U.S. Fish and Wildlife Service Final Report: 2023 Peregrine Falcon Status Assessment, Sustainable Take Rate, and Take Limits

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Cover Photo: Arctic peregrine falcon (*Falco peregrinus tundrius*) in northern Alaska by Ted Swem, U.S. Fish and Wildlife Service.

EXECUTIVE SUMMARY

Peregrine falcons are one of the most desirable species of raptor for use in the sport of falconry. However, take (or harvest) from the wild was prohibited for several decades while the species recovered from widespread population declines caused by pesticide contamination. Limited falconry take of peregrine falcons was resumed in 2007 after the species had sufficiently recovered but take was tightly managed to ensure continued recovery was not impeded. Currently, peregrine falcon take in the eastern United States (US) is restricted to a narrow temporal window in autumn to focus harvest on migrants originating from north of 54º latitude, whereas in the western US take is limited to the breeding and pre-migration period to focus take on residents. These constraints were implemented to achieve specific management objectives at the request of some state fish and wildlife agencies in the US, and provincial and territorial governments and the Canadian Wildlife Service in Canada. Peregrine falcon populations have continued to grow since 2007, and falconers and some state fish and wildlife agencies recently requested that the US Fish and Wildlife Service (Service) reassess the status of the species to determine if relaxation of these restrictions is warranted. This status assessment was undertaken in response to those requests.

For this assessment, we compiled and analyzed band recovery, nest monitoring, Breeding Bird Survey (BBS), and autumn migration count data for peregrine falcons from across North America (including Greenland), focusing on the period 2008–2020. We followed prior convention and evaluated information separately for the highly migratory northern peregrine falcons (those from north of 54º latitude, hereafter the northern management population [NMP]), and the more sedentary southern peregrine falcons (hereafter the southern management population [SMP]). We developed management population-specific integrated population models (IPMs) to combine survival, productivity, and count data, and used the output from each IPM for inference. Mean (95% credible interval [CRI]) survival probabilities estimated from the IPMs were lower for first year (Y1) peregrine falcons in the SMP (0.44 [0.42–0.46]) than in the NMP (0.51 [0.45–0.57]) and higher for after first year (AY1) birds in the SMP (0.81 [0.79–0.82]) than in the NMP (0.78 [0.77–0.81]). The estimated mean number of fledged young or advanced-age young present per occupied nesting territory was higher in the SMP (1.73 [1.69–1.77]) than in the NMP (1.37 [1.26–1.51]). Both management populations showed an overall increasing trend (SMP λ 2009–2019: 1.043 [1.017–1.082]; NMP λ 2000–2019: 1.016 [1.007–1.025]).

We conducted a prescribed take level (PTL) analysis for both management populations and estimated mean r_{max} (the maximum possible population growth rate under typical environmental conditions in the absence of take or density dependent feedback) as 0.23 (0.003–0.58) in the NMP and 0.17 (0.13–0.22) in the SMP. Although the mean estimate of r_{max} for the NMP appeared higher than the SMP, the posterior distribution for the NMP had a higher variance (SD = 0.19) and was more skewed as indicated by the difference between the median (0.18) and mean compared to the SMP (SD = 0.02, median = 0.17). Consequently, the 95% CRI's of r_{max} for the NMP overlapped the SMP, indicating that the differences are not statistically large. Given these estimates of r_{max}, and assuming nonlinear density dependence, we estimated the mean take rate at maximum sustainable yield (MSY) was 0.11 (0.01–0.36) for the NMP and 0.11 (0.04–0.18) for the SMP. Mean population size estimates from the IPMs for the most recent years with data (2020 in the NMP and 2019 in the SMP) were 94,366 (69,991–122,299) total (i.e., Y1 + AY1) and 26,875 (15,776–40,339) Y1 individuals in the NMP, and 9,583 (7,532–12,027) total and

3,193 (2,335–4,251) Y1 individuals in the SMP. If peregrine falcon take for falconry was "normalized" and treated the same as take for most other raptors, maximum allowable take would be 5% of annual production in each management population; all removals would be of Y1 individuals. Under this most liberal scenario and our estimated current age-specific estimates of population size, take at the population level would be ~1.5%, well below that at MSY, and thus, according to harvest theory, sustainable and likely resulting in equilibrium population sizes only slightly below carrying capacity in each management population. Thus, normalization of peregrine falcon take could potentially result in the annual removal of 1,324 Y1 individuals from the NMP, and 158 Y1 individuals from the SMP; actual allowable take numbers would be determined by the Service in consultation with the Flyway Councils. Current annual take of peregrine falcons by falconers in the US averages < 50% of the available allocation of 309 birds, and thus, the effect of further increasing allowable take on future demand remains unknown.

INTRODUCTION

The peregrine falcon (*Falco peregrinus*) is one of the most widely distributed birds in the world occurring on every continent except Antarctica with 19 recognized subspecies (White et al. 2020). North American peregrines occupy open landscapes near cliffs, river canyons, coastlines, and cities, and eat mostly birds with 450 species being identified as prey (White et al. 2020). Peregrine falcons are one of the more desirable raptor species for use in falconry, and from 1938–1970 falconers regularly captured wild peregrine falcons in the United States (US) for use in the sport (Ward and Berry 1972). Allowing take of wild peregrine falcons for falconry (hereafter "take", or "harvest") temporarily ended in 1970 when two of the three subspecies of peregrine falcons in the US (the American and Arctic peregrine falcon, *F. p. anatum* and *F. p. tundrius*, respectively) were listed under the Endangered Species Act (Title 50 of the Code of Federal Regulations [CFR] Part 17.11). The decline of peregrine falcons worldwide has been attributed to contamination by chlorinated hydrocarbon pesticides such as dichlorodiphenyltrichloroethane (DDT) and its metabolite dichlorodiphenyldichloroethylene (DDE), which negatively affected reproduction, and several related pesticides, which may cause reduced survival (Nisbet 1988; Cade et al. 1988). Use of DDT and other organochlorine pesticides in Canada and the US was severely restricted starting in 1972 (USFWS 1998), after which peregrine falcon populations in North America began slowly recovering (Kiff 1988). *F. p. tundrius* was removed from the list of threatened and endangered wildlife in 1994 (USFWS 1994), and *F. p. anatum* was removed from the list in 1999 (USFWS 1999).

Soon after *F. p. anatum* was delisted, falconers requested that states and the US Fish and Wildlife Service (Service) allow resumption of take of wild peregrines for falconry. Fulfilling that request was complicated by the fact that peregrine falcons were still listed under the Species at Risk Act in Canada (COSEWIC 2017), as well as by many state fish and wildlife agencies in the US. Following a lengthy review process and international negotiation, a limited falconry take of wild juvenile (first year, Y1) peregrine falcons was allowed in the western US beginning in 2001, and that take was expanded to the eastern US in 2008 (USFWS 2008; see Historical Background section for more details).

Recently, falconers and some states requested that the Service relax some of the constraints on peregrine falcon take. The formal requests include: (1) extending take periods in the western US; (2) increasing take limits in the western US to reflect information on current population size; and (3) "normalizing" take of peregrine falcons throughout the US so that take of this species would be managed like that of most other raptors. If normalized, the federal framework would be modified to allow states to set their regulations to allow take of Y1 peregrine falcons by falconers at any time of the year, but subject to a population-wide take limit equal to 5% of estimated annual production. States would be free to enact more restrictive (but not more liberal) regulations, and they would be expected to coordinate take through the Flyway Councils to ensure compliance with the take limits at the scale of the management population (USFWS 2007, 2008). Implementing any of these changes would require that the Service replace or update and supplement the 2008 Environmental Assessment (EA; USFWS 2008) that establishes the current harvest strategy for peregrine falcons. The first step in that process is to assess the current status of peregrine falcons in North America (including Greenland) so that any new harvest alternatives can be scientifically evaluated relative to their anticipated effects on peregrine falcon populations.

The purpose of this report is to provide an updated assessment of the status of North American peregrine falcons to inform discussions of possible changes to the current harvest strategy. In 2008, the Service subdivided the North American distribution of peregrine falcons into two management populations based on biological criteria: (1) a highly migratory northern management population (NMP) north of 54° latitude that included the entire North American range of *F. p. tundrius* and the northern portions of the ranges of both *F. p. anatum* and the Peale's peregrine falcon (*F. p. pealei*), the third North American subspecies which occurs along the Pacific maritime coast in the northwestern US, Canada, and southeastern Alaska; and (2) a more sedentary southern management population (SMP) south of 54° latitude that included most of the range of *F. p. anatum* and *F. p. pealei*, (USFWS 2008: Figure 1). The SMP was further subdivided into eastern and western components based on socio-political considerations in 2008, but here we combined those subpopulations into the SMP.

For this assessment, we: (1) conducted a comprehensive analysis of band recovery data provided by the U.S. Geological Survey (USGS) Bird Banding Laboratory (BBL) to update estimates of age-specific peregrine falcon survival for both the NMP and SMP; (2) obtained and analyzed contemporary data on numbers of occupied peregrine falcon nesting territories and productivity (number of fledged young or advanced-age young present per occupied nesting territory) from US state agencies, Canadian provincial and territorial agencies, nongovernmental organizations, and other federal agencies; and (3) analyzed count data specific to each management population. For the SMP, we analyzed USGS Breeding Bird Survey (BBS) data as our index to annual population size. The BBS does not sample much of the NMP but given the highly migratory nature of that management population, autumn migration counts do. We obtained autumn migration count data for all autumn hawk migration count sites in North America that annually report counts of >100 migrant peregrine falcons from the Hawk Migration Association of North America and analyzed these data as an index to population trends in the NMP. We developed independent submodels for each of these data sets (i.e., survival, productivity, BBS counts, and migration counts), but for inference we integrated them using management population-specific integrated population models (IPMs). IPMs take advantage of the shared information on demographic rates provided by the demographic and count data, and usually result in more precise estimates of survival, reproduction, and population size, as well as, under some conditions, allowing for the estimation of demographic parameters for which specific data are lacking (Schaub and Abadi 2011; Plard et al. 2019; Schaub and Kéry 2022). Finally, we used the results of the IPMs to assess the population-level effects of peregrine falcon take using the prescribed take level (PTL) framework that has been widely used in other similar migratory bird take assessments (Runge et al. 2009; Johnson et al. 2012; Zimmerman et al. 2019, 2022; Millsap et al. 2022).

HISTORICAL BACKGROUND

As noted in the Introduction, widespread use of chlorinated hydrocarbon pesticides in the middle of the 20th century caused many populations of peregrine falcons around the world to decline substantially (Nisbet 1988; Cade et al. 1988). In response, two of three peregrine falcon subspecies occurring in North America (*F. p. tundrius* and *F. p. anatum*) were added to the list of Threatened and Endangered Wildlife and Plants in the US in 1970 (USFWS 1994, 1999). The third North American subspecies, *F. p. pealei*, was not listed. As a result of this protection, take of *F. p. tundrius* and *F. p. anatum* from the wild for use in falconry was suspended. Subsequent

prohibitions on the use of DDT and related pesticides and other conservation actions facilitated population recovery, leading to the delisting of *F. p. tundrius* and *F. p. anatum* in 1994 and 1999, respectively (USFWS 1994, 1999).

Removing the protections of the Endangered Species Act allowed for the incremental resumption of take of peregrine falcons for falconry, which would be managed to balance the desire for sustainable harvest with lingering conservation concerns for some local populations. In 1999, the International Association of Fish and Wildlife Agencies (now the Association of Fish and Wildlife Agencies) initiated discussions regarding the resumption of falconry take of peregrine falcons with the Service and the Canadian Wildlife Service. Subsequently, state fish and wildlife agency involvement in these discussions was coordinated through the four administrative migratory bird flyways (the Atlantic, Mississippi, Central, and Pacific Flyways; Anderson and Padding 2015). These discussions paved the way for administrative actions by the Service to resume falconry take of wild peregrine falcons in the US.

The first step in the process occurred in 1999, when the Service published a notice of intent to develop two separate EAs, one for take of wild nestling *F. p. anatum* west of 100° W longitude, and another for the take of autumn migrants, primarily *F. p. tundrius* (USFWS 1999). In 2001, the Service published an assessment of the potential falconry take of nestling *F. p. anatum* west of 100° W longitude and implemented a harvest plan (USFWS 2001). That EA and the decision was withdrawn in 2002 in response to a legal challenge (USFWS 2004). A revised EA was issued in 2004 that evaluated six alternatives that varied in the proportion of the annual production of nestlings that could be taken in the western US (USFWS 2004). The 2004 EA concluded that take of 5% of nestlings would only minimally affect continuing population increase/recovery and would be undetectable in population monitoring; this approach, to be managed by the states, was implemented.

