confidence interval of this estimate did not include $\lambda = 1.0$, the value for a stable population. This means that, if their model and its assumptions are valid, the population was in a state of decline during the period of our study.

The second model, configured at our request, estimated potential growth rate on the assumption that all maturing eagles enter the breeding segment. Part of our rationale was that, once a declining population loses its floating segment, the floater-to-breeder transition rate is moot and only adds variance to the trend estimate. This was of particular concern because the available floater-to-breeder transition rate estimate lacked precision (CV=66.7%). Moreover, the floater-to-breeder transition rate can be expected to change with population size and therefore cannot be modeled as a constant. Franklin, Wilson, and Shenk's (1998) estimate of λ in the second (potential growth rate) model was 0.9880, a value statistically indistinguishable from unity. A Moffat life table model developed by Hunt (1998) yielded a virtually identical value for λ . Sensitivity analyses for both the matrix and Moffat models found the population most responsive to changes in adult survival and least affected by variation in juvenile survival and reproduction.

Several biological considerations suggest that the potential growth rate of the population is actually lower than estimated. First, we are likely overoptimistic in assuming perfect efficiency by non-territorial eagles in filling breeding vacancies by the next breeding season. Second, eagles newly acquiring territories would be initially less fecund than those being replaced, reducing net population productivity. Third, true survival rates are likely lower than estimated because a proportion of transmitters were destroyed by turbine blades.

On the other hand, several factors may operate in favor of population persistence. If floaters immigrating from other subpopulations are available, they may buffer the breeding segment against decline. Moreover, average territory quality— and hence average per capita reproduction— can be expected to increase if the number of territories declines. Other points of optimism include the observed 100% annual territorial reoccupancy rate and the low incidence (3%) of subadults as members of breeding pairs, an indication that a reserve of floaters continues to exist.

The wind industry at Altamont Pass has recently initiated a number of measures that may reduce the rate of turbine blade strikes. These include modification of existing turbines, the removal of turbines in "high-risk" areas, and the replacement of turbine models with others thought to be more benign. In the latter case, the replacements are more efficient, the net result being far fewer turbines. To track the efficacy of these and other possibly mitigating changes, PBRG will continue to radio-tag eagles, monitor eagle movements and survival, conduct an annual nest survey, and model the accruing data to reassess the population trend.

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Adult golden eagle (photo by Daniel Driscoll)

1.0 INTRODUCTION

On the basis of field surveys, Orloff and Flannery (1992) estimated that several hundred raptors are killed annually by turbine blade strikes, wire strikes, and electrocutions at the Altamont Pass Wind Resource Area (WRA) near Livermore, California. The most common fatalities were those of red-tailed hawks (*Buteo jamaicensis*), American kestrels (*Falco sparverius*), and golden eagles (*Aquila chrysaetos*), with lesser numbers of turkey vultures (*Cathartes aura*), common ravens (*Corvus corax*), barn owls (*Tyto alba*), and others. The numbers of discovered fatalities among certain species did not always correspond to their observed abundance in the WRA. Although Orloff and Flannery witnessed no turbine strikes, they believed that the tendency of hawks and eagles to directly pursue prey rendered them more vulnerable to collisions with structures than did the more tentative scavenging flights of turkey vultures and ravens.

Among the species of raptors killed at Altamont Pass, the one whose local population is most likely to be impacted is the golden eagle. Besides its being less abundant than the others, the breeding and recruitment rates of golden eagles are naturally slow, increasing their susceptibility to population decline as a result of mortality influences. Golden eagles are a Species of Special Concern in California (California Fish and Game Department 1992), and reductions have been documented in the southern part of the state (Scott 1985, Harlow and Bloom 1987). The golden eagle is afforded special federal protection because of its inclusion within the Bald Eagle Protection Act as amended in 1963. There are no provisions within the Act that would allow the killing ("taking") of golden eagles by WRA structures.

This report, in partial fulfillment of National Renewable Energy Laboratory (NREL) Subcontract XAT-6-16459-01, is the third and final of a series detailing the results and conclusions of field studies conducted in the Altamont Pass region from January 1994 to June 1997, with additional data (through December 1997) on eagle survival provided by the senior author. The primary purpose of the investigation is to estimate the extent to which turbine strikes and other hazards associated with wind energy production at Altamont Pass alter the demographic potential of the golden eagle population inhabiting the surrounding area.

This report focuses on analyzing the trend of the population and, although intended to communicate all information essential to the interpretation of the conclusions, the reader may benefit by having on hand our first and second reports to NREL. In the first (Hunt et al. 1995), we review pertinent aspects of the natural history and ecology of the golden eagle, describe the study area in some detail, explain our field methods, report our first-year results, and provide a glossary of terms. In the second report (Hunt et al. 1997), we discuss our sampling strategy and some of the biases and assumptions associated with vital rate (survival and reproduction) estimation and model development. Both documents chronicle our progress in population sampling, describe the ongoing results of surveys, and show the evolution of our thinking with respect to data interpretation. This report duplicates those portions of the earlier ones considered appropriate to clarity and substance.

2.0 STUDY AREA

The study area, defined by the movements of golden eagles we radio-tagged near the WRA, is bounded to the north by the Sacramento River Delta, to the east by the San Joaquin Valley, to the west by San Francisco Bay and urban areas extending from Berkeley to San Jose, and to the south by that portion of State Highway 152 running from Hollister to San Luis Reservoir.

The WRA itself (approximately 141 km²) is mostly grassland, an area of private cattle ranches on gently rolling hills composed almost entirely of European annual grasses, with occasional rocky outcroppings and widely scattered stands of oak, eucalyptus, and California buckeye (*Aesculus californica*). The windy season extends from April through September, although there are occasional windy days during the remainder of the year.

The grasslands east of the WRA gradually descend to the agricultural flatlands of the San Joaquin Valley. To the north, the habitat is an extension of that found on the WRA: low hills covered by oak savanna (grassland with scattered stands of oak) and occasional eucalyptus groves. West of the WRA is a series of ridges running from northwest to southeast. On these ridges, the habitat on the southwest-facing slopes is primarily grassland, while on the slopes facing northeast it is mostly blue oak (*Quercus douglasii*) savanna and woodland. Further to the northwest, the hills rise to the steeper peaks of Mt. Diablo, which exceeds 1,000 m in height. Here the habitat becomes more diverse, and includes blue and live oak (predominantly *Quercus agrifolia*) woodland, chaparral, sage scrub, savanna, and open grassland. Land use in this area is mainly pastoral, with moderate recreational use in parks.



The Altamont Pass Wind Resource Area (photo by Daniel Driscoll)

The Livermore Valley, which lies to the west of the WRA, is principally urban and light industrial in use. Vineyards and golf courses are scattered throughout, and ranches dominate the outlying areas. The town of Livermore supports 63,000 people, with 55,000 living in nearby Pleasanton. Surrounding the urban center are rolling hills of valley oak (*Quercus lobata*) and blue oak savanna. In addition to ranching, there are three large reservoirs in the southern part of the valley (Del Valle, San Antonio, and Calaveras reservoirs) managed for municipal water and, in some cases, recreation. A fourth, Los Vaqueros Reservoir, is under development in the northern portion of the valley adjacent to the WRA.

South of the Livermore Valley lies the Diablo Range, a relatively large, sparsely inhabited, mountainous region, bordered on the east by the San Joaquin Valley and on the west by the city of San Jose and the Santa Clara Valley. The Diablo Range comprises an area of roughly 3,500 km² and contains several peaks over 1,000 m in height. The diverse habitat includes blue oak/foothill pine, black sage (*Salvia mellifera*), California sagebrush (*Artemisia californica*), chaparral, and oak savanna. Much of the land is used for cattle ranching, and there are several large parks. A corridor of rolling grassland extends from the WRA southeastward and surrounds the Diablo Range.

Adjacent to habitats occupied by breeding golden eagles in Alameda, Contra Costa, and Santa Clara counties is a rapidly growing metropolitan complex. During the 1980s, the human population of these three counties increased by over 17% (California Department of Water Resources 1994) and, by 2015, the population is expected to approach 4.5 million (Association of Bay Area Governments 1996).

3.0 THE GOLDEN EAGLE: BACKGROUND INFORMATION

Properly estimating the population trend of any species requires knowledge and understanding of its life history and ecology. Our experience during this project has revealed many sources of potential misinterpretation in this regard. Therefore, we summarize those facts we believe are appropriate to the analysis and its assumptions and provide additional information of probable interest to the reader. For further reading on golden eagles and related topics, we recommend Newton (1979), Gargett (1975, 1977), Haller (1982, 1996), Tjernberg (1985), and Watson (1997).

3.1 Natural History

Distributed throughout the Northern Hemisphere, golden eagles are among the largest of raptors, with wingspans of up to 2.3 m and weights approaching 7 kg. Females are about 25% heavier than males, a difference relating to their divergent roles during the breeding season. Until the young are half-grown, the female guards the nest while the male provides food. The larger size of the female increases her effectiveness in brooding and nest defense, while the smaller male is a better forager because of his ability to carry larger prey relative to his own weight and to achieve higher rates of acceleration. The participation of the male throughout the reproductive cycle renders him virtually essential to brood survival, a condition contrasting with that of many non-raptors in which males are largely superfluous after courtship and insemination.