In 2006, Millsap and Allen (2006) used deterministic matrix models to evaluate the effects of multiple harvest-level scenarios on the size and age structure of raptor populations of numerous species, including peregrine falcons. Their analysis resulted in recommendations that harvest of juvenile raptors be limited to half of the maximum sustainable yield (MSY) up to a maximum of 5% of the Y1 age class for species with an estimated MSY harvest rate of $> 10\%$, which included peregrine falcons. For species (or populations) that did not meet this criterion, Millsap and Allen (2006) recommended a harvest rate of $\leq 1\%$ of the Y1 age class. This paper was fundamental to a new EA issued in 2007 that established standards for falconry take limits for all raptor species in the US, considering published data for, and the unique biology of, each species (USFWS 2007). The 2007 EA and its subsequent implementation supplanted the previously existing standards for take of nestling peregrine falcons in the western US.

In 2008, the Service completed the second peregrine falcon EA, primarily evaluating the take of migrant peregrine falcons in the eastern US, but also reassessing the take of nestling/fledgling peregrine falcons in the western US (USFWS 2008). For the purpose of management, this EA subdivided peregrine falcons nesting in North America and Greenland into three management populations: (1) Northern (NMP), including both *F. p. tundrius* and *F. p. anatum* that originate and nest north of 54° N latitude; (2) Western (WMP), consisting of *F. p. anatum* that originate from natal sites at or west of 100° W longitude and south of 54° N latitude, and all *F. p. pealei*; and (3) Eastern (EMP), consisting of all peregrine falcons (*F. p. anatum* and individuals of all

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other subspecies released there) originating from natal sites east of 100° W longitude and south of 54° N latitude. The EA and Management Plan evaluated the likely effects of harvest to source populations under eight alternatives. Using data on movements derived from band recoveries for peregrine falcons banded as nestlings and recovered during their first year, and conservative estimates of population size for each management population, the EA estimated the proportion and numbers of the Y1 age class of each management population that would potentially be exposed to harvest risk under each alternative to estimate the likely makeup of harvest.

Although the Service concluded that these biological analyses showed peregrine falcons were robust enough to support normalization of falconry take, the Canadian Wildlife Service, several eastern Canadian provinces, and some eastern US state fish and wildlife agencies expressed a strong preference for a more conservative approach. As a result of that input, the preferred alternative, which was ultimately implemented, included several constraints. First, to limit take of peregrine falcons in the EMP to ≤ 1% of annual production, the EA set an annual take limit of 36 Y1 peregrine falcons and constrained take to the period 20 September to 20 October east of 100° W longitude. This period coincides with the peak period of migration of peregrine falcons from the NMP. The timing constraint was designed to ensure that < 36% of the peregrine falcons taken in the east originated from the EMP to achieve the objective of limiting take from the that management population. Second, west of 100° W longitude (including Alaska), the EA set an annual take limit of 116 peregrine falcons and constrained the take to the nesting period through 31 August. These constraints were designed to ensure peregrine falcon take in the western US excluded *F. p. anatum* originating from natal areas in Canada, which at that time were still listed under the Canadian Species at Risk Act (USFWS 2008). The EA also assumed an annual falconry harvest of up to 2 migrant peregrine falcons in Canada and up to 25 in Mexico.

The harvest strategy established in the final 2008 EA has largely guided peregrine falcon take for falconry since that time, with some adjustments. The most significant adjustment was implemented in 2017, when the Service updated the take limit for autumn-migrant peregrines from 36 to 144. This change reflected new credible information on the number of Y1 migrant peregrine falcons produced annually in the NMP (Franke 2016). Additional support for this adjustment was provided by analysis of deuterium levels in breast feathers of migrant Y1 peregrine falcons captured in the autumn harvest; deuterium is a stable isotope of hydrogen that has been widely used to estimate the latitude of origin of birds and other animals (Rubenstein and Hobson 2004). Those analyses showed that 75% of peregrine falcons captured during the autumn harvest window in the eastern US had deuterium levels indicating they originated in the NMP (Franke et al. 2016); the EA assumed northern migrants would comprise at least 64% of the take, so this information confirmed that objective was being met. When implementing this adjustment, the Atlantic, Mississippi, and Central Flyways advocated that the Service adopt the conservative 10th quantile of Franke's (2016) Y1 population size estimate for the NMP for the purposes of establishing the updated take limit. The Service accepted that recommendation and used the updated conservative estimate of 18,000 autumn-migrant peregrine falcons in the same take models as was used for the 2008 EA to arrive at the new take limit of 144 (USFWS 2017). In this same announcement, the Service reiterated a commitment to review population and take data for Canada, the US, and Mexico every five years or at the request of the flyways to reassess take limits.

Another adjustment occurred in 2010, when the Service published an announcement that future decisions regarding the allocation of take of nestling peregrine falcons in the western US would be delegated to the flyways, with input from the Service as requested (USFWS 2010). Use of the administrative flyway councils to allocate take of peregrine falcons was envisioned in the 2008 EA; this Federal Register announcement implemented that approach. A similar process involving the Atlantic, Mississippi, and Central Flyways is used to allocate take of autumn-migrant peregrine falcons (USFWS 2017).

The 2008 peregrine falcon harvest strategy has served as the framework for governing take of peregrine falcons for falconry in the US for 15 years. Consistent with the harvest strategy, state fish and wildlife agencies have requested that the Service consider making the changes described in the Introduction. This report is a crucial step in the process of considering those changes.

METHODS

Survival

Banding Data

Peregrine falcons were banded throughout the US and Canada for individual studies (Figure S1). Most were banded as nestlings just prior to fledging or captured and banded during autumn or spring migration periods. Each captured individual was banded with uniquely numbered aluminum leg bands, and often with additional markers such as colored leg bands, satellite transmitters, or various other visible tags. We limited our sample to birds banded with aluminum leg bands because we were unsure whether other markers influenced survival and reporting probabilities. We used recoveries of banded peregrine falcons that were opportunistically found dead and reported to the BBL (USGS Bird Banding Laboratory 2019); the vast majority of banded peregrine falcons were not encountered, or, if encountered, not reported to the BBL. We used these banding and recovery data to estimate survival rates. We had sufficient bandings and recoveries from 1980–2018 to include in the survival analysis.

Because management of peregrine falcon take targets Y1 birds, we wanted to develop a model that could estimate the appropriate demographic parameters potentially influenced by management. Specifically, the 2007 and 2008 EAs specify that falconers could take a maximum of 5% of annual production, so we wanted to estimate survival of Y1 birds from the late nestling stage to autumn migration (which corresponds to the interval in which nestling and recently-fledged peregrines would be taken, i.e., passage birds), and from autumn to spring migration. Although migration periods are similar for the NMP and SMP (for individuals in this management population that migrate), nesting and fledging of NMP peregrine falcons occur later in summer. Therefore, we specified management population-specific seasons for our analysis. We pooled subadults (second-year individuals, Y2) with older birds in our analysis, so we estimated survival for Y1 and AY1 age classes. For the NMP, most banding of migrating birds occurs April through May and September through October, while most banding of nestlings occurs July through August. Based on these patterns, we established the summer survival period in the NMP for AY1 birds to be 1 May to 1 October (5 months) and for Y1 birds to be 1 August to 1 October (2 months). The winter survival period extended from 1 October to 1 May of the following year (7 months) for both age classes to allow birds that survived the winter following

fledging to transition to the same annual schedule as AY1 birds. The autumn banding period for the SMP was the same as for the NMP; however, spring (April–June) and fledging (May–July) periods were slightly different. Therefore, AY1 summer survival for the SMP was mid-May through 1 October (4.5 months) and Y1 summer survival was from mid-June through 1 October (3.5 months). Like the peregrine falcons in the NMP, Y1 birds that survived the winter transitioned to the AY1 schedule, so the winter survival period for AY1 and Y1 birds was from 1 October to mid-May (7.5 months) for the SMP. Most banding efforts for Y1 birds target the period just before fledging (Steenhof and Newton 2007), so we assumed that survival between banding and fledging was ~1 for Y1 birds.

To summarize, we separately estimated survival rates for the two management populations (SMP and NMP), which entailed specifying two age classes (Y1 and AY1) and two survival periods (summer and winter). Because the breeding seasons of the two management populations are slightly offset, to reflect latitudinal gradient in the timing of breeding, we defined the summer and winter survival seasons and the timing of transition from Y1 to AY1 slightly differently.

Survival Submodel

We used the dead recovery model developed by Seber (Williams et al. 2002:398) to estimate seasonal survival rates from the banding and recovery data. The Seber model includes two parameters: (1) a recovery probability, which is defined as the probability that a dead bird is found and its identity (i.e., band number) reported to the BBL; and (2) a survival probability. We used Bayesian methods with a multinomial likelihood to analyze the banding and recovery data (Equation 1).

$$Recovery.matrix_{a,s}^{MP} \sim Multinomial(Cell.probabilities_{a,s}^{MP}, Releases_{a,s}^{MP}) \tag{1}$$

The releases were vectors of the total bandings for each year (length = number of years) by age class (a; Y1 and AY1), season (s; summer and winter), and management population (MP; NMP and SMP). The recovery matrix was a summary of the number of bands recovered in each season and year for each vector of releases (rows = number of years, columns = seasons (2) per year). The cell probabilities were a matrix based on the parameters (survival [S] and recovery [r] probabilities) to be estimated from the data (see Table S1 [Supplemental Information] for cell probabilities of a hypothetical 3-year study). We used a binomial model with a logit link to estimate the survival and recovery parameters in the cell probabilities and random effects to test for annual variation in survival. We specified non-informative normal ($\mu = 0$, τ [precision] = 0.000001) priors for the regression coefficient parameters (β, γ), and assumed normal (0, $1/\sigma^2$) distributions for the random year effects with Gamma (0.001, 0.001) priors for standard deviation (σ). Preliminary assessment of the data indicated that recovery rates may be increasing in the SMP and decreasing in the NMP. We were concerned that using a random-effects parameterization like that used for survival may result in a biased mean if rates were trending in one direction, and so we compared a random year-effect on recovery to one with a trend.

We assumed survival probabilities differed between age classes but did not know if survival and recovery probabilities varied between seasons, management populations, or among years. Although recovery rate is not a parameter of direct interest, previous work indicated that bias in that parameter could bias survival in these models (Nichols et al. 1982). Therefore, we explored

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the influence of these factors on both recovery and survival (see Table S2 [Supplemental Information]). Our primary parameters of interest for management are age class-, season-, and management population-specific survival. Therefore, we conducted model selection using deviance information criterion (DIC; Spiegelhalter et al. 2002) to evaluate the performance of candidate models (see Table S3 [Supplemental Information]). The trend model performed better than the random-effects parameterization, so we used the trend model for all models where r varied by year.

The survival submodel that fit the data best indicated that survival varied between age classes, seasons, and management populations, and recovery varied between management populations and among years (Equations 2 and 3; Table S3 [Supplemental Information]) and this model was used in the IPMs (see Integrated Population Models section).

$$\text{logit}(S_{a,s}^{MP}) = \beta_{a,s}^{MP} \tag{2}$$

$$\text{logit}(r_t^{MP}) = \beta^{MP} + \gamma^{MP} \times T \tag{3}$$

Here, given that separate IPMs were run for the NMP and SMP, for each management population (MP), $\beta_{a,s}^{MP}$ is the mean age- and season-specific survival probability on the logit scale, β^{MP} and γ^{MP} are the recovery probability intercept and slope, respectively, on the logit scale, and T is a integer covariate from 1 to 39 (for 1980 to 2018). After identifying the top model, we compared the random-effect and trend model once again to ensure that this pattern was not different for the model used in the IPMs. We calculated concentration (C) to quantify relative precision in the binomial survival estimates (Equation 4; Link and Barker 2009).

$$C = \frac{SD}{\sqrt{p \times (1-p)}} \tag{4}$$

Here, p and SD represent the mean and standard deviation of the posterior survival probabilities.

Reproductive Output

Data

Our population model required an annual estimate of reproductive output defined as the total number of young fledged. We assumed that the total number of young fledged is derived from the proportion of breeding-aged birds that attempted to breed ($p.br$) and productivity (P), which is the average number of juveniles fledged per occupied breeding territory. The Service obtained peregrine falcon reproductive data for 2009–2020 from US state and federal agencies, Canadian provincial and territorial agencies, nongovernmental organizations, and other federal agencies. The reproductive data required for modeling were management population- and year-specific number of occupied nesting territories (i.e., presence of an adult pair or evidence of reproduction) and productivity (i.e., number of fledged young or advanced-age young present per occupied nesting territory).

Proportion Breeding

We did not have direct data available for estimating *p.br*, so we used information from other components of the IPMs to estimate this demographic rate as a latent variable. We assumed that *p.br* was constant among years and allowed it to vary by management population (i.e., $p.br^{MP}$). We specified a non-informative prior $mean.p.br^{MP} \sim$ Uniform(0,1) and allowed the IPM to inform a posterior estimate of $p.br^{MP}$. Initial attempts to run the IPM indicated that $p.br^{SMP}$ was near 1, so we fixed $p.br^{SMP} = 1$, but let the IPM for the NMP estimate $p.br^{NMP}$ in the final version of the models.

Productivity Submodel

We estimated productivity of peregrine falcons in the NMP and SMP with generalized linear mixed effects models; productivity was modeled with a Poisson log-linear model. We determined if there was temporal variation in productivity by evaluating models with and without a year random effect using DIC (Spiegelhalter et al. 2002). We specified non-informative normal ($\mu = 0$, $\tau = 0.001$) priors for β_0, uniform (0, 10) priors for σ, and assumed a normal (0, $1/\sigma^2$) distribution for the random effect.

The productivity submodel that included a random effect for year fit the data best (Equations 5–7) and this model was used in the IPMs (see Integrated Population Models section).

$$Young_t^{MP} \sim Poisson(P_t^{MP} O_t^{MP}) \tag{5}$$

$$\log(P_t^{MP}) = \beta_0^{MP} + \varepsilon_t^{MP} \tag{6}$$

$$\varepsilon_t^{MP} \sim Normal(0, (\sigma_t^{MP})^{-2}) \tag{7}$$

Here, for the tth year for each MP, $Young_t^{MP}$ is the number of fledged young or advanced-age young present, P_t^{MP} is mean productivity, O_t^{MP} is the number of occupied nesting territories, and ε_t^{MP} is year random effect. This submodel estimates the average number of juveniles fledged per occupied breeding territory, so we divided P_t^{MP} by 2 to adjust to fledglings per breeding bird when integrating this submodel in the IPM.

Abundance

SMP – Breeding Bird Surveys

The annual North American BBS (Sauer et al. 2013) provides a species-specific index of the number of birds counted during spring in the SMP (see map in Sauer et al. 2013:4). Volunteers conduct the BBS by recording all birds seen or heard along assigned roadside routes throughout the breeding season from the southern US north through southern Canada (see Sauer et al. 2013 for full details of the BBS). Routes, which include 50 stops spaced 800 m apart, are surveyed once per year. Most surveys are conducted in June, but some are conducted in late May in southern parts of the US or from early July in northern parts of southern Canada. Surveys begin 30 minutes before local sunrise and the observer records all birds seen or heard within 400 m during a 3-minute interval. Peregrine falcons in the Y1 age class are unlikely to have fledged

when the BBS is conducted over most of the BBS survey area, and therefore, are not likely to be counted during sampling.

Counts from the BBS are analyzed using a log-linear model at the scale of individual strata created from the intersection of state and Bird Conservation Regions. The log-linear model allows for overdispersion and includes stratum (s) by year (y) categorical effects ($\gamma_{s,y}$; Link et al. 2020) to model annual estimates based on counts. The model also includes sample unit (observer-route combination) and observer experience (i.e., first time observer versus not first time) to account for variation due to these sources. Link et al. (2020) estimated that for peregrine falcons, a model assuming (1) stratum by year effects were conditionally independent (i.e., $\gamma_{s,y}$ is normally distributed with mean $\gamma_{s,y-1}$) and (2) overdispersion specified by a central t distribution to account for extreme counts fit the peregrine falcon data best. They assigned non-informative normal ($\mu = 0$, $\tau = 0.000001$) and gamma (0.001, 0.001) priors to the mean and precision parameters, respectively. To aggregate to annual indices across the SMP, we weighted annual stratum-specific indices by the proportion of the total area in each stratum, then aggregated across all strata within a year (Sauer et al. 2013). Each year, the BBS indices are produced with an estimate and standard error that can be aggregated to various larger scales. We applied the weights to 10,000 posterior estimates of the indices, aggregated among strata for each year, and then calculated the summary statistics among the 10,000 estimates to use in the IPM. Thus, we used the indices derived by this model as our time series for the SMP IPM. The final indices from this model are the average number of peregrine falcons seen per route for each stratum and year. Although the BBS indices do not represent the population size of peregrine falcons in numbers of individuals, the other parameters in our IPM are rates (survival) or ratios (recruitment), so if the BBS indices accurately capture annual population change (λ), they provide an appropriate time series for our IPM (e.g., Ahrestani et al. 2017; Robinson et al. 2018).

NMP – Migration Counts

We used standardized autumn migration counts as an index to population size in the NMP IPM. Nearly all northern peregrine falcons are migratory and pass through the coterminous US enroute to their wintering grounds anywhere from the southern US to Argentina (White et al. 2020). Thus, autumn migration counts from sites where reasonably large numbers of migrating peregrine falcons are seen each year should provide a reliable index to overall population trends in the NMP.

We obtained autumn migration count data for peregrine falcons from 2000–2020 from the Hawk Migration Association of North America (HMANA), with the concurrence of the individual count site managers. We selected count sites where substantial numbers of peregrines are seen each year, subjectively focusing on sites that had average total annual counts over the most recent five-year period of > 100 peregrine falcons. Peregrine falcons from the NMP pass through the coterminous US primarily between 20 September and 20 October, and during this period their numbers greatly exceed the number of peregrine falcons from the SMP in the eastern half of the US (USFWS 2008). We used only autumn migration counts conducted during this temporal window and from this region of the coterminous US, southern Canada, northern Mexico, and Belize to ensure counts were primarily of individuals originating from the NMP.

There were 17 hawk count sites that met our initial criteria for inclusion in this study (Table 1). Eleven of these sites provided data for all but one or two years for the full period of our analyses (2000–2020) and counts were conducted in the years before and after missing years (Table 1). For the two sites with missing counts (i.e., Florida Keys Hawkwatch [2009 and 2017] and Smith Point [2008]), we imputed missing counts with estimates based on the median of counts in the years immediately before and after the missing years. Therefore, we included these 11 sites in our migration count analyses (Table 1).

Typically at each site, daily counts were conducted from early morning through late afternoon throughout the autumn migration period with at least one primary and occasionally several observers conducting the counts (see https://hawkcount.org/). The data provided by HMANA included number of peregrine falcons counted, number of minutes of observation by the primary observer, and number of minutes of observation by all designated observers for each site each year. Crewe et al. (2016) showed that for raptors frequently encountered at hawk migration count sites, analyses of annual count sums were efficient and generally unbiased. Because our data set was selected to include only migration count sites where substantial numbers of peregrine falcons were counted and we filtered the data to the time window when most peregrine falcons from the NMP were migrating, we believe our data were appropriate for analysis of annual count sums.

We used log-linear models with a Poisson distribution for our analysis of the migration count data. We included count effort as an offset in our models, but we had two measures of effort to consider, one based only on the effort of the primary observer and a second based on efforts of all formal observers. We computed Pearson product-moment correlation coefficients between counts and each measure of effort for each site, and for each site we used the measure of effort that was most strongly correlated with the counts for the offset. Initially, we included a slope term in our model as recommended by Crewe et al. (2016), but after evaluating a series of preliminary models and finding no support for a slope coefficient, we excluded it from the model. Given our hypothesis that these counts, in sum, should reflect annual trends in northern peregrine falcon numbers, we decided to use a common intercept that reflected an overall mean rate (given the offset for count effort). Our candidate model set included models with random effects for site and/or year and an overdispersion term that accounted for site by year variation (Table S4 [Supplemental Information]). The migration count model that included the overdispersion term fit the data best (Equation 8; Table S4 [Supplemental Information]).

$$\log(\lambda_{i,t}) = 1 \times \log(T_{i,t}) + \beta_0 + noise_{i,t} \tag{8}$$

Here, at the ith site in the tth year, $\lambda_{i,t}$ is the mean count, $T_{i,t}$ is the number of count minutes, β_0 is the common intercept, and $noise_{i,t}$ is the overdispersion term and assumed to follow a normal $(0, 1/\sigma^2)$ distribution. We specified a non-informative normal ($\mu = 0$, $\tau = 0.01$) prior for β_0, and a uniform (0, 100) prior for σ.

Integrated Population Models

We structured the IPMs to estimate relevant parameters for informing take for peregrine falcons. The primary parameters we needed were seasonal Y1 survival rates and current age-specific population size. In addition, estimates of demographic rates with uncertainty provided inference

regarding harvest potential for the two management populations. We modeled the NMP and SMP separately to account for different demographic rates, which could influence harvest potential, and timing of available data. The available abundance time series for the SMP is the BBS, which is conducted during the spring breeding season. Therefore, the annual cycle for the SMP went from spring to spring. The available abundance time series for the NMP was autumn migration counts, so the IPM for the NMP extended from autumn to autumn of each year.

Each IPM included a survival submodel that estimates age- and season-specific survival rates, a productivity submodel that estimates the mean number of young fledged or advanced-age young present per occupied nesting territory per year, and the proportion of breeding aged birds that attempt to breed. We used a state-space (Buckland et al. 2004, Kéry and Schaub 2012) formulation to integrate the time series (BBS indices in the SMP and migration counts in the NMP) with the demographic submodels to appropriately model the true latent population-size index while incorporating uncertainty in the annual indices with an explicit observation process. Each IPM estimated abundance indices for Y1, Y2, and after second year (AY2) age classes. We assumed Y2 and AY2 peregrine falcons had the same survival probability (hereafter AY1 survival) and that birds did not breed until their third spring after fledging (i.e., Y2 birds that transition to AY2 do not breed until the spring after transition).

We used the following post-breeding transition matrix model (Caswell 2001) to represent the stage-structured population dynamics for the SMP:

$$
\begin{bmatrix}
0 & 0 & S_{AY1,Su}^{SMP} \times S_{AY1,Wi}^{SMP} \times p.br^{SMP} \times \dfrac{P_t^{SMP}}{2} \\
S_{Y1,Su}^{SMP} \times S_{Y1,Wi}^{SMP} & 0 & 0 \\
0 & S_{AY1,Su}^{SMP} \times S_{AY1,Wi}^{SMP} & S_{AY1,Su}^{SMP} \times S_{AY1,Wi}^{SMP}
\end{bmatrix}
\times
\begin{bmatrix} I_{Y1}^{SMP} \\ I_{Y2}^{SMP} \\ I_{AY2}^{SMP} \end{bmatrix}_t
=
\begin{bmatrix} I_{Y1}^{SMP} \\ I_{Y2}^{SMP} \\ I_{AY2}^{SMP} \end{bmatrix}_{t+1}
$$

where $S_{Y1,Su}^{SMP}$ and $S_{AY1,Su}^{SMP}$ are age-specific summer survival and $S_{Y1,Wi}^{SMP}$ and $S_{AY1,Wi}^{SMP}$ are age-specific winter survival (see Survival section for details of seasonal periods), $p.br^{SMP}$ is the latent proportion of birds attempting to breed, P_t^{SMP} is time-dependent productivity, and I_{Y1}^{SMP}, I_{Y2}^{SMP}, and I_{AY2}^{SMP} are annual age-specific latent BBS indices for Y1, Y2, and AY2 birds, respectively. Note that although we use "summer" and "winter" as seasonal terms, midpoints occur during spring and autumn, so the combined summer and winter periods represent a full year. Thus, this model assumes that Y1 birds are derived from AY2 birds that survive and reproduce (Equation 9), Y2 birds are surviving fledglings from the previous year (Equation 10), and AY2 birds are Y2 and AY2 birds that survive the year (Equation 11).