Golden eagles in our study area forage primarily on live mammals in open grassland habitats. In winter, eagles readily utilize carrion, including deer and cattle carcasses, and may exploit waterfowl

concentrations. California ground squirrels (*Spermophilus beecheyii*) are the dominant prey in the Diablo Range study area. In 339 prey items from collections made at golden eagle nests in the study area in 1994, we estimated that the California ground squirrel represented 69% of prey numbers and 64% of prey biomass. The second most important species was the black-tailed jackrabbit (*Lepus californicus*) at 8% biomass; the third was the black-tailed deer (*Odocoileus hemionus*) at 6%. In all, mammals accounted for 92% of prey biomass, followed by 7% for birds, and 1% for reptiles. We caution the reader that these percentages represent only a cursory index of the overall eagle diet during a single breeding season. A more accurate appraisal would require direct and systematic observations of foraging adults, concurrent observations of prey deliveries, and further sampling of nest remains (Hunt et al. 1992).

Because of the mild climate, California ground squirrels in our study area are available to eagles throughout the year. In this respect, they differ from many other ground squirrel species that aestivate and/or hibernate for long periods. California ground squirrel populations do not appear to cycle in abundance over multiyear periods as do, for example, jackrabbits, the main prey of golden eagles in most western states. However, prolonged winter rainfall in some years may reduce ground squirrel availability and overall numbers (Grinnell and Dixon 1918).

Golden eagles in the interior central Coast Ranges of California occur primarily in grazed, open grasslands and oak savanna, with lesser numbers in oak woodland and open shrublands. With increasing urbanization, much of the remaining golden eagle habitat in central and southern California is located within private ranches used for livestock grazing.

Over much of their range, golden eagles prefer cliffs for nesting, but in the Diablo Range study area, all but a few pairs nest in trees, including several oak species (*Quercus* spp.), foothill pine (*Pinus sabiniana* and *P. coulteri*), California bay laurel (*Umbellularia californica*), eucalyptus (*Eucalyptus* spp.), and western sycamore (*Platanus racemosa*). The Diablo Range eagles nest mainly in oak savanna and oak woodland. Open grasslands are generally unsuitable for nesting due to lack of suitable structures. However, a few pairs of eagles nest on electrical transmission towers traversing grasslands.

Golden eagle pairs in the Diablo Range participate in courtship and nest building in December and January, lay 1–3 eggs in February and March (incubation lasts 6.5 weeks), and fledge their 10- to 11-week-old young from mid-May to late June. Fledglings usually stay within their natal territories until mid-August, although some individuals may remain in the vicinity until December.

3.2 Population Ecology

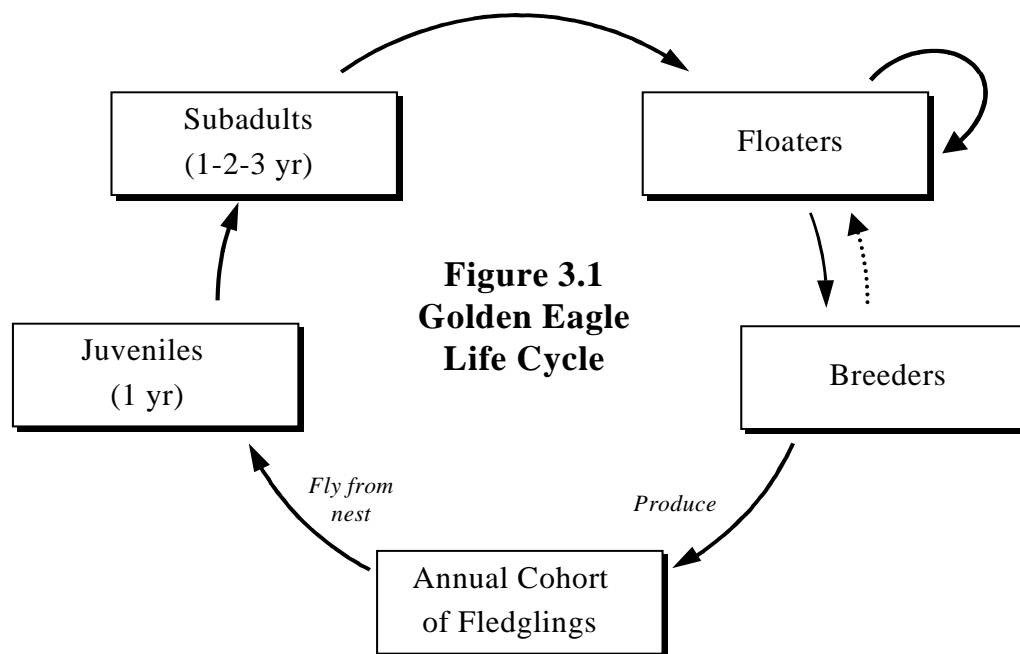
Healthy golden eagle populations contain four population segments: *breeders*, *juveniles*, *subadults*, and *floaters* (see Figure 3.1). Differing environmental and behavioral factors may influence the numbers of each within a population. *Breeders* are individuals four years old or older that defend territories containing a potentially successful nest. Because breeding pairs of golden eagles partition the landscape into a mosaic of territories from which other adults are excluded, there is an upper limit to the number of breeders within any defined area.

For golden eagles, territorial boundaries tend to remain fairly stable from year to year (Marzluff et al. 1997), and eagles can often be seen performing displays known as undulation flights that serve as a

warning to other eagles to stay away (Harmata 1982). As in other bird species, the size and density of eagle territories are a function of either food or nest site availability, depending on which is the limiting factor. In years of low prey availability, eagles may forgo breeding but still occupy and maintain their territories. The relationship between territory density and food supply is therefore most apparent over the long term and suggests that the elements defining the nesting territory are largely physiographic.

Juveniles are eagles less than one year old, and *subadults* are one, two, and three years of age. The number of juveniles in each yearly cohort is restricted first by output from a limited number of breeding pairs per unit area of landscape, and further by mortality factors. Numbers of eggs, nestlings, and fledglings may be affected by food scarcity, weather events, human disturbance, predation, and other factors. After fledging, the itinerant juveniles and subadults experience further attrition, both natural and human-related.

*Floater*s are adults without breeding territories (Brown 1969). The existence of floaters is an indication that all habitat suitable for breeding is occupied by territorial pairs (Hunt 1988,1998). In order to breed, a floater must either wait for a vacancy or forcefully evict a territory owner (Gargett 1975). To understand the dynamics of floating segments, imagine a vacant region colonized by a few pairs of eagles, each pair defending a territory from trespass. If conditions are favorable, the population grows until all serviceable breeding locations are occupied by pairs, at which point floaters begin to accumulate. Growth in the floating segment ceases when the annual number of fatalities in the overall population matches the annual number of young produced. Because the latter fluctuates within fixed limits as a result of environmentally imposed restrictions to the size of the breeding segment, there is a resulting stabilization in floater numbers and overall population size, a phenomenon known as Moffat's equilibrium (Hunt 1998).



Floaters safeguard the breeding segment by quickly replacing breeders that have died. On the other hand, if the number of floaters is large relative to the number of breeders, floater competition for nesting territories may reduce the reproductive rate (Hansen 1987). Haller (1996), studying golden eagles in the Alps, showed that frequent incursions of floaters attempting to usurp breeding territories caused nests to fail. This inverse relationship between natality and the number of floaters is an example of a density-dependent feedback mechanism that may regulate the overall number of eagles in the population.

The production of a robust floating segment is not only indicative of population stability; it is also a measure of a population's potential as a source of recruits to the larger landscape. Our results are showing that the Livermore Valley and surrounding environs are of exceptional quality as nesting and foraging habitat for golden eagles. Therefore, it is fair to assume that, in the absence of high levels of human-related mortality, the area can be expected to contribute to population stability within the larger region. The potential of the population to act as a "source" (Pulliam 1988) and, indeed, the measure of its own stability, lies in its capacity to produce adult eagles. That potential is reflected in the ratio of floaters to breeders (F:B) when the population is at equilibrium with the existing regime of natality and mortality (see Hunt 1998).