$$ I_{Y1,t+1}^{SMP} = I_{AY2,t}^{SMP} \times \left(S_{AY1,Su}^{SMP} \times S_{AY1,Wi}^{SMP} \times p.br^{SMP} \times \frac{P_t^{SMP}}{2} \right) \tag{9} $$

$$ I_{Y2,t+1}^{SMP} = I_{Y1,t}^{SMP} \times \left(S_{Y1,Su}^{SMP} \times S_{Y1,Wi}^{SMP} \right) \tag{10} $$

$$ I_{AY2,t+1}^{SMP} = \left(I_{Y2,t}^{SMP} + I_{AY2,t}^{SMP} \right) \times \left(S_{AY1,Su}^{SMP} \times S_{AY1,Wi}^{SMP} \right) \tag{11} $$

We used a slightly modified model for the NMP to account for seasonal differences in the time series:

$$
\begin{bmatrix}
0 & 0 & S_{\text{AY1,Wi}}^{\text{NMP}} \times p.\,br^{\text{NMP}} \times \dfrac{P_t^{NMP}}{2} \times S_{\text{Y1,Su}}^{\text{NMP}} \\
S_{\text{Y1,Wi}}^{\text{NMP}} \times S_{\text{AY1,Su}}^{\text{NMP}} & 0 & 0 \\
0 & S_{\text{AY1,Wi}}^{\text{NMP}} \times S_{\text{AY1,Su}}^{\text{NMP}} & S_{\text{AY1,Wi}}^{\text{NMP}} \times S_{\text{AY1,Su}}^{\text{NMP}}
\end{bmatrix}
\times
\begin{bmatrix}
I_{\text{Y1}}^{\text{NMP}} \\
I_{\text{Y2}}^{\text{NMP}} \\
I_{\text{AY2}}^{\text{NMP}}
\end{bmatrix}_t
=
\begin{bmatrix}
I_{\text{Y1}}^{\text{NMP}} \\
I_{\text{Y2}}^{\text{NMP}} \\
I_{\text{AY2}}^{\text{NMP}}
\end{bmatrix}_{t+1}
$$

Here, $S_{\text{Y1,Su}}^{\text{NMP}}$ and $S_{\text{AY1,Su}}^{\text{NMP}}$ are age-specific summer survival and $S_{\text{Y1,Wi}}^{\text{NMP}}$ and $S_{\text{AY1,Wi}}^{\text{NMP}}$ are age-specific winter survival (see Survival section for details of seasonal periods), P_t^{NMP} is time-dependent productivity, $p.\,br^{\text{NMP}}$ is the latent probability of successfully breeding, and $I_{\text{Y1}}^{\text{NMP}}$, $I_{\text{Y2}}^{\text{NMP}}$, and $I_{\text{AY2}}^{\text{NMP}}$ are annual age-specific latent migration count indices for Y1, Y2, and AY2 birds, respectively. Note that we rearranged the order of seasons in the NMP to represent the progression of ages from the autumn migration counts. Therefore, Y1 birds in the autumn count are derived from AY2 birds that survive the winter following the autumn migration count, that reproduce the following spring, and then the fledged young must survive the summer to the following autumn count (Equation 12), Y2 individuals are Y1 birds from the previous autumn that survive the winter as Y1 birds, transition to Y2 individuals in the spring, and then survive the summer as Y2 (with AY1 survival rates) to the following autumn (Equation 13), and AY2 individuals are Y2 and AY2 birds that survive the winter and summer periods following the autumn migration (Equation 14).

$$
I_{\text{Y1},t+1}^{\text{NMP}} = \left(I_{\text{AY2},t}^{\text{NMP}} \times S_{\text{AY1,Wi}}^{\text{NMP}} \times p.\,br^{\text{NMP}} \times \frac{P_t^{NMP}}{2} \right) \times S_{\text{Y1,Su}}^{\text{NMP}} \tag{12}
$$

$$
I_{\text{Y2},t+1}^{\text{NMP}} = I_{\text{Y1},t}^{\text{NMP}} \times \left(S_{\text{Y1,Wi}}^{\text{NMP}} \times S_{\text{AY1,Su}}^{\text{NMP}} \right) \tag{13}
$$

$$
I_{\text{AY2},t+1}^{\text{NMP}} = \left(I_{\text{Y2},t}^{\text{NMP}} + I_{\text{AY2},t}^{\text{NMP}} \right) \times \left(S_{\text{AY1,Wi}}^{\text{NMP}} \times S_{\text{AY1,Su}}^{\text{NMP}} \right) \tag{14}
$$

Integrating time series with submodels

As noted above, we used different IPMs for each management population to allow us to account for differences in the annual cycle and timing of counts for each management population (Figures 2 and 3).

For the SMP, we assumed transitions among age classes and years in the state model were stochastic with a log-normal distribution (Equations 15–17) because the BBS indices were a small (<0.1) and continuous index to population size that had to be ≥0. We assumed a non-informative prior distribution for the process precision $\frac{1}{\sigma_{\text{process}}^2} \sim$ Gamma(0.001, 0.001).

$$
I_{\text{Y1},t+1}^{\text{SMP}} \sim Lognormal\left(I_{\text{AY2},t}^{\text{SMP}} \times \left[S_{\text{AY1,Su}}^{\text{SMP}} \times S_{\text{AY1,Wi}}^{\text{SMP}} \times p.\,br^{\text{SMP}} \times \frac{P_t^{SMP}}{2} \right], \frac{1}{\sigma_{\text{process}}^2} \right) \tag{15}
$$

$$
I_{\text{Y2},t+1}^{\text{SMP}} \sim Lognormal\left(I_{\text{Y1},t}^{\text{SMP}} \times \left[S_{\text{Y1,Su}}^{\text{SMP}} \times S_{\text{Y1,Wi}}^{\text{SMP}} \right], \frac{1}{\sigma_{\text{process}}^2} \right) \tag{16}
$$

$$
I_{\text{AY2},t+1}^{\text{SMP}} \sim Lognormal\left(\left[I_{\text{Y2},t}^{\text{SMP}} + I_{\text{AY2},t}^{\text{SMP}} \right] \times \left[S_{\text{AY1,Su}}^{\text{SMP}} \times S_{\text{AY1,Wi}}^{\text{SMP}} \right], \frac{1}{\sigma_{\text{process}}^2} \right) \tag{17}
$$

For the NMP, we specified a Poisson distribution for Y1 peregrine falcons to accommodate productivity (Equation 18), which was a ratio rather than a probability and we used a binomial distribution for Y2 and AY2 birds because changes in migration counts were a function of the previous year's count (an integer) and annual survival probabilities (Equations 19 and 20).

$$I_{Y1,t+1}^{NMP} \sim Poisson\left(\left[I_{AY2,t}^{NMP} \times S_{AY1,Wi}^{NMP} \times p.br^{NMP} \times \frac{P_t^{NMP}}{2}\right] \times S_{Y1,Su}^{NMP}\right) \tag{18}$$

$$I_{Y2,t+1}^{NMP} \sim Binomial\left(I_{Y1,t}^{NMP}, S_{AY1,Wi}^{NMP} \times S_{AY1,Su}^{NMP}\right) \tag{19}$$

$$I_{AY2,t+1}^{NMP} \sim Binomial\left(I_{Y2,t}^{NMP} + I_{AY2,t}^{NMP}, S_{AY1,Su}^{NMP} \times S_{AY1,Wi}^{NMP}\right) \tag{20}$$

We specified the observation model for the SMP as:

$$I_{BBS,t} \sim Normal\left(I_{Y1,t}^{SMP} + I_{Y2,t}^{SMP} + I_{AY2,t}^{SMP}, \frac{1}{\sigma_{BBS,t}^2}\right), \tag{21}$$

where, $I_{BBS,t}$ and $\sigma_{BBS,t}^2$ are the estimates and sampling variance from the BBS analyses described above, and were included as data in the SMP IPM. Similarly, we specified the observation model for the NMP as:

$$I_{Mig,t} \sim Normal\left(I_{Y1,t}^{NMP} + I_{Y2,t}^{NMP} + I_{AY2,t}^{NMP}, \frac{1}{\sigma_{Mig,t}^2}\right), \tag{22}$$

where, $I_{Mig,t}$ and $\sigma_{Mig,t}^2$ are the estimates and sampling variance from the fitted indices of the migration counts, and were included as data in the NMP IPM. We used the BBS index and SD and the migration count estimate and SD to specify the priors for the first population index in the state model for the SMP and NMP, respectively. We partitioned the first index into age-specific values using stable age distributions from previous analyses (Millsap and Allen 2006). After the first timestep, we updated the proportion of individuals in each age class based on estimated age-specific demographic rates and population changes from the IPM. The proportion of the population in each age class was of particular importance to estimating actual population sizes (see below).

We used the IPMs for each management population to derive estimates of total recent population sizes (N_{2019}^{SMP} and N_{2020}^{NMP}) based on the demographic rates and indices used in the analyses. Several states and studies provided an estimate of nesting pairs over a large portion of the SMP ($N = 1,565$; USFWS 2008) in 2008 as part of the delisting process for peregrine falcons. Therefore, we assumed that $2 \times 1,565 = 3,130$ was a starting population size estimate of breeding (AY2) peregrine falcons for the SMP in 2008, and used annual estimates of population growth rate from the IPM (i.e., I_{t+1}^{SMP}/I_t^{SMP}) to estimate updated breeding population size changes from 2009 to 2019 ($N_{AY2,t}^{SMP}$). We adjusted $N_{AY2,t}^{SMP}$ by the proportion of AY2 ($N_{AY2,t}^{SMP}/p_{AY2,t}^{SMP}$) to get a total N (N_t^{SMP}) for each year (p_t is the year-specific proportion of individuals in the relevant age class). We based p_1 on the stable-stage distribution of the population matrix and then updated p_t based on the IPM after year 1. Although the estimate of the number of breeding pairs in 2008 did not have an associated variance estimate, we used uncertainty in growth rate from the IPM to add uncertainty in our estimates of N_t^{SMP}. We used a slightly modified approach for

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estimating N_t^{NMP}. Franke (2016) derived an estimate of the number of juvenile peregrine falcons in 2000 using a Lincoln-Petersen estimator ($N_{Y1,2000}^{NMP} = 21,280$). We used annual estimates of growth rate of Y1 (i.e., $I_{Y1,t+1}^{NMP}/I_{Y1,t}^{NMP}$) from the IPM to track changes in $N_{Y1,t}^{NMP}$ and calculated total population size ($N_t^{NMP}= N_{Y1,t}^{NMP}/p_{Y1,t}^{NMP}$) for each year.

Models were run in R 4.1.2 (R Core Team 2021) using jagsUI 1.5.2 (Kellner 2021; model code available upon request). We ran our models with three chains of 100,000 iterations each with a thinning rate of 5, and discarded the first 10,000 MCMC samples as burn-in. We considered models to have converged if the Gelman-Rubin convergence statistic $\hat{R}$ was < 1.1 (Gelman and Hill 2007), the chains were mixed well (low autocorrelation), sufficient effective samples were obtained, and posterior density plots showed similar smooth shapes between chains that differed from the uninformed priors.

Take Assessment

The intent of the recommended allowable take in the 2007 and 2008 EAs was that authorized take would be sufficiently below maximum sustainable take (i.e., conservative) to avoid authorizing take that could unexpectedly harm populations given the absence of intensive monitoring data (USFWS 2007, 2008). Accordingly, the Service estimated that 5% of annual production of Y1 peregrine falcons could be taken for falconry at that time (USFWS 2007, 2008). Fixed take rates (e.g., 5% of Y1) could lead to increases in the number of birds taken in increasing populations; however, the number of falconers that apply for permits is limiting, so we suspect that further increases in populations that could occur would not necessarily result in a proportionate increase in take. Because the recommendation of 5% of Y1 birds was not based on an explicit harvest assessment, we used the results of the IPM to explore how the recommended alternative may influence the two peregrine falcon management populations.

Prescribed Take Level

We conducted two assessments to explore how these quotas would compare with estimated harvest potential of the population based on information derived from the IPMs. First, we estimated allowable take using the PTL method, which has been used to inform sustainable take levels for other raptors (Runge et al. 2009; Millsap et al. 2022; Zimmerman et al. 2022). The PTL framework combines a management objective (F_O), an estimate of growth rate (r_{max}), population size (N), form of density-dependence (θ) and risk tolerance of the decision maker on failing to achieve the management objective (Equation 23; Runge et al. 2009, Johnson et al. 2012).

$$PTL_t = F_O \times \frac{r_{max} \times \theta}{\theta + 1} \times N_t \tag{23}$$

The risk tolerance of the decision maker is expressed as a quantile of the data used to estimate r_{max}, N, or overall PTL. For example, a risk-averse decision maker who is concerned about over-harvesting peregrine falcons, could select to use the lower 20th quantile of r_{max}, N, or PTL to reduce the risk of over-harvest in the face of uncertainty in demographic rates and population size. Although setting risk tolerance is beyond the scope of our assessment, we provide PTL estimates for the median and 20th quantiles as has been done in previous assessments for raptors

(USFWS 2016) as an example of various levels of risk tolerance. The PTL framework is derived from harvest theory and density-dependent growth (Runge et al. 2004, 2009). The parameter θ accommodates non-linear density dependence in growth rates (Johnson et al. 2012). A θ near 1 represents linear density dependence, whereas values > 1 indicate that density dependence is strongest near carrying capacity (K) and values < 1 indicate that density dependence is strongest at lower population sizes (Williams 2013). We would expect species such as the peregrine falcon, with relatively high survival rates, to have $\theta > 1$. However, θ is difficult to estimate from field data, leading to uncertainty about the relationship between θ and general life history traits (Clark et al. 2010). Therefore, we estimated allowable take under linear and non-linear assumptions to compare the effect of this assumption on allowable take.

We estimated r_{max} for each management population by fitting a discrete logistic model with time series data (Meyer and Millar 1999). We used the BBS indices and standard error from the hierarchical model (Link et al. 2020) for the SMP. Estimation of r_{max} is more efficient and reliable with longer time series, and time series that include changes from a relatively low to high population size, which were available in the BBS data. We fit the model using a state-space approach where we modeled a latent population index (I_t^{SMP}) as a function of r_{max}^{SMP}, K^{SMP}, and I_{t-1}^{SMP} (Equation 24).

$$I_t^{SMP} = I_{t-1}^{SMP} + r_{max}^{SMP} \times I_{t-1}^{SMP} \times \left(1 - \frac{I_{t-1}^{SMP}}{K^{SMP}}\right) \tag{24}$$

We added stochasticity to the latent population index I_t^{SMP} by assuming a lognormal distribution with a process variance sampled from a gamma distribution. We linked the state model with the BBS data in an observation model (Equation 25).

$$BBS_t \sim Normal\left(I_t^{SMP}, \frac{1}{\sigma_{BBS,t}^2}\right) \tag{25}$$

The BBS indices used to estimate r_{max}^{SMP} were the same used in the IPM. However, we used a different time series (1980-2018) here compared to the IPM (2000-2018) and, therefore, used different symbols to reflect the observed indices (i.e., BBS_t here and $I_{BBS,t}$ for the IPM). We note that although BBS_t and I_t^{SMP} are indices of population size rather than actual population size, estimates of r_{max}^{SMP} would be representative of the peregrine falcon SMP if the BBS adequately tracks population change because r_{max}^{SMP} is a rate rather than an absolute number. The BBS does not occur throughout the range of the NMP, so we used the derived estimates of N_t^{NMP} and their SD estimated from the IPM in the same discrete logistic state-space models used for the SMP. We used the same discrete logistic model (Equation 26) and the observation model (Equation 27) for the NMP as used for the SMP.

$$I_t^{NMP} = I_{t-1}^{NMP} + r_{max}^{NMP} \times I_{t-1}^{NMP} \times \left(1 - \frac{I_{t-1}^{NMP}}{K^{NMP}}\right) \tag{26}$$

$$N_t^{NMP} \sim Normal\left(I_t^{NMP}, \sigma_{N_t^{NMP}}^2\right) \tag{27}$$

Although the data for the NMP discrete logistic (i.e., the N_t^{NMP}) are population size estimates rather than an index like the BBS, we used I_t^{NMP} to differentiate the latent population size from

the data in equations 26 and 27. We incorporated process variance in the same manner as in the SMP for the discrete logistic model for the NMP. The IPM for the NMP spanned 21 years and appeared to provide an adequate time series to fit the discrete logistic model for that management population. We used the methods described by Niel and Lebreton (2005) to specify a prior distribution for r_{max}^{SMP} and r_{max}^{NMP}. This method is based on allometric relationships between r_{max}, maximum survival probability (i.e., at low population densities), and age at first breeding. Although most peregrine falcons do not breed until their third year (i.e., 2 years after fledging), some occasionally breed in their second year, particularly in depressed or expanding populations (White et al. 2020). Because we are interested in estimating r_{max} for both populations, we used the earlier breeding age for deriving this prior. Johnson et al. (2012) used captive birds to develop a model to predict maximum survival rate as a function of body mass. We used that function and a body mass of 1.2 kg (average female mass reported in White et al. 2020) to derive an estimate of maximum survival and associated uncertainty. We simulated 10,000 survival estimates to derive an estimate of mean r_{max} and $\sigma_{r_{max}}^2$ from the model derived by Niel and Lebreton (2005), and then transformed them to a log-normal distribution for the prior on r_{max} in the discrete logistic models. We had no prior information on K, but assumed that both management populations were likely not above K. However, we wanted to allow for that possibility and specified a uniform ($0.8 \times \overline{N}$, $2 \times \overline{N}$) prior distribution for both management populations. We sampled 200,000 iterations with a burn-in of 20,000 and thinning of 10 to fit the discrete logistic models for both management populations. We used runjags (Denwood 2016) in R 4.1.2 (R Core Team 2021) to analyze the discrete logistic models.

We used the estimates of mean total N from the most recent years that were derived within the IPMs in the PTL calculations for each management population (N_{2020}^{NMP} = 94,366, SD = 13,370; N_{2019}^{SMP} = 9,583, SD = 1,138). F_O represents a manager's desired population size relative to K and ranges between 0 and 2. F_O = 1 represents MSY and the population is expected to equilibrate near K/2. F_O > 1 equilibrates further below K/2 and is only used for conflict resolution (e.g., reduce property damage) or for overabundant or invading species, whereas F_O < 1 is expected to allow populations to equilibrate closer to K and is used for species of concern or in situations where managers want to be more conservative than MSY when allowing take. For this assessment, we used F_O = 0.75 based on previous PTL assessments for raptors (USFWS 2020; Millsap et al. 2022; Zimmerman et al. 2022). Although we used F_O = 0.75 and present results from various quantiles (i.e., risk tolerance) for this status and take assessment, these two components are based on policy decisions that are beyond the scope of our objectives for this report. The final decisions on F_O and risk tolerance would be made in the EA prepared to analyze the environmental consequences of any proposed changes to the peregrine falcon harvest strategy that result from this status assessment. The PTL is not age structured because r_{max} and N are characteristics of the overall population. Because the harvest of peregrine falcons targets Y1 birds, which contribute proportionately less to population growth as estimated from sensitivity analyses, the estimates of allowable take from the PTL will be conservative (i.e., taking the PTL quota from only Y1 birds would have less of an effect on growth rates than taking the quota from AY2 birds).

The components of PTL are often based on data with small sample sizes and contain large uncertainty, so propagating error to the final estimates of PTL to express this uncertainty is important for transparency to decision makers and stakeholders (Runge et al. 2009). We used

Monte Carlo simulations to randomly select 10,000 samples of demographic parameters (r_{max}, N_t, and θ) to incorporate uncertainty from the data into our estimates of PTL. We converted the means and standard deviations of r_{max} and N_t to the log scale and sampled values from a log-normal distribution to avoid sampling negative values for parameters that must be ≥ 0. We used estimates of r_{max} and the model developed by Johnson et al. (2012:1119) to estimate θ and uncertainty in θ.

Yield Curves

For the second assessment, we used the results of the IPMs to derive yield curves for both management populations to assess how current take compares to MSY derived directly from the age-structured demographic data used in the IPM analyses. Deriving yield curves requires density dependence in growth rates, which is suspected to operate primarily through reproduction (Ferrer et al. 2004; White et al. 2020). Therefore, to construct yield curves, we used results from the IPMs to estimate density dependence in productivity. We estimated density dependence for each management population by regressing productivity (response variable) and population size (predictor variable). We used annual productivity estimates ($\hat{P}_t^{MP}$) and latent estimates of I_t^{SMP} and N_t^{NMP} in the regression and assumed that errors were distributed normally on the log scale. For the SMP, because the BBS is conducted in spring, we aligned productivity and I^{SMP} for the same year in the linear model (Equations 28 and 29).

$$\log(\hat{P}_t^{SMP}) \sim Normal\left(\mu_t^{SMP}, \sigma_{\hat{P}_t^{SMP}}^2\right) \tag{28}$$

$$\mu_t^{SMP} = \beta_0 + \beta_1 \times \log(\hat{I}_t^{SMP}) \tag{29}$$

In contrast, the index for the NMP occurs post-breeding in year *t* and includes Y1 birds produced that year. Therefore, we altered the data slightly to match fecundity in the spring of year *t*, with N^{NMP} from the autumn of year *t*-1 (e.g., fecundity in the spring of 2020 would be regressed with the counts of birds from the autumn of 2019; Equations 30 and 31):

$$\log(\hat{P}_t^{NMP}) \sim Normal\left(\mu_t^{NMP}, \sigma_{\hat{P}_t^{NMP}}^2\right) \tag{30}$$

$$\mu_t^{NMP} = \beta_0 + \beta_1 \times (\hat{N}_{t-1}^{NMP}) \tag{31}$$

The intercept β_0 represents expected mean productivity at low population densities when resources are not limiting. The clutch size of peregrine falcons is commonly 3 in the NMP, and slightly < 4 in the SMP, but observations of clutch sizes of 5 and 6 have been observed (White et al. 2020), so we fixed the intercept to a number on the log scale to reflect maximum fecundity at low population size based on these observations. In addition, we wanted the density-dependent relationship to reflect realistic *K*, which should approximate the estimate in the discrete logistic model. An intercept of log(5.75) achieves this relationship for both management populations. Thus, the density-dependent relationship was specified to (1) match observed productivity data, (2) use productivity at low densities that is consistent with the maximum possible, and (3) provide estimates of *K* like estimates from the time series data in a discrete logistic model. We fit the regression for each management population separately using the lm function in the *stats* package in R 4.1.2 (R Core Team 2021).

We derived the yield curves by replacing annual productivity estimates in the same age-structured models used in the IPM analysis with the regression model described above. We then simulated population growth under sequential take rates from 0 to 0.5 in increments of 0.005. For each take rate, we simulated population sizes for 1,000 years and saved the final estimate of population size and total take (H; in number of birds). The population would stabilize at K under a take rate of 0 and the population would decline to 0 at a take rate = r_{max}. Plotting the equilibrium N (x-axis) and H (y-axis) for each take rate results in a quadratic yield curve that crosses the x-axis at K and 0, and peaks at MSY ($K/2$). Theoretically, every point on the yield curve is sustainable; however, areas on the right side of the yield curve (e.g., $H <$ MSY) are stable, whereas points to the left of MSY are unstable and could lead to overharvest with unreliable data. Points under the yield curve are expected to grow to a point on a yield curve if take increases with increasing population size (i.e., if the take rate is maintained as populations increase).

RESULTS

Integrated Populations Models

SMP

Our sample of banded peregrines consisted of 24,892 Y1 and 290 AY1 individuals banded in the spring/summer period, and 1,213 Y1 and 132 AY1 individuals banded during the fall migration. Of the peregrines banded in our study, a total of 2,119 that were banded as Y1 and 30 that were banded as AY1 died and had their bands reported to the BBL. Posterior estimates of mean (95% credible interval [CRI]) survival for peregrine falcons in the SMP were 0.44 (0.42–0.46) for Y1 birds and 0.81 (0.79–0.82) for AY1 birds (Table 2). Mean recovery probability between 1980 and 2018 was ~0.08 but appeared to increase over the time from approximately 0.04 in 1980 to 0.13 in 2018. For the SMP, we received peregrine falcon productivity data that met our criteria for inclusion in the models from 44 US states and 3 Canadian provinces totaling 6,051 broods from 2009–2020 (Table S5 [Supplementary Information]). Estimated mean productivity for peregrine falcons in the SMP was 1.73 (1.69–1.77) fledged young or advanced-age young present per occupied nesting territory (Figure 4).