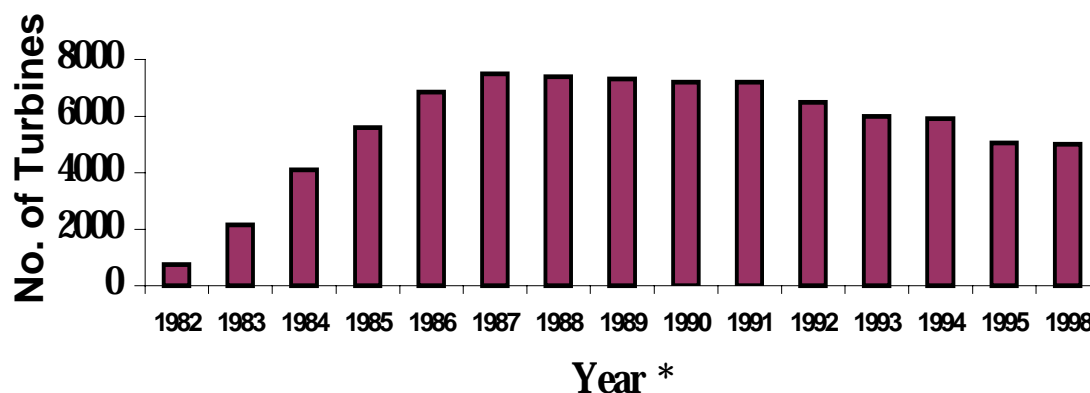
4.0 APPROACH TO ESTIMATING THE POPULATION TREND

Step changes in vital rates do not exert their full influence on an eagle population until they have been in place for many years, an interval roughly equal to maximum individual life span, during which all age classes in the population have been affected by the change. Wind energy generation at Altamont Pass first reached significant levels during the mid-1980s, when most of the turbines now in existence were erected (see Figure 4.1). We assume that, during that period, turbine blade strikes altered survival rates within the golden eagle population surrounding the WRA. As a consequence of reduced survival in one or more population segments, the trend of the population was redirected either toward a different point of equilibrium (with no change in the size of the breeding segment), or toward the loss of the population's capability of generating a floating segment. In the latter case, if immigrant floaters were available to fill territorial vacancies and thereby counter normal attrition in the breeding segment, the population would persist. If floaters were unavailable, the population would decline to extinction. Because we are unable to assess immigration rates, we must focus entirely on the action of survival and reproductive rates intrinsic to a defined population.

It follows that a decrease in survival rates resulting from WRA casualties would produce either (1) a smaller equilibrium population native to the affected area, with no change in the territorial component, or (2) a population dependent upon immigration for its existence. We will direct our inquiry toward determining which of these two outcomes can be expected to result from the influence of the vital rates estimated from our field data. For this purpose, we will first calculate the potential growth rate of the population under the artificial assumption that all maturing adults become breeders. A positive growth rate would suggest the equilibrium scenario, whereas a negative growth rate would support the dependence scenario.

Alan Franklin, Tanya Shenk, and Ken Wilson from Colorado State University developed two models to assess the trend of the eagle population (Shenk, Franklin, and Wilson 1996, Franklin et al. 1998). The first calculates the rate of population change by considering not only the estimated survival and reproductive rates, but also the rate at which floaters become breeders. By doing so, Franklin, Wilson, and Shenk propose to estimate the trend of the population existing during the period of our study. The second model, configured at our request, calculates the potential rate of population change under the assumption that all eagles become breeders upon reaching adulthood. Both models compute the standard error of the trend estimate. If the growth rate estimate predicts a floating segment, we will use a model developed by Hunt (1998) to predict the stage structure of the population at Moffat's equilibrium. Finally, we will assess the impact of WRA-related mortality by modeling the population trend in the absence of that influence, assuming no bias of competing risk factors (see Section 5.5). The degree to which all these appraisals will reflect the true state of the population depends on the validity of model assumptions, the accuracy of vital rate estimates, and the degree to which conditions prevailing during the 42 months of our study reflect those of the longer term.

Figure 4.1 Wind Turbine Development at Altamont Pass



* Data for the years 1996 and 1997 is unavailable.

We have defined the study area on the basis of the movements of eagles we radio-tagged primarily within 30 km of the WRA. Delineating the population impacted by turbine strikes is more problematic. The question of the spatial extent of WRA influence would be especially important if the trend of the population, as represented by our samples within the study area, were estimated to be negative (alternative # 2). The status of outlying populations as sources of recruitment would then clearly be a matter of inquiry. If, on the other hand, population equilibrium was predicted within the study area, the spatial question would be less important.

5.0 SAMPLING THE POPULATION

To assess the demographic trend of the population, we must estimate annual survival rates of each population segment, the reproductive rate, and, for the purpose of Franklin et al.'s Model #1, the floater-to-breeder transition rate. Our sampling program falls into three general categories of effort: (1) radio-tagging, (2) radio-tracking, and (3) nesting surveys. We describe field methods for each of these in our previous reports (Hunt et al. 1995, 1997). In this section we summarize these methods and discuss the biases and assumptions of sampling that pertain to the population analysis.

5.1 Radio-tagging

We radio-tagged 179 golden eagles representing four population segments: juveniles, subadults, floaters, and breeders. We tagged all but a few of our sample of itinerant eagles (i.e., floaters, subadults, and itinerant juveniles) within about 10 km of the WRA. We tagged juveniles mainly as 8- to 9-week-old fledglings at nests within about 20 km of the WRA. We caught most of the breeders within this same array of nesting territories.

We attached 65-g transmitters in backpack configuration using 1.3-mm teflon ribbon held together with waxed cotton embroidery thread over the carina, a procedure that allows the transmitter to eventually fall off (Garcelon 1985, Hunt et al. 1992). Each unit was equipped with a mortality sensor designed to activate when the transmitter remained motionless for four hours. The manufacturer of the transmitters (Biotrack) estimated battery life at four to five years.

By the end of the study, we were able to obtain a rough estimate of transmitter reliability by monitoring the incidence of transmitter failure among radio-tagged breeders; their continued presence in the territories could be verified visually. Of the four failures, all occurred long before the end of expected battery life. To calculate the "survival rate" of transmitters, we treated the failed ones as deaths and censored dead eagles for the period from January 1994 to June 1997.

(photo by Daniel Driscoll)



According to the Trent Rongstad formula (Trent and Rongstad 1974), the yearly transmitter survival probability was 0.928 (95% C.I.=0.836 – 0.975).

The literature on the effects of transmitters on birds (e.g., Gessaman and Nagy 1988, Massey, Keane, and Boardman 1988, Hooge 1991, Foster et al. 1992, and Peitz et al. 1993) shows that, in some cases, transmitters reduced flight speeds, survival, and/or reproduction, whereas, in others, no effect could be detected (e.g., Vekasy et al. 1996, Marzluff et al. 1997). Where documented, the consequences appear largely species-specific and dependent on package size and attachment configuration.

During the past decade we have placed our 65-g detachable units on hundreds of bald and golden eagles and have detected no impacts on survival, nor has there been any indication that tags interfered with territory acquisition or breeding (Hunt et al. 1992). However, because a comparison of survival between samples of tagged and untagged eagles is unavailable, we shall remain uncertain as to a possible difference. We note, however, that our transmitters weigh only about 1.3% of the weight of the average female and 1.7% of the male. Comparative studies in the literature deal largely with transmitters in range of 2.5–5.0% of body weight.

Our methods of determining the ages of the three classes of subadults are based on those developed by Pete Bloom (Western Foundation of Vertebrate Zoology) and Bill Clark (Cape May Bird Observatory), who showed us how to interpret the complex pattern of overlapping feather molt. Using their system, we are able to estimate the natal year for subadults by distinguishing between juvenile, subadult-1 (Basic I), subadult-2 (Basic II), near-adult (Basic III), and adult (Definitive) plumages.

Sample sizes representing the four population segments increased during the course of the study, not only because new eagles were tagged, but because eagles recruited from one segment to another. For example, when juveniles reached one year of age, they became subadults and began to contribute survival data for that segment. The same was true for "near-adults" (third-year subadults in Basic III plumage) that became floaters (or occasionally breeders) by acquiring adult plumage in their fifth calendar year of life. We chose 15 June as the date of transition from one yearly age class to the next, a convention that provides a full year of tracking data for the juvenile segment, which fledges from late May to early July. Fledglings tagged in the weeks prior to 15 June were included in the age class that began with that date.

Rather than focus on one sex for survival estimation, we chose to radio-tag both sexes (see Appendix A in Hunt et al. 1997 for explanation). We did so in consideration of funds available and the resulting uncertainty of capturing enough individuals of a preselected sex to achieve a level of statistical confidence appropriate to modeling. Furthermore, we lacked insight into which sex was limiting (see Section 3.1, above). If we inadvertently chose the one in surplus, our modeling results would be far less predictive of population impacts than a pooled sample of both sexes. The latter, of course, would tend to produce a better-case scenario than a data set focusing on the limiting sex, i.e., if the cause for limitation was a difference in age-specific survival.

5.2 Radio-tracking

Weather permitting, we conducted roll-call censuses of the study area once per week by airplane, beginning 14 January 1994. For this purpose we used a single-engine Cessna (Skylane 182) fitted with side-facing antennas on the wing struts and a switch box in the cabin enabling separate monitoring of antennas. In each survey flight, we scanned all transmitter frequencies along a course designed to locate all the birds in the study area. We used a GPS (global positioning system) unit to obtain transmitter locations and recorded position fixes in degrees, minutes, and hundredths of minutes latitude and longitude and estimated routine accuracy within about 0.6 km of the transmitter (see Marzluff, Vekasy, and Coody 1994). Later, we overlaid these fixes on maps depicting vegetation (digitized from satellite photographs) and other features with a computer-mapping program. We located eagles through 21 June 1997, after which we recorded only whether eagles were alive or dead in otherwise identical surveys (through December 1997).