Results from the IPM indicate that the overall mean population size of the SMP increased from 5,788 (5,200–6,400) in 2009 to 9,583 (7,532–12,027) in 2019 (Figure 5), which represents an annual growth rate (λ) of 1.043 (1.017–1.082). The estimated mean number of Y1 individuals in the SMP in 2019 was 3,193 (2,335–4,251). The SMP population size continues to demonstrate significant growth (see Figure 5).

NMP

The survival models for the NMP were based on 8,447 Y1 and 2,295 AY1 peregrines banded in the spring/summer, and 14,999 Y1 and 2,497 AY1 peregrines banded during the fall migration. Of those banded, 332 banded as Y1 and 58 banded as AY1 died and were reported to the BBL. Posterior estimates of mean survival for peregrine falcons in the NMP were 0.51 (0.45–0.57) for Y1 birds and 0.78 (0.77–0.81) for AY1 birds (Table 2). Recovery probabilities were low (~0.016%) and appear to be stable from 1980 to 2018. The estimated mean proportion of AY2 birds breeding annually was estimated to be 0.93 (0.79-1.00). For the NMP, we received

peregrine falcon productivity data that met our criteria for inclusion in the models from Alaska, Nunavut, and Greenland totaling 1,383 broods from 2009–2019 (Table S5 [Supplementary Information]). Estimated mean productivity for peregrine falcons in the NMP was 1.37 (1.26–1.51) fledged young or advanced-age young present per occupied nesting territory (Figure 4). We had productivity data for 2009–2019, but our time series of interest was 2000–2020 to accommodate scaling our annual abundance observations to a total population size estimate from 2000. Although we lacked data on observed productivity for 2000–2008 and 2020, we were able to estimate latent productivity for these years in the IPM because we had data for the other relevant parameters (i.e., survival and abundance) (Figure 4). Unsurprisingly, the CRIs for estimates for years with no productivity data were larger than for years with data (Figure 4).

Results from the IPM indicate that the overall mean population size of the NMP increased from 70,880 (57,108–84,640) in 2000 to 94,366 (69,991–122,299) in 2020 (Figure 6), which represents an annual growth rate (λ) of 1.016 (1.007–1.025). The estimated mean number of Y1 individuals in the NMP in 2020 was 26,875 (15,776–40,339). The marked decrease in population size in 2018 reflects substantial decreases in both productivity and migration count data that year (Figures 4 and 6). The apparent trend in growth of the NMP suggested that this management population may have reached a point whereby density-dependent factors are influencing the proportion of breeders (see Figure 6).

Take Assessment

Allowable take estimates from the PTL ranged from ~500 (20th quantile for linear density dependence) to ~800 (median for non-linear density dependence) for the SMP, and from ~2,000 (20th quantile for linear density dependence) to ~5,600 (median for non-linear density dependence) for the NMP (Table 3). The large difference in estimated allowable take between the two management populations was due to differences in estimated population size (N_{2019}^{SMP} 9,583, N_{2020}^{NMP} 94,366) rather than estimates of growth rate ($r_{max}^{SMP} = 0.17$, $r_{max}^{NMP} = 0.23$). The discrete logistic models indicated that both management populations were near carrying capacity ($K^{NMP} \sim 93,000$ in number of individuals, $K^{SMP} \sim 0.02$ in BBS index), which we expressed in the yield curves. Yield curves for both management populations indicated that observed population size and current estimates of take are well on the right side (Figures 7 and 8), indicating that current levels of take are sustainable and stable given current estimates of demographic rates and population size. Current levels of take are below 50% of what is allowed under the current regulations and harvest strategy (Table 4). Under current falconry regulations and depending on how managers choose to address risk and distribute take, normalization of peregrine falcon take could potentially result in take in the SMP of 158 Y1 individuals and in the NMP of 1,324 Y1 individuals annually (Figure 9). Actual take would likely be considerably less given the realized take numbers over the past several years.

DISCUSSION

The demographic rates in both the SMP and NMP are consistent with those reported from other healthy peregrine falcon populations around the world (White et al. 2020). The IPM outputs indicate both management populations are likely increasing, the SMP at a greater rate than the NMP and with some evidence of recent declines between years in the NMP. Under the current

falconry framework, allowable take across both management populations could range as high as 1,482 Y1 individuals annually, although typically the Service uses more conservative values to reduce the risk of overharvest given uncertainty in both population size estimates and in the estimates of the sustainable take rates. Take would also need to be balanced across the two management populations to ensure it does not exceed the upper limit for either management population. Given current demand relative to existing take limits, it seems unlikely the updated take limits for either management population would be exceeded under normalization even in the absence of additional regulatory or policy constraints. This assumption could be verified under the existing falconry reporting requirements by tracking the timing and location of future peregrine falcon take. According to analyses reported in the 2008 EA (USFWS 2008), most peregrine falcons captured between 20 September and 20 October in the eastern three flyways are likely to have originated in the NMP, whereas most peregrine falcons captured at other times of the year outside the breeding range of the NMP and west of the Continental Divide are likely to have originated in the SMP. This information could be used as the basis for management triggers that would be implemented if take in either management population approached the take limit. Similarly, it would be desirable to track take from the SMP to ensure it is not geographically imbalanced to the point of risking overharvest regionally (e.g., in the eastern or western part of the SMP). An important caveat is that the analyses presented in the 2008 EA that would inform these assessments should be updated as part of any future EA the Service prepares regarding take of peregrine falcons.

The approach taken in this assessment can be updated in the future to determine whether changes in peregrine falcon population trajectory or resilience to take are occurring. We recommend that such an update be conducted no less than once every five years, as recommended for all raptors subject to falconry take (USFWS 2007). This is particularly important for the NMP, where count data show recent declines in some years. This highlights the importance of continuing and perhaps better organizing the professional and citizen-science activities that provided the data used in this assessment. State, provincial, territorial, and non-governmental nest monitoring efforts, autumn migration counts, BBS counts, and nest and migration banding were all instrumental in our assessment. Many of the citizen-science initiatives, like autumn migration counts and migration banding, lack even modest funding support, which places their availability in the future in doubt. Modest governmental investments in these activities should be considered given the importance of these data in management of peregrine falcons and other raptors.

ACKNOWLEDGMENTS

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Table 1. Autumn migration hawk count sites that met initial criteria for inclusion in the study and those sites with sufficient data to include in the peregrine falcon migration count analyses (Analyzed).

Count site	Location	Analyzed (no/yes)
Belize Raptor Watch	Belize	no
Cape Henlopen Hawk Watch	Delaware	no
Cape May	New Jersey	yes
Corpus Christi HawkWatch	Texas	yes
Fire Island	New York	yes
Florida Keys Hawkwatch	Florida	yes
Fort Sheridan	Illinois	no
Guana Reserve	Florida	no
Hawk Cliff Hawkwatch	Ontario, Canada	yes
Hawk Hill	California	no
Hawk Ridge	Minnesota	yes
Illinois Beach State Park	Illinois	yes
Kiptopeke Hawkwatch	Virginia	yes
Lighthouse Point	Connecticut	yes
Smith Point	Texas	yes
Veracruz River of Raptors Cardel, MX	Veracruz, Mexico	no
Veracruz River of Raptors Chichicaxtle, MX	Veracruz, Mexico	yes

Table 2. Mean survival, standard deviation (SD), 95% credible intervals (CRI), and median survival by age class (Y1 = first year; AY1 = after first year) and season for peregrine falcons in the southern (SMP) and northern (NMP) management population estimated from the integrated population models. Concentration is a measure of CV for binomial variables (Link and Barker 2009) where smaller values represent more precise estimates.

Management population	Age	Season	Mean	SD	2.5th CRI	Median	97.5th CRI	Concentration
SMP	Y1	Winter	0.655	0.012	0.632	0.655	0.679	0.025
		Summer	0.716	0.010	0.697	0.716	0.735	0.022
		Annual	0.438	0.011	0.417	0.438	0.460	0.022
	AY1	Winter	0.890	0.005	0.880	0.890	0.900	0.016
		Summer	0.906	0.004	0.898	0.906	0.915	0.014
		Annual	0.807	0.006	0.795	0.807	0.819	0.015
NMP	Y1	Winter	0.607	0.025	0.557	0.607	0.656	0.051
		Summer	0.993	0.007	0.975	0.995	1.000	0.084
		Annual	0.509	0.029	0.454	0.509	0.566	0.058
	AY1	Winter	0.855	0.010	0.836	0.855	0.874	0.028
		Summer	0.918	0.008	0.902	0.918	0.933	0.029
		Annual	0.785	0.010	0.765	0.784	0.805	0.024

Table 3. Prescribed take level (PTL) parameters and credible intervals (CRI) used to estimate allowable take of peregrine falcons in the southern (SMP) and northern (NMP) management population under linear and nonlinear density dependence (DD).

Management population	PTL parameter[a]	DD form	Mean	SD	2.5th CRI	20th CRI	Median	80th CRI	97.5th CRI
SMP	r_{max}		0.17	0.02	0.13	0.15	0.17	0.19	0.22
	theta		3.62	4.41	0.32	1.00	2.24	5.22	15.54
	h_{max}	linear	0.09	0.01	0.07	0.08	0.09	0.10	0.11
	h_{max}	nonlinear	0.11	0.04	0.04	0.08	0.12	0.14	0.18
	H	linear	614	111	429	519	604	705	857
	H	nonlinear	813	273	284	581	816	1,037	1,349
	N		9,583	1,138	7,532	8,648	9,518	10,472	12,027
NMP	r_{max}		0.23	0.19	0.003	0.03	0.18	0.23	0.58
	theta		3.72	4.72	0.27	0.96	2.23	5.31	16.64
	h_{max}	linear	0.09	0.09	0.01	0.03	0.06	0.13	0.34
	h_{max}	nonlinear	0.11	0.09	0.01	0.04	0.08	0.16	0.36
	H	linear	6,310	6,634	767	2,038	4,375	8,898	24,603
	H	nonlinear	7,460	6,579	886	2,609	5,565	11,052	25,566
	N		94,366	13,370	69,991	83,016	93,720	105,366	122,299

[a] r_{max} = maximum population growth rate; theta = density-dependent effect; h_{max} = maximum allowable take rate; H = allowable take estimate; N = population size.

Table 4. Peregrine falcon allowable take (under current federal and state regulations and policy) and realized take for 2018–2020 as reported by state fish and wildlife agencies.

			Year					
			2018		2019		2020	
Flyway	Age class	State	Allocated	Taken	Allocated	Taken	Allocated	Taken
Pacific	Nestling	AK	41	2	41	0	41	2
		AZ	7	2	7	3	7	3
		CA	0	0	0	0	0	0
		CO	4	2	4	0	4	0
		ID	2	0	2	1	2	2
		MT	6	3	5	0	6	1
		NV	0	0	0	0	0	0
		NM	4	4	4	2	4	2
		OR	13	0	10	1	10	2
		UT	17	13	17	12	17	14
		WA	12	5	12	8	12	9
		WY	5	2	5	0	NA	NA
Pacific	Total (- AK)		70	31	66	27	62	30
Pacific	Total (+ AK)		111	33	107	27	103	35
Central	Passage	TX	30	20	30	20	30	17
		OK	8	2	6	2	6	2
		KS	10	2	6	2	6	2
		NE	0	0	6	0	6	0
Central	Total		48	24	48	24	48	21
Mississippi	Passage	AL	4	0	1	0	1	1
		AR	5	1	6	3	6	2
		IA	5	0	5	0	5	0
		IL	5	1	2	1	2	1
		IN	5	0	6	0	3	1
		KY	0	0	0	0	1	0
		LA	0	0	1	1	1	0
		MI	5	1	5	1	4	1
		MN	5	0	5	3	5	1
		MO	0	0	0	0	0	0
		MS	4	2	6	2	8	6
		OH	0	0	0	0	0	0
		TN	5	2	5	0	3	0
		WI	6	5	6	4	9	2
Mississippi	Total		48	12	48	15	48	15
Atlantic	Passage	ME	5	0	5	3	2	2
		MA	0	0	0	0	0	0
		RI	0	0	0	0	0	0

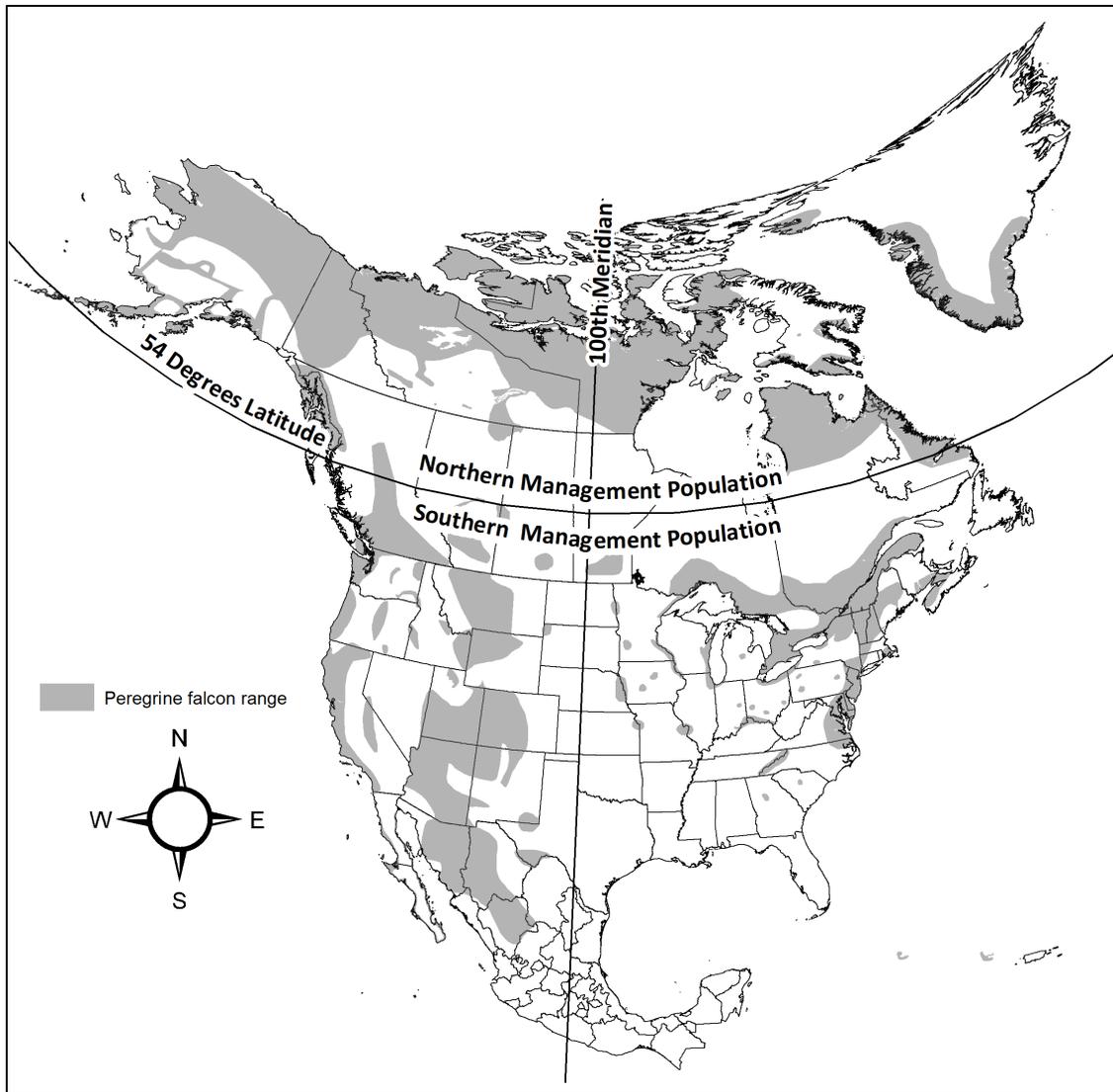|							
	PA	5	0	5	1	4	0
	NJ	6	3	5	1	5	3
	MD	6	4	6	6	8	8
	WV	0	0	0	0	1	0
	VA	5	5	5	3	7	3
	NC	5	5	6	2	6	1
	SC	5	1	5	0	2	0
	GA	5	2	5	1	5	2
	FL	6	3	6	2	8	4
Atlantic	Total	48	23	48	19	48	23

Figure 1. Range map of the northern and southern management populations of peregrine falcons in North America.
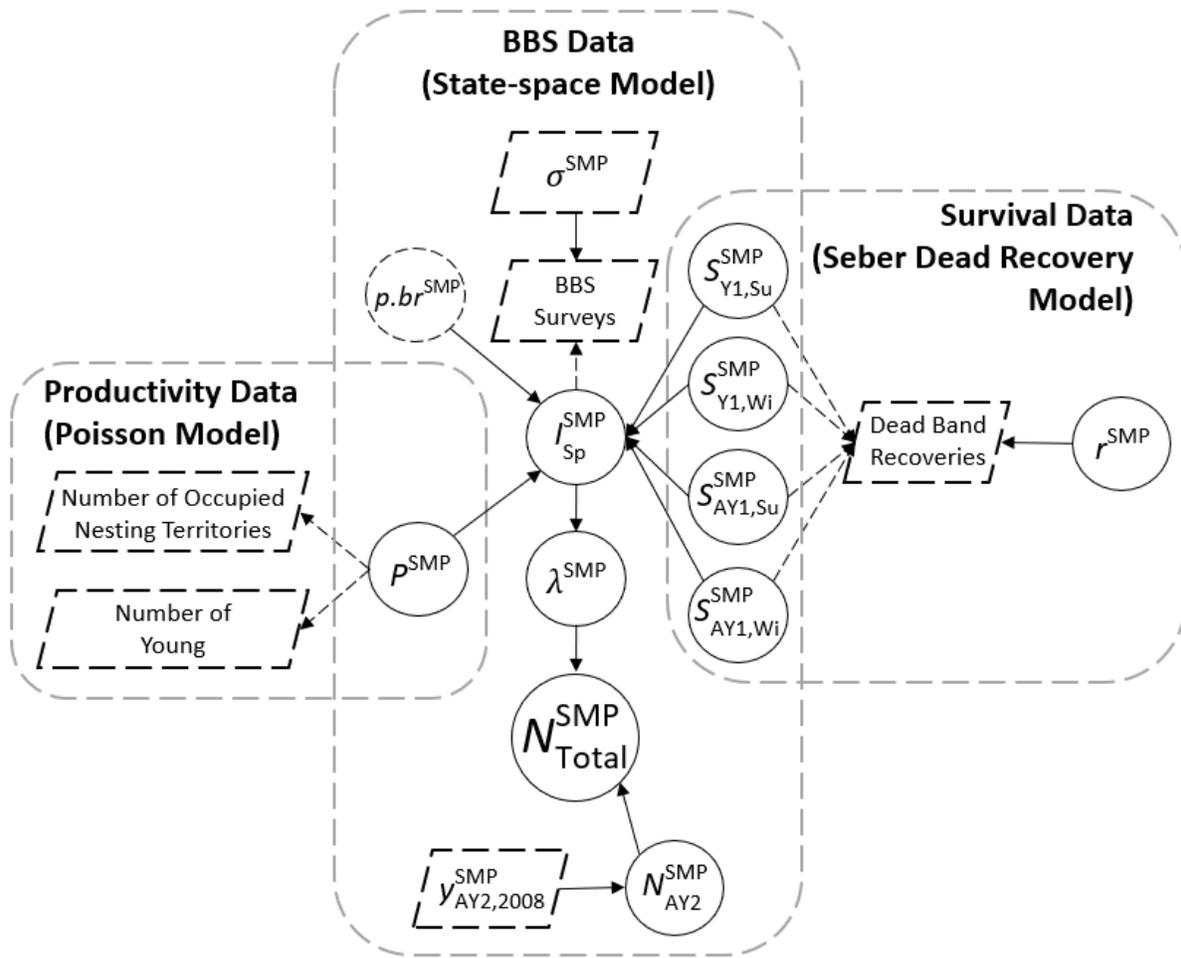
Figure 2. Graphical representation of integrated population model for the Southern Management Population (SMP) of peregrine falcons. Y1 = first year; AY1 = after first year; AY2 = after second year; Sp = spring; Su = summer; Wi = winter; S = seasonal survival; r = recovery probability; $p.br$ = probability of breeding (latent parameter); P = productivity; I = BBS index; σ = BBS index standard deviation; $\lambda = I_t / I_{t-1}$; y = observed number of AY2 birds in 2008 (USFWS 2008).
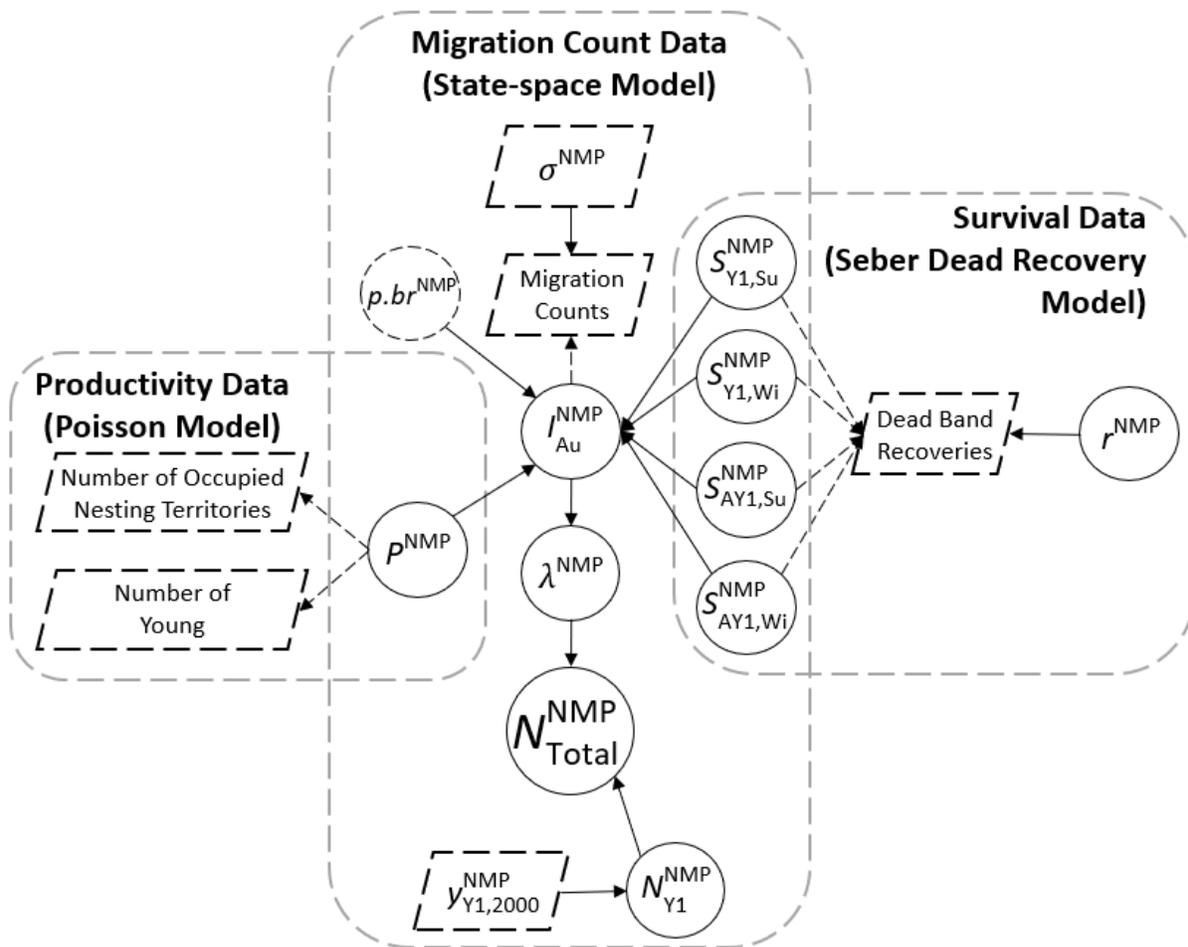
Figure 3. Graphical representation of integrated population model for the Northern Management Population (NMP) of peregrine falcons. Y1 = first year; AY1 = after first year; Su = summer; Au = autumn; Wi = winter; S = seasonal survival; r = recovery probability; $p.br$ = probability of breeding (latent parameter); P = productivity; I = migration count index; σ = migration count standard deviation; $\lambda = I_t/I_{t-1}$; y = observed number of Y1 birds in 2000 (Franke 2016).
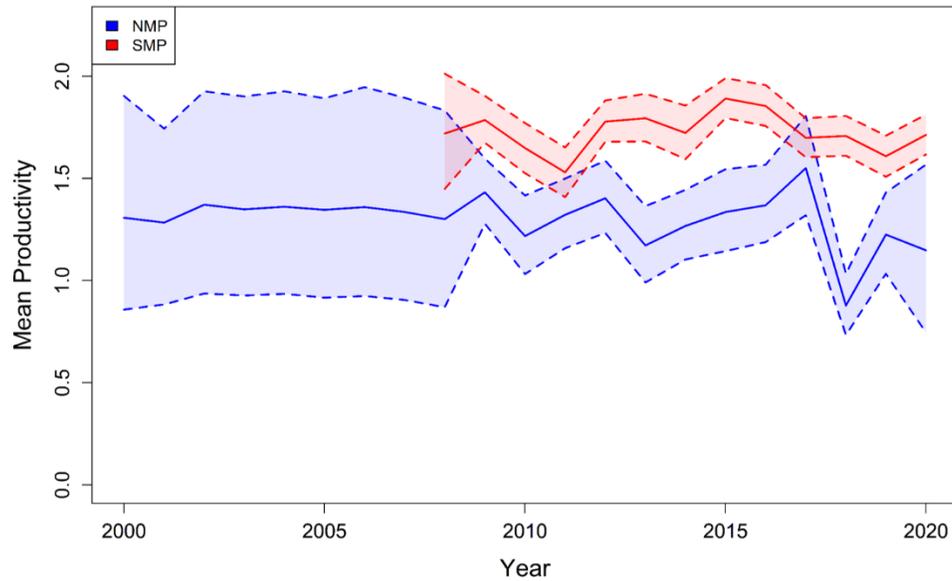
Figure 4. Annual mean productivity (number of fledged young or advanced-age young present per occupied nesting territory) of peregrine falcons in the southern (SMP) and northern (NMP) management populations. Solid line connects annual estimates and dashed lines are the 95% credible interval.