When we detected a mortality signal, we obtained a more accurate fix by flying lower to obtain finer references to the signal. We recorded visual landmarks to facilitate later ground access. As soon as feasible, usually within one day, we traveled to the site by road vehicle and on foot, located the carcass, and recorded information pertaining to the cause of death. We collected carcasses for necropsy. Some of the necropsies were performed at the U.S. Fish and Wildlife Service (USFWS) Laboratory in Madison, Wisconsin, some at the California Fish and Game (CFG) Laboratory at Rancho Cordova, and some by other veterinarians. Casualties within the WRA were processed by KENETECH employees under the direction of the USFWS.

5.3 Censoring

If conditions were ideal for survival rate estimation, sample size would not be reduced by emigration, all the transmitters would continue to function, and we would detect all extant transmitters on every roll-call survey. Instead, some of the eagles move in and out of the area or depart altogether, some temporarily escape detection even though they are present (this is uncommon on a per-eagle basis), and some of the transmitters fail. Possible causes of transmitter failure include battery discharge, circuit breakage, component malfunction, antenna dislocation, separation of attachment ribbon bindings, and transmitter destruction. All but the last of these (see Section 5.4) may be fairly regarded as occurring independently of the eagle's fate.

This assumption of independence allows for a system of censoring in which eagles whose transmitters have failed or those that have departed—the two possibilities are indistinguishable—are deleted from survival calculations (see Hunt et al. 1995). The assigned date of deletion is midway between the date of last detection and that of the first indication of signal disappearance. If, in the case of an eagle leaving the study area or being missed in the survey, the signal is later redetected, the eagle is reinstated within the current survival interval. However, survival status during the period of signal absence is not restored, even though the eagle was obviously alive during that period. The reason is that, if the eagle was indeed outside the study area during the period of signal absence, considering it alive through that period would contribute to an upward bias in the survival estimate for the overall sample. Although survival might eventually be verified by the return of the bird, its death outside the study area would likely never be known (Bunck, Chen, and Pollock 1995).

5.4 Transmitter Destruction Bias

Under certain conditions, transmitters may be destroyed by the mortality agent, a factor that violates a core assumption essential to accurate survival estimation from radio-telemetry data: that censoring is independent of fate (Bunck 1987). Although several modes of transmitter destruction may conceivably be caused by a lethal agent, including poaching and car kills (Heisey and Fuller 1985), none seems more likely than a turbine blade strike. In our opinion, a strike virtually anywhere along the 40-cm length of the transmitter or its antenna would either destroy its function entirely or reduce its signal-generating capability.

Not surprisingly, three of the turbine casualties of radio-tagged eagles recorded during our study were discovered, not by means of telemetry, but by wind industry employees who happened upon them in the course of maintenance work. In two cases, it was clear that the turbine blades had destroyed transmitter function, and in the third, we were unable to find the transmitter despite a lengthy visual search and use of a metal detector. These events suggest the very real possibility that more tagged birds have been killed in the wind plant than are apparent in our data, a prospect that would result in an underestimate of population impact.

One way of estimating the number of destroyed transmitters is to use existing casualty data to calculate the probability of destruction per turbine strike. For nearly a decade, Green Ridge Services Company (formerly KENETECH) has been collecting information on golden eagles and other raptors killed and injured at the WRA. The data consist of photographs and detailed descriptions of wounds and dismemberment. Karen Loughheed of , Green Ridge Services Company (formerly KENETECH) examined the reports of 119 golden eagle casualties in the WRA collected from 1989 to the present, which contained sufficient data for analysis. Of these, 80 blade strikes involved heads and appendages only, while 39 included the body trunk. Loughheed judged that in 37 of the latter cases the blade would likely have destroyed a transmitter, an overall incidence of 31%.

Two golden eagles in the WRA (photo by John Gilardi)



The maximum number of eagles whose transmitters might have been destroyed by turbines can be approximated by examining the movements of censored eagles prior to signal disappearance (Pollock et al. 1989). Relocation data (through 21 June 1997) show that some were never detected near the WRA, whereas others were there frequently in the weeks prior to signal loss. The former can be censored with little danger of error; however, the latter include the possibility of a turbine strike.

5.5 Survival Rate Estimation

To calculate annual survival rates for each population segment, we used the Kaplan-Meier estimate as developed by Pollock et al. (1989) for staggered entry of radio-tagged individuals. By using this technique, we are assuming that (1) individuals are sampled randomly, (2) survival time is independent for each eagle, (3) the radio-tag does not influence survival, and (4) censoring is not related to the eagle's fate (see Section 5.4). The Kaplan-Meier procedure calculates the survival rate in each of a series of successive periods and then multiplies it by the survival value obtained for the previous period. The survival estimate for the entire series is therefore cumulative, declining over time. The survival interval chosen for our calculations was four weeks.

Sampling bias may arise when the fates of birds radio-tagged as members of the same pair or as siblings are not independent. For breeders, the question of sampling independence applies when the samples of radio-tagged breeder sexes are pooled for survival estimation. There were four pairs in which both members were tagged, and in one case, both members of a tagged pair died six weeks apart, although under different circumstances and at an interval of 13 km. Considering the lack of apparent bias in the survival data, we opted not to purge any tagged breeders from the survival computation of pooled sexes. Neither did we refine our data set for sibling juveniles. Although local circumstances influencing post-fledging mortality may affect siblings equally, the death of one individual may actually increase the chance of the other surviving, particularly in cases involving food or sibling aggression.

To model the proportional effect of turbine-related deaths on the population, we censored the eagles killed by the turbine strikes on their estimated death dates and recalculated Kaplan-Meier rate estimates of net survival. We did this on the assumption that the risk of turbine death is independent of the risks from other mortality agents. That assumption would be invalid if, for example, turbines kill disproportionate numbers of eagles stressed by poisoning, disease, or malnutrition. Heisey and Fuller (1985) comment that mortality factors affecting natural populations are rarely independent. As an example, they argue that censoring deaths resulting from fox predation on rabbits would not allow one to conclude that the net survival rate would apply to the rabbit population when foxes were eliminated from the study area. They maintained that, "... other sources [would] no longer have to compete with fox mortality and hence [would] claim a larger number of deaths," a reasonable point with regard to competing predators.

In the case of eagles killed by turbines, it is true there would be more deaths from other causes if the turbines were eliminated because there would very likely be more eagles. But that is not the question. Rather, the question is whether per capita death *rates* from the aggregate of other causes would increase. We argue that they would do so only if density-dependent factors came into play,

i.e., the effects of crowding on vital rates (Ricklefs 1990). One might be increased food competition, which could elevate the per capita risk of mortality from a variety of factors (eagles have virtually no predators, and most eagle deaths in our study area have been human-related). It is unknown at what point during population growth the action of density feedback upon survival would begin to have its effect, given the prodigious mobility of golden eagles, the width of their food-niche in west central California, and the large areas of grasslands without trees for nesting (survival habitat). Another density-dependent factor, this time affecting natality rather than survival, might be floater interference with nest success (see Section 3.2).

We cannot consider causal density dependence in our analysis because we have no way to predict the level of its appearance. Rather than retreat from any analysis whose outcome might be affected by density dependence, we can simply say that the population predicted under a regime of increased vital rates might be restricted to a lower level by the action of density dependent forces. In any case, we would be far more confident in the security of an eagle population regulated by density feedback than one below the level at which such checks might present themselves.

5.6 Estimating the Reproductive Rate

In January 1994, we began searching for all territorial pairs of eagles in the area within about 30 km of the WRA boundary. We chose that distance on the somewhat arbitrary assumption that this would be the maximum distance a breeding eagle might travel to the WRA to forage for its young.

We were aided in our nest search by people who knew of nesting pairs active during the last decade (see Acknowledgments at end of report). Our initial visits to these approximately 15 known nesting areas gave us an early understanding of preferred habitat upon which to base our surveys. Our main technique for locating nests was to observe areas of habitat we presumed suitable for eagle nesting. Where pairs were seen or suspected, we observed the terrain for long periods from stationary vantage points. Obtaining permission from landowners often required letter writing and numerous phone calls. In some cases, we were denied access altogether.

Eagles were most conspicuous in January and February when they were engaged in territorial (undulation) displays prior to egg laying. Before the blue oaks and other deciduous trees acquired their leaves, eagles and their nests were more visible than at later times when we searched for adults soaring together or carrying prey to nests. We revisited areas to see whether eagles were incubating; pairs not doing so by April were deemed unproductive. We later returned to nests where we had observed incubation to determine whether broods were present and to count the number and ages of young. Young were considered to have fledged if they reached eight weeks of age.

The natality parameter we are using to model the population is the number of fledged young per territorial pair, the latter being only those pairs observed during or before incubation. This method avoids the bias relating to the fact that successful pairs are easier to locate and identify late in the breeding season than pairs that have failed (see Steenhof and Kochert 1982, Steenhof 1987). When we started the study in January 1994, we knew of the existence of relatively few pairs, but found many more during the course of the spring when young were in the nest. We were therefore obliged to discount that year and base our estimate entirely on surveys conducted in 1996 and 1997, when all requirements of objectivity were met (Steenhof 1987). In addition to the reproductive rate

estimate, the results of successive nesting surveys provided an estimate of the territory reoccupancy rate, an important component of the Moffat's equilibrium model.

6.0 RESULTS OF POPULATION SAMPLING

This section presents the results we obtained from those aspects of our field study pertaining specifically to population modeling as described in Section 7.0. For a fuller understanding in the context of the ecology of the eagle population around Altamont Pass, we refer the reader to our two previous NREL reports (Hunt et al. 1995, 1997). We anticipate an analysis of the wealth of data we possess on the behavior of the eagles and the movements of those radio-tagged, particularly in relation to habitat features and human activity.



Fledgling golden eagle (photo by Daniel Driscoll)

6.1 The Radio-tagged Samples

From January 1994 through July 1996, we radio-tagged 179 golden eagles, including 76 females and 103 males. Of these, there were 79 juveniles, 45 subadults, 17 floaters, and 38 breeders. As explained in Section 4.1, effective sample sizes increased among the subadult, floater, and breeder categories when individuals in one segment transitioned to another. Therefore, by mid-June 1997, we had obtained telemetry data on 106 subadults, 40 floaters, and 43 breeders in addition to the 79 juveniles.

6.2 Evidence of Residency

We determined from the aerial roll-call surveys that the eagles we had radio-tagged tended to remain within the study area. Of the 179 tagged eagles, six are known to have departed and an additional 17 were censored on the basis of signal disappearance (data through mid-June 1997). An unknown number of these departed, whereas others may have remained alive or dead within the study area with failed or destroyed transmitters (see Sections 5.1 and 5.4).

6.3 Distribution of Radio-tagged Eagles

Not only did the radio-tagged eagles tend to remain in the study area, the vast majority of relocations were within 30 km of the WRA boundary (Hunt et al. 1995, 1997). Table 6.1 suggests a difference in the tendency of eagles in each of the four population segments to enter the WRA. To some extent, the differences may be related to the proximity of tagging location to the WRA (Hunt et al. 1997); however, there are expected differences in behavior as well. Breeders, for example, rarely visited the WRA, not only because of territory distance from it, but also because of their very limited home ranges. This is fortunate, because the trend of population change is most sensitive to changes in adult survival. Some of the juveniles remained at natal territories for extended periods after fledging, but after leaving them, their tendency to enter the WRA appeared comparable to that of subadults and floaters as a proportion of total relocations. Nevertheless, turbines killed no tagged juveniles.

Table 6.1 Relocations and fatalities of radio-tagged golden eagles in the WRA from January 1994 through 21 June 1997. The reason the total number of birds in each segment exceeds the number tagged is that juveniles advanced to subadulthood a year after fledging and third-year subadults became floaters or breeders.

Segment	Birds	Individuals in WRA	Total Relocations	Relocations in WRA	WRA-Related Kills
Juvenile ¹	62	40 (65%)	1343	259 (19%)	0
Subadult	95	67 (71%)	3337	818 (25%)	14
Floater	38	24 (63%)	1534	319 (21%)	3
Breeder	43	10 (23%)	1706	26 (2%)	0
Total	238	141	7920	1422	17

¹Data reported here represent relocations of juveniles only outside their nest areas.

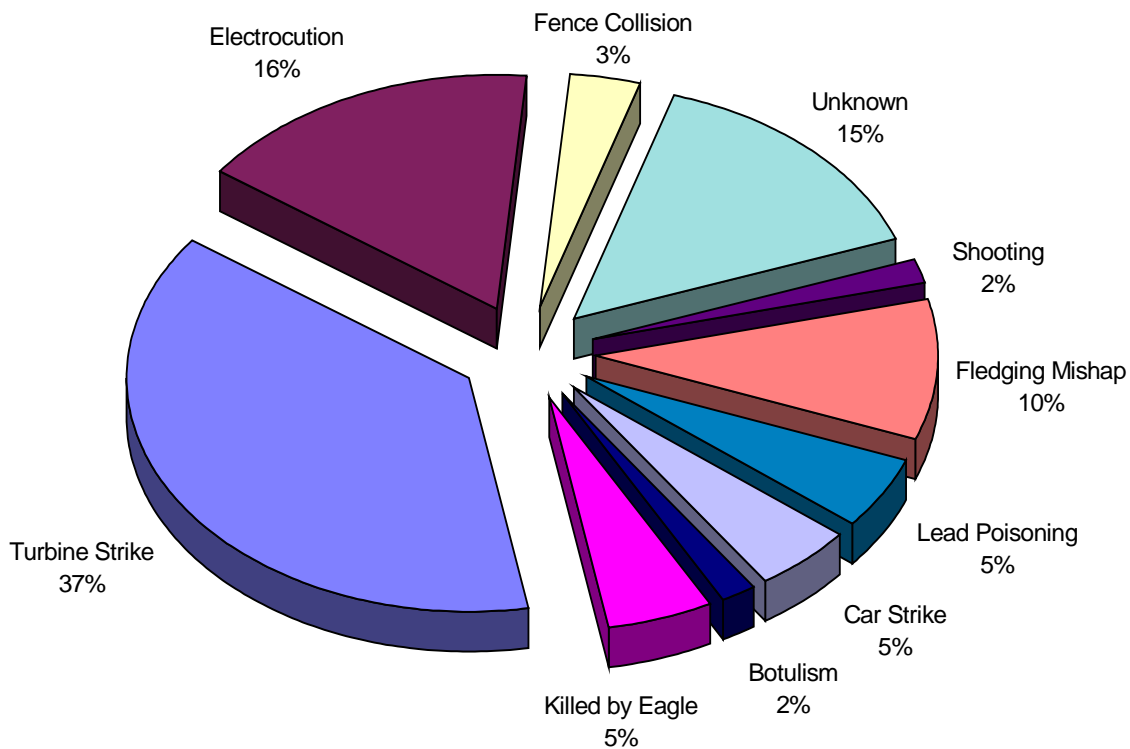
6.4 Fatalities

We recorded 61 deaths among the radio-tagged eagles within the study area from January 1994 through December 1997. Figure 6.1 shows the apportionment of deaths per cause, of which turbine blade strikes comprised 37.7%. Among the turbine strike fatalities, 19 were of subadults, 3 were floaters, and only 1 was a breeder (Table 6.2). This is not surprising because breeders seldom visited the WRA. The lack of turbine kills among the tagged sample of juveniles, despite their frequent occurrence in the WRA (see Table 6.1), suggests that their behavior is less conducive to turbine interaction.

6.5 Survival Rates

In early December 1997, Hunt met with Franklin, Wilson, and Shenk in Ft. Collins, Colorado, for the purpose of refining the survival data obtained through 2 December 1997. A computer program (MARK, White and Burnham 1998) was used to select the most parsimonious set of Kaplan-Meier survival estimates among the various groupings of life stages and sexes (Franklin et al. 1998). The result was a pooling of survival data from juveniles, subadults, and floaters of both sexes to produce a single estimate of annual survival for non-territorial eagles (0.7867, SE=0.0263). The estimate for territorial eagles (breeders) was 0.8964 (SE=0.0371). To isolate the effect of turbine-related mortality under the assumption of no competing risk (see Section 5.5), we (this report) later censored the turbine-killed eagles on the estimated date of death (see Section 5.3), and recalculated the rate for subadult+floater eagles at 0.8678 (SE=0.0187).

**Figure 6.1. Fatalities of 61 Golden Eagles
Radio-tagged and Recovered in the Diablo Range
(January 1994 - December 1997)**



True survival rates may be lower than estimated because of the possibility of transmitter destruction by the mortality agent. First, consider Karen Loughheed's estimate that 31% of turbine blade strikes would destroy transmitter function (see Section 5.4). Then recall the three cases of transmitter destruction among the 22 turbine kills of subadults and floaters (see Table 6.2). If the 19 subadults

and floaters with intact transmitters represent 69% of the total (100% minus 31%), we would expect 27 to have been killed rather than 22. Also, consider that among the candidates for transmitter destruction (data compiled through mid-June 1997) were 17 eagles whose signals disappeared without evidence of departure, transmitter failure, or transmitter detachment. We can possibly eliminate six of these from consideration on the basis of their being detected rarely or never near the WRA boundary. Of the remaining 11 censored eagles, 5 were in the WRA on the survey prior to signal loss.

6.6 Results of Reproduction Surveys

6.6.1 Reproductive Data. Our natality estimate was based on surveys conducted in 1996 and 1997. Our 1996 sample included 57 pairs, producing 39 fledglings for an average of 0.68 young per pair (SE=0.11). In 1997, 59 pairs fledged 35 young for an average of 0.59 young per pair (SE=0.11). Pooling the data for the two years yields a single estimate of 0.64 (SE=0.08) (however, see Sections 6.6.2 and 6.6.3 below). Brood size for the four years varied from 1.44 to 1.62 fledglings, comparable to values reported for other populations. The results of our 1998 survey, not included in the analysis, showed 64 pairs producing 37 young for an average of 0.58 fledglings per pair (see Appendix A), a value virtually identical to that obtained the previous year.

6.6.2 Fledgling Sex Bias. Among 78 eagles we examined as fledglings (≥ 8 weeks old) during 1994–1996, 47 were males and 31 were females. The departure of this ratio from unity is not significant by Chi-square ($\chi^2=3.28$, d.f.=1, $p=0.07<10$). However, the direction of male to female bias was consistent over the three years of sampling: 18:13, 13:9, 16:9. Moreover, among the 69 eagles radio-tagged as itinerants, there were 42 males and 27 females. This suggestion of a preponderance of males in the population at large is not significant by Chi-Square ($\chi^2=3.26$, d.f. =1, $p=0.07<10$); again, however, there was a degree of consistency in the direction of M:F bias among the itinerant categories: floaters = 12:6, subadults = 27:17, and free-ranging juveniles = 3:4.

These observations suggest that females may be the limiting sex in the Diablo Range population (see Sections 3.1 and 5.1). The truth of this depends on whether (1) the observed preponderance of males in the fledgling samples is normal for the population over the long term, and (2) there is no strong sex bias in survival rates after eagles leave the nest. With regard to the latter condition, Franklin et al. (1998) did not detect a sex bias within our samples that would justify the calculation of sex-specific survival rates: instead, the sexes could be parsimoniously pooled for survival estimation.

The literature on sex biases in nestling raptors offers a variety of evolutionary interpretations, including the possibility that parents can manipulate the primary sex ratio of eggs in response to environmental circumstances (Wiebe and Bortolotti 1992). The skewing of sex ratios in golden eagles has been reported for other populations (Edwards et al. 1988) and appears, at least circumstantially, associated with prey abundance cycles. Whether the bias is controlled by parental manipulation of the primary ratio or through siblicide during periods of food shortage has not been demonstrated (see Bortolotti 1989).

Table 6.2 Radio-tagged Golden Eagle Casualties, January 1994–December 1997

Cause of Death	Juvenile	Subadult	Floater	Breeder	Totals
Turbine Strike					
Male	0	11	3	0	14
Female	0	8	0	1	9
Electrocution					
Male	2	2	2	0	6
Female	1	2	1	0	4
Car Strike					
Male	0	1	1	0	2
Female	0	1	0	0	1
Shooting					
Male	0	0	1	0	1
Female	0	0	0	0	0
Botulism					
Male	0	0	0	1	1
Female	0	0	0	0	0
Lead Poisoning					
Male	0	0	0	0	0
Female	0	2	0	1	3
Probable Poisoning					
Male	0	1	0	0	1
Female	0	0	0	0	0
Fence Collision					
Male	1	0	0	0	1
Female	0	1	0	0	1
Killed by Eagle					
Male	0	0	1	1	2
Female	0	0	0	1	1
Fledgling Mishap					
Male	4	N/A	N/A	N/A	4
Female	2	N/A	N/A	N/A	2
Unknown					
Male	2	0	2	1	5
Female	1	0	1	1	3

6.6.3 Reproductive Estimate for Modeling Purposes. Because of the suggestion that females are the limiting sex in the Diablo Range population, there is reason to model the reproductive rate for that sex alone in estimating the population trend, size, and age structure. Based on the fledgling sex ratios reported in Section 6.6.2 and the reproductive data in Section 6.6.1, the reproductive rate is estimated at 0.2543 (SE=0.0975) female young per occupied breeding territory (see Franklin et al. 1998).

6.6.4 Territory Density. We earlier reported an extraordinary density of eagle pairs in an 820-km² area of (mainly) oak savanna near the town of Livermore (Hunt et al. 1995, 1997). During the 1997 nesting survey, we found additional territories within that area, bringing the current total of known, active territories to 44. This density of one pair per approximately 19 km² is among the highest recorded for the species (see Table 3.2 in Hunt et al. 1995), and is doubtless even higher because we have been unable to survey much of the area.

6.6.5 Territory Occupancy. We found all territories occupied by pairs in one year to be reoccupied by pairs in the next. Breeders known to have died were soon replaced. Indeed, there was evidence of fierce competition for territories. When we found a radio-tagged breeder male lying paralyzed from botulism near its nest in early February 1997, his mate had already acquired a new partner. At another territory where both radio-tagged adults died during September and October 1996, a new pair had taken possession by mid-January 1997 and possibly earlier. In early March 1997, we found a radio-tagged breeder male in its territory freshly killed by another eagle. Three days later, we observed a pair of adults there. In January 1994, a breeder female was killed by another eagle and soon replaced, possibly by the bird that killed her. In none of these cases did the surviving eagles produce young in the year of replacement. We observed no nesting territories held by lone eagles.

6.6.6 Floater-to-Breeder Transition Rate. Radio-telemetry allowed us to crudely estimate the transition rate of non-territorial eagles to territorial (breeder) status. Among our radio-tagged sample of potential territory holders, i.e., floaters and near-adults (third-year subadults in Basic III plumage), three near-adult females and one near-adult male acquired territories (see Section 6.6.7). During our four-year study, we recorded the presence of tagged female potential recruits in the study area for a total of 540 two-week periods. By the Kaplan-Meier method, the recruitment rate estimate for females (near-adults plus floaters) is 0.13 per annum, and 0.02 for males (1,362 two-week periods of detection). From these data, Franklin et al. (1998) calculated a single transition rate value of 0.0090 (CV=66.67%) for use in their first Leslie matrix model (see Section 8.1).

We recorded two additional cases of radio-tagged eagles taking possession of breeding territories. Both involved breeders that left their territories, became floaters temporarily, and then secured another (previously known) territory.

6.6.7 Subadults as Territory-holders. Other than the four near-adult recruits mentioned above, we observed very few subadults as members of territorial pairs. We saw a pair, both subadults, at a territory in 1994 (copulating) and again in the same territory in 1995. We observed mixed pairs (an adult with a subadult) at two additional territories in 1994. Throughout the study, among 231 total pairings where we observed both pair members, we recorded 7 pairings (in 5 territories) in which one or both members were subadults, an incidence of 3.0% of the entire sample.

All three tagged females that became territory-holders during the study were third-year subadults. However, this suggestion of high subadult-to-breeder transition may have resulted from sampling error, i.e., the near-adult and floater samples were skewed to the younger age categories as a result of the maturing of eagles tagged as subadults. The first instance of subadult recruitment was in June 1995 when, during the prior two months, there were only two possible female candidates for breeder transition, both of which were third-year subadults. (There were no tagged female floaters detected in the study area.) The second transition occurred in February 1996 when, during the two previous months, there had been five transition candidates, three of which were near-adults and two were one year older (first-year floaters). The third transition was in November 1996, when there had been 10 candidates: 5 of these were near-adults, three were first-year floaters, one was a second-year floater, and one was an older floater tagged in the month of the observed transition. Thus, over one-half of the tagged sample of eagles potentially transitioning to territorial status consisted of third-year subadults.

7.0 POPULATION EQUILIBRIUM MODEL

The equilibrium model we developed to predict the status of the golden eagle population is based on the principle that territorial bird populations stabilize as a consequence of restricted fecundity per unit area of landscape (Moffat 1903, Murray 1979, 1982, Hunt 1988, 1998; see Section 6.6.5). With the assumption of annual constancy in both vital rates and territory occupancy, a stable population with a stable age distribution develops. Equilibrium population size and the floater-to-breeder ratio can be modeled with a simple life table model if breeders and floaters have the same survival rate. Consider that C is the size of the annual cohort fledging within the defined area, j is the annual survival rate of juveniles, s is the rate for subadults, v is the number of years of subadulthood after the juvenile year (golden eagles are subadults for 3 years), a is the adult survival rate, and w is the maximum number of years of adulthood. (We are assuming this to be 21 years.) Beginning with cohort C , the numbers of individuals in subsequent age classes at equilibrium are

$$Cj, Cjs, Cjs^2, Cjs^v, Cjs^va, Cjs^va^2, \dots, Cjs^va^{w-1}$$

In our data, breeder survival estimates are appreciably higher than those of floaters. Therefore, modeling population size requires an estimate of breeder age distribution. If territory ownership tends to fall to younger adults rather than older ones, and floaters survive at a lower rate than breeders, population size would be higher than under opposite circumstances. This effect of breeder age distribution on modeling results would be most apparent in populations with proportionally large numbers of floaters, and less consequential in populations with small floating segments at equilibrium.

To accommodate the effect of breeder age distribution on population size, we assume, on one hand, that the oldest eagles hold territories. By also considering the opposite assumption, the bounds of variation in population size can be modeled. The literature tends to support the first assumption in showing that young eagles hold territories more frequently in depleted populations, i.e., those presumed to contain few floaters (Steenhof, Kochert, and Doremus 1983, Bergo 1984).

Breeder age distribution has no effect on calculations of potential growth rate because, under that regime, all adults would hold territories and have the survival rate of breeders. To calculate the growth rate, we iterate the survivorship schedules of the yearly cohorts, allowing subsequent ones to increase or decrease as a direct consequence of adult survival. The results are consistent with those of a normal life table and with a standard Leslie matrix model (Model #2 in Franklin et al. 1998).

8.0 MODELING RESULTS

8.1 Results of Leslie Matrix Model

Franklin et al. (1998) developed a model (#1) specifically for our project that considers annually based estimates of (1) stage-specific survival rates, (2) reproductive rate, and (3) a floater-to-breeder transition probability, the latter being based on the proportion of radio-tagged floaters (and third-year subadults) that acquired breeding territories during the study. From these parameters, Franklin, Wilson, and Shenk employed matrix algebra to solve for the annual rate of population change (λ). They calculated λ at 0.9068 (SE=0.03). The 95% confidence interval of their estimate (0.8437-0.9699) did not include $\lambda = 1.0$ (the value for a stable population), meaning that, if their model and its assumptions are valid, the population was in a state of decline during our study. If the parameter estimates represented their true values, the model would indicate that the population was declining at about 9% per year, a precipitous rate.

One problem with the first model of Franklin, Wilson, and Shenk is that it models the floater-to-breeder transition rate as a constant. This is unrealistic because the parameter varies strongly with population size. Indeed, the transition rate should approach zero when the floater population reaches zero. Therefore, we requested Franklin, Wilson, and Shenk to construct a second (standard) Leslie matrix model (#2) that assumes that all maturing eagles immediately enter the breeding segment. Another reason we requested this calculation is that, if the true value for λ is less than 1.0 and the breeding segment is not buffered by immigrant floaters, the population will eventually lose its floating segment (see Section 3.2). Thus, if the model predicts the total loss of floaters, the inclusion of the floater parameter becomes moot and only adds to the variance of the estimate. This is of particular concern because the floater-to-breeder transition rate estimate we were able to obtain lacks precision (CV=66.67%).

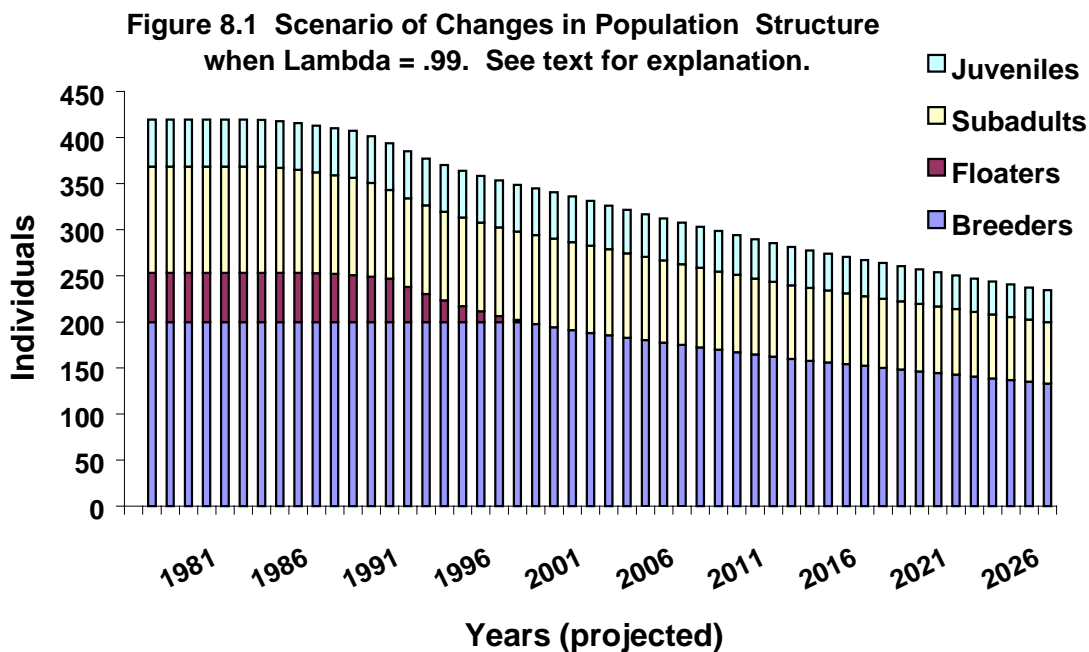
Franklin et al.'s estimate of λ in the potential growth rate model was 0.9880 (SE=0.0396), a value statistically indistinguishable from unity. However, several biological considerations suggest a lower value. First, the model is doubtless overoptimistic in assuming perfect efficiency by eagles reaching the third year of subadulthood in filling breeding vacancies by the next breeding season. Second, the age structure of a reduced floating segment would be skewed toward the younger age categories. Because these young eagles, and indeed any newly territorial eagle, would be initially less fecund than those being replaced (Steenhof et al. 1983, Newton 1998), net productivity would be reduced, thus accelerating the rate of decline.

8.2 Moffat's Equilibrium Model

The Moffat's equilibrium model yielded a potential growth rate of 0.9906. This value, like the two scenarios modeled by Franklin et al. (1998) suggests that the defined population is not at Moffat's equilibrium, i.e., the population cannot generate and sustain a floating segment. If true, an eventual decline of the breeding segment is predicted, unless (1) a supply of immigrant floaters is available to fill breeding vacancies, or (2) the current vital rate regime ameliorates. As expected, sensitivity analyses for both the matrix and life table models found the population most responsive to changes in adult survival and least affected by variation in juvenile survival and reproduction (Noon and Biles 1990, Bowman, Schempf, and Bernatowicz 1995, Hunt 1998).

In the absence of turbine-related fatalities and with the assumption of no competing risk factors, i.e., no density-dependent compensation accompanying the modeled increase in survival (see Section 5.5), the Moffat model estimates a potential growth rate of 1.0236. Under this regime, and consistent with the assumption of vital rate constancy, a population of 100 pairs would reach Moffat's equilibrium at about 220 females (breeder age distribution would not be a significant factor), and there would be about 36 floaters per 100 female breeders at fledging time ($F:B=0.37$). Such a population would be considered intrinsically stable.

Figure 8.1 illustrates the expected change in stage structure of a golden eagle population declining from an initial state of equilibrium at a rate of 1% per annum ($\lambda=0.99$) over a 50-year period. The graph reflects the change of a single input parameter, namely, the reduction of the itinerant survival rate from 0.8678 to 0.7867 (the modeled net impact of turbine development) (see Section 5.5). Note that there is no suggestion of decline among the breeding segment until the floater reserve is exhausted (Wilcove and Terborgh 1984).



9.0 DISCUSSION

Because of the rarity of published or unpublished studies of eagles or any other raptor species in which survival estimation has been sufficient for population modeling, it is difficult to compare our results with those of other investigations. We know of no such data for other populations of golden eagles. Therefore, let us examine the findings of Bowman et al. (1995), who estimated the vital rates of the bald eagle (*Haliaeetus leucocephalus*) population at Prince William Sound, Alaska, following the Exxon Valdez oil spill.¹ Point estimates of survival rates were as follows: adults, 0.88; subadults, 0.95; and juveniles, 0.71. The reproductive rate was 0.43 young per territorial female. Applying these parameters to the Moffat model (Hunt 1998), the potential growth rate would be 1.06, and the equilibrium population deriving from 100 pairs would be about 325 females, of which about 100 would be floaters ($F:B=1.0$).

To what extent the status of golden eagle populations is typified by these values is unknown, but they describe a far more robust population than that suggested by our data for the golden eagles around Altamont Pass. If the Prince William Sound population does indeed maintain one surplus adult for every surviving breeder at fledging time, the population would clearly be considered a “source” of recruits to less favorable habitats in the surrounding landscape. In contrast, the Altamont eagles appear at or below the threshold of “sink” population status. Let us examine additional evidence for and against this supposition.

9.1 Territorial Subadults

The clearest indication that a population lacks the security of an adequate floating segment is a high incidence of subadults as members of breeding pairs (Newton 1979). We are thus encouraged by the relatively low (approximately 3%) observed incidence of territorial subadults in the Diablo Range (see Section 6.6.7). In contrast, Bergo (1984) reported that 46–58% of pairs of golden eagles in his study area in west Norway included at least one individual in subadult plumage, and in 19% of cases, both individuals were subadults. He speculated that the population had been below carrying capacity for some time. The incidence of subadults as pair members in Idaho was inversely correlated with winter adult densities, but apparently unrelated to jackrabbit abundance (Steenhof et al. 1983); when eagle populations were high, adult eagles tended to fill territory vacancies.

9.2 Reproductive Rate

The modeling results suggest that the population may decline to extinction if there are no immigrant floaters to buffer the loss of breeders. However, if the number of breeding pairs were to decrease, the per-territory reproductive rate would increase as remnant eagle pairs tended to occupy the more productive sites. For example, in a population of Spanish imperial eagles (*Aquila adalberti*), mean annual productivity per territory decreased as the population increased (Ferrer and Donozar 1996). The authors explained the change by demonstrating that sites of highest quality were occupied first, followed by expansion into lower-quality sites in the second period (see also Dohndt, Kempnaers, and Adriaensen 1992, Rodenhouse, Holmes, and Sherry 1997). Hence, a reduction in overall productivity resulted from lower average site quality. If the reverse is true for a declining population,

¹ Bald eagles share certain demographic characteristics with golden eagles, e.g., reproductive rates are similar, and both species tend to reach adulthood (show definitive plumage) in the fifth year of life.

the reproductive rate can be expected to increase, possibly to the point of stabilizing the population, albeit at a reduced level.

Our reproductive rate estimate of 0.64 fledglings per pair is lower than the 0.79 average reported for the species (see Table 6.2 in Hunt et al. 1995). The apparent male bias is likely also atypical. To what extent reproductive rates and sex ratios vary over the long term cannot be known without a longer period of sampling.

9.3 Biases Affecting Survival Estimation

Considering possible biases in survival rate estimation, we regard the following as most problematic: (1) transmitter destruction by lethal agents, (2) the fate of emigrant juveniles, and (3) tagging location of itinerants.

To consider the possibility that turbine-destroyed transmitters existed in addition to those known to have been destroyed (see Sections 5.4 and 6.5), we recalculated the survival rate for non-territorial eagles after weighting it with five phantom casualties (added to periods with the greatest number of turbine deaths). We obtained a value of 0.7662 (SE=.0219). The result reduced the potential growth rate estimate in the Moffat model from 0.9906 to 0.9840.

The second process that might impart an upward bias to the population estimates is the possibility that juveniles leave the study area because they are unable to obtain food (Newton 1998). Juveniles lack experience in food acquisition and competitive access to foraging areas and thus comprise the segment most vulnerable to food shortage. It might well be adaptive for a starving juvenile to emigrate on the chance of finding food elsewhere, an event that would prevent the detection of its death. Among 72 juveniles we radio-tagged as fledglings, we censored 11 (15%), of which four were known to have departed (see Section 5.1 in Hunt et al. 1997). Two of these traveled over 300 km south of the study area: one (Case J8) was found dead (hit by a road vehicle); we found the transmitter of the other (Case J4) almost two years after its last detection.

Finally, there is the question of how the capture locations of radio-tagged subadults and floaters may have affected their tendency to enter the WRA. We caught most of the 62 itinerants in the WRA vicinity in 1994 and 1995. Despite their high mobility within the study area, there is the possibility of bias. As a way of assessment, we examined the gross movements of those subadults originally tagged as fledglings. Figures 7.1 and 7.2 in Hunt et al. (1996) clearly show that these tended to gravitate toward the WRA, approximating the distribution of eagles we tagged as subadults. This circumstantial evidence and that of general residency suggest that the bias of capture location is not strong, although a more careful analysis of movements of the two samples is indicated.

9.4 The Affected Population

One way of assessing the geographic extent of WRA influence on the eagle population is to truncate the relocation data at specified radii from the WRA boundary. First, we recalculated the survival rate of itinerants (subadults and floaters) occurring within a 20-km radius from the center of the WRA (n=3,273 relocations; data through mid-June 1997). In modeling the results (Moffat model), we assumed that distance from the WRA would not be an important factor in survival of juveniles and breeders, considering that neither appeared much influenced by turbine blade strikes (see Table 6.2). With subadult/floater survival at 0.7430 (S.E.=0.04) within the 20-km circle, λ was 0.9785.

For the 30-km radius (4,243 relocations), we calculated subadult/floater survival at 0.7680 (S.E.=0.03), giving a λ value of 0.9844.

9.5 Have Turbines Benefited Eagles?

Reviewers of an earlier draft of this report suggested that the wind turbines at Altamont Pass may have increased golden eagle survival by increasing ground squirrel density and providing perching structures. We do not regard this as a tenable hypothesis for several reasons. First, the WRA has a long history of grazing, a factor favoring both high ground squirrel (and jackrabbit) densities (Evans and Holdenried 1943, Linsdale 1946, Fitch 1948, Estep and Sculley 1987) and their vulnerability to eagles (Kochert 1987). Thus, the WRA was doubtless excellent ground squirrel and golden eagle habitat long before the building of the turbines. Although it is plausible that the additional soil disturbance associated with turbine structures and the roads servicing them have increased ground squirrel abundance in the WRA, we believe that such an increase in food supply could not even remotely compensate demographically for the mortal risk to eagles associated with the presence of the turbines. Consider that, at the date of this writing, at least 10 of 25 eagles tagged as fledglings in 1994 have been killed by turbine blade strikes. All 10 were killed after reaching subadulthood when a maximum of only 20 tagged birds from the 1994 cohort could still be detected within the study area, a 50% attrition rate.

Our observations in the WRA suggest that turbine structures are not of particular importance to foraging eagles. In 94 sightings of perched eagles in the WRA, 34 (36%) were on transmission towers, 33 (35%) were on the ground, 23 (24%) were on wind turbine towers, and 4 (4%) were on other perching structures. The commonly observed mode of foraging was contour hunting, an in-flight behavior (Hunt et al. 1995). Turbines disrupt an otherwise open landscape. Openness is known to be the key factor in golden eagle foraging habitat worldwide (Marquiss, Ratcliffe, and Roxburgh 1985, Watson 1992, 1997).

10.0 PROJECT CONTINUATION

PBRG has received promise of further funding by the California Energy Commission to radio-tag eagles, monitor their movements and survival, and to conduct annual nest surveys. The work will track efforts by the wind industry to reduce the rate of turbine blade strikes at Altamont Pass. Among possibly mitigating measures are plans to modify and/or remove turbines in "high-risk" areas. The industry will replace turbine models with others thought to be more benign. The replacements, reputedly more efficient by a ratio of seven to one, will result in fewer turbines overall in the WRA. PBRG will continue to model the accruing data to estimate changes in the trend of the eagle population and to identify those features of wind energy generation most conducive to golden eagle mortality.

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APPENDIX A

Results of the 1998 Golden Eagle Reproductive Survey in the Area Surrounding Altamont Pass

(NREL CONTRACT NO. AAT-8-18210-01)

DATE OF REPORT: JULY 21, 1998

The Predatory Bird Research Group (PBRG) at the University of California is conducting a long-term study of the impacts of wind energy generation on the population dynamics of golden eagles (*Aquila chrysaetos*) inhabiting the Diablo Mountain Range. The project, now in its fifth year, requires estimates of survival and reproduction as input parameters for population trend analysis, the predictive power of which depends upon the accuracy of these estimates. The reproductive rate parameter is problematic because of the unknown extent to which climate, prey fluctuations, and other factors may influence nesting success and brood size from year to year. Moreover, only two years of survey data are available: 1996 and 1997. For these reasons, the National Renewable Energy Laboratory (NREL) has provided partial funding for a third reproductive survey. This report details its results.

Methods

We define the natality parameter as the number of fledged young (≥ 54 days, Steenhof 1987) per territorial pair, the latter being only those pairs observed during or before incubation. This requirement overcomes the bias that successful pairs are easier to locate and identify late in the breeding season than pairs that have failed (Steenhof and Kochert 1982, Steenhof 1987).

Meeting these standards required several visits to each territory. We collected occupancy data during the courtship and incubation period of the breeding cycle, from early January through mid-April. After determining occupancy, we revisited territories one to three times during the incubation period (February–April), until either an active nest site was located or the lack of one determined; known pairs that had shifted to alternate nests required an extra visit or two. We revisited each active territory to estimate the age of the brood so as to schedule the final visit in May or June when the young would be of proper age for counting. Thus, it was necessary to observe some territories on four or more occasions. We attempted to determine in all cases whether pair members displayed subadult plumage.

One person performed the entire survey from 5 January through 23 June 1998. In all, the survey required 111 visits to the study area and approximately 1,000 hours of work.

Results

The 1998 territory reoccupancy rate was 100%, and all territories contained pairs rather than single adults. Of the 79 territorial pairs observed, 4 were newly discovered. We had surveyed 74 of the 75 previously known territories last year; the remaining territory (North Peak), unsurveyed in 1997, had been occupied by a pair in 1996. Only 1 of the 156 territorial individuals observed was identified as subadult.

We determined the reproductive outcome at 64 territories, all of which met the standard of having been observed early in the nesting season. Thirty-five pairs failed to fledge young, 21 produced one fledgling, and 8 had two fledglings, a reproductive rate of 0.58 fledglings per occupied territory. Brood size averaged 1.28 young. Barren nests resulted either from pairs failing to lay eggs or from losses during or following incubation. We know that three pairs failed in the egg stage, two in the chick stage, and four in either the egg or chick stage. We do not know what proportion of the remaining failed pairs laid eggs. Two broods we observed lost one of two chicks around the fifth week of life. We detected five breeder replacements occurring either prior to or early in the breeding season; none of these pairs with new members was successful in producing young.

Summary and Discussion

Despite the extraordinary amount of rainfall and the high number of rainy days, the 1998 reproductive rate of 0.58 young per territorial pair was virtually identical with the figure from the previous year. The proportion of productive pairs was actually higher in 1998 than in 1996 or 1997, yet average brood size was appreciably smaller, i.e., there were relatively few two-chick broods.

Although it is tempting to conclude from these last three years that reproduction varies but little on an annual basis, our data suggest that the first year of our study, 1994, was one of much higher reproduction. Admittedly, our 1994 estimate of 1.27 fledged young per occupied territory (48 young at 37 sites) was likely biased in favor of successful nests found late in the breeding season. However, if we imagine a scenario of having surveyed in 1994 all 64 of the territories we surveyed in 1998, and if every one of the additional 27 sites (64 minus 37) had failed, the reproductive rate in 1994 would have been 0.75 young per occupied territory, higher than all the other years. Despite the more thorough surveys in 1996–1998, we counted a maximum of only 39 young, compared with 48 in 1994. There can be little doubt that the eagle population produces far more young in some years than in others.

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