Figure 5. Annual peregrine falcon abundance (solid line) and 95% credible interval (dashed lines) estimated from the integrated population model for the southern management population. Red asterisks represent empirical population size estimates from 2008 (population size at the time of delisting under the Endangered Species Act), 2012 (population size as estimated from the post delisting monitoring program), and 2019 (population size as estimated by state and provincial management agencies for this report).
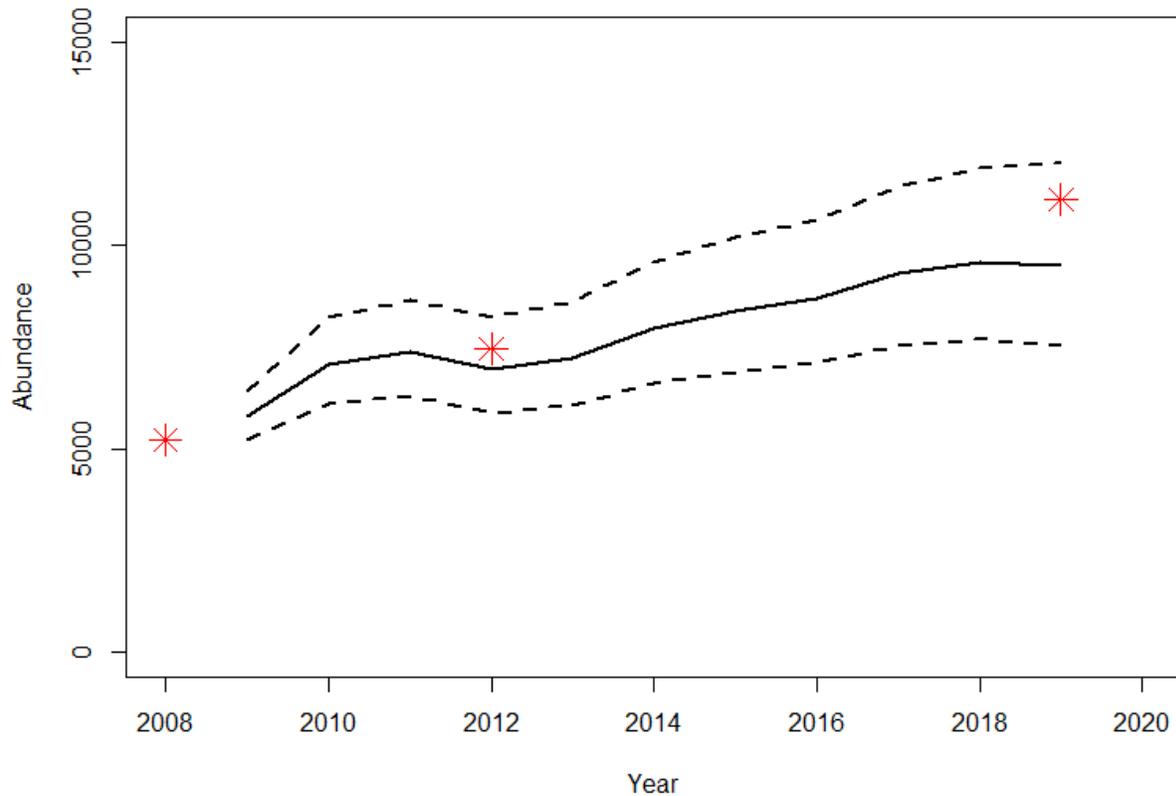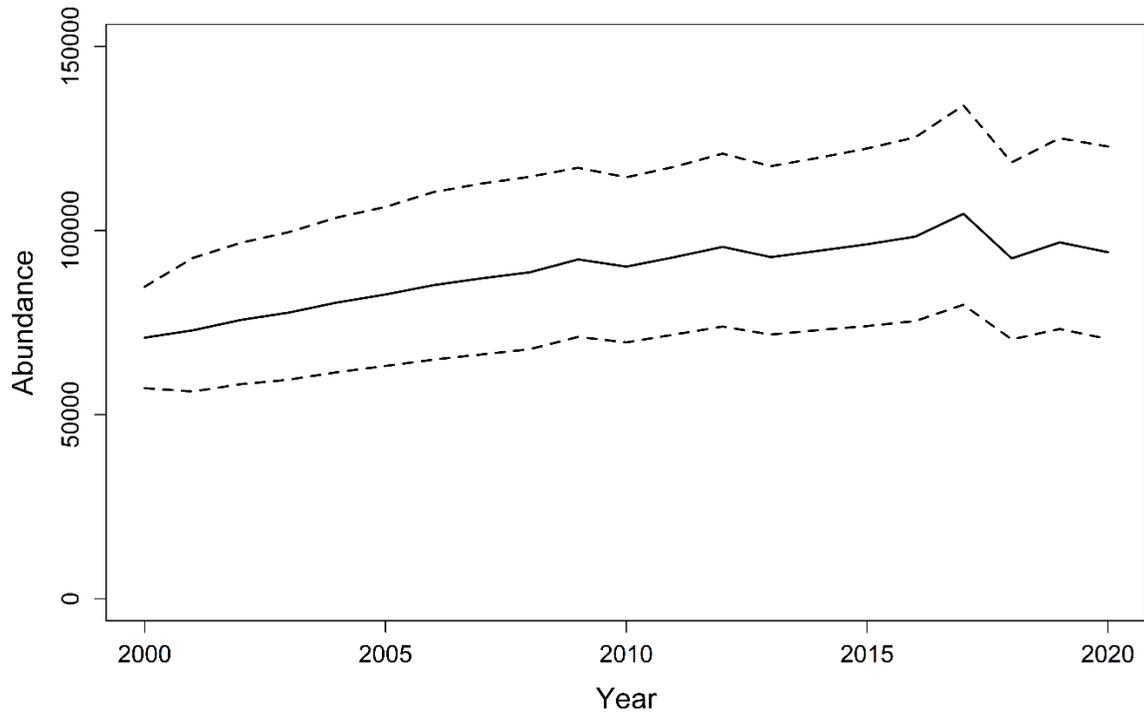
Figure 6. Annual peregrine falcon abundance (solid line) and 95% credible interval (dashed lines) estimated from the integrated population model for the northern management population.

Figure 7. Yield curve (black line) for falconry take of first year (Y1) peregrine falcons from the southern management population. Vertical blue line indicates the expected equilibrium harvest and population size at a take rate of 0.05. Red asterisk represents the best current estimate of population size and allowable annual take.
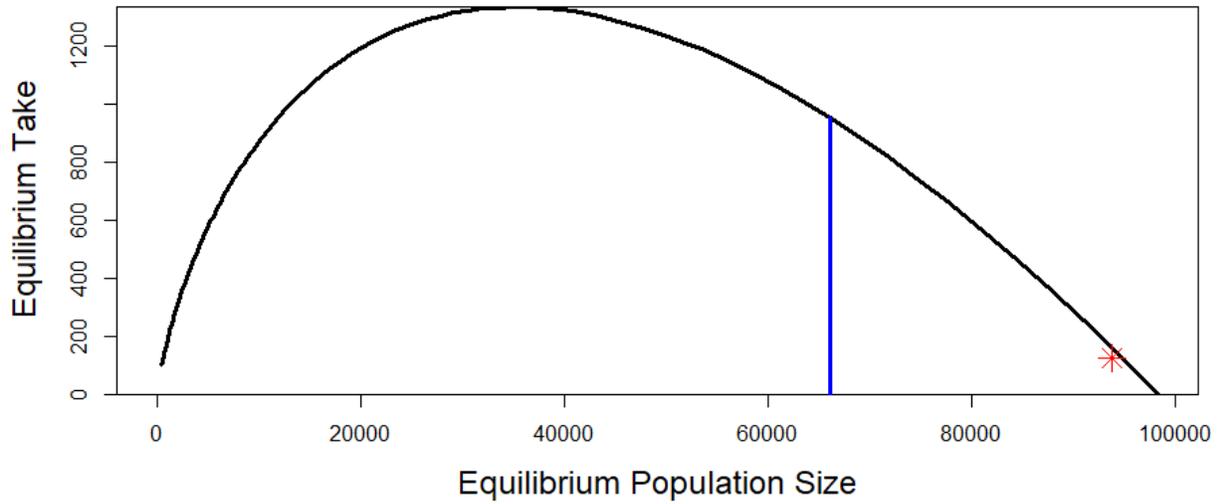
Figure 8. Yield curve (black line) for falconry take of first year (Y1) peregrine falcons from the northern management population. Vertical blue line indicates the expected equilibrium take and p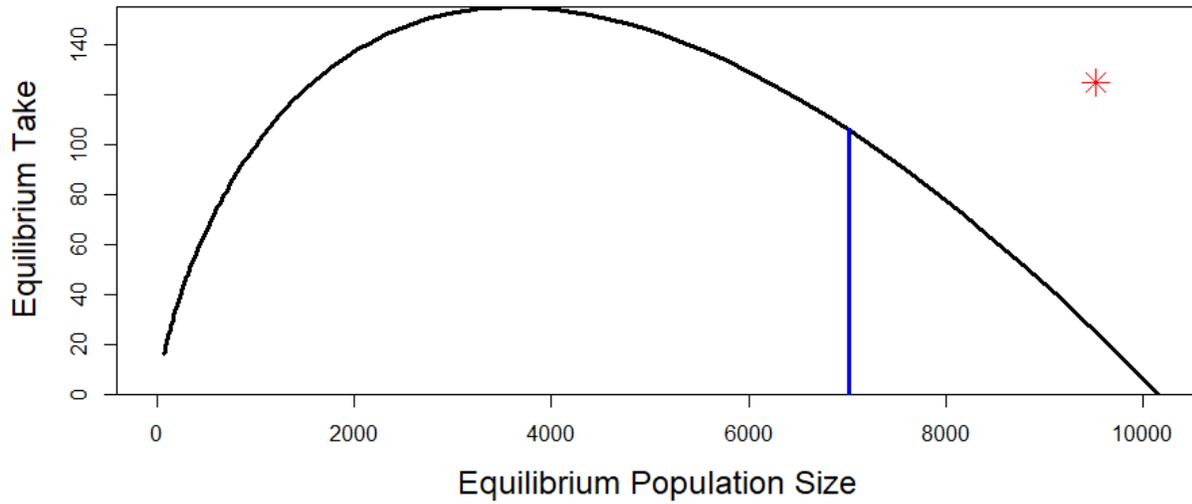opulation size at a take rate of 0.05. Red asterisk represents the best current estimate of population size and allowable annual take.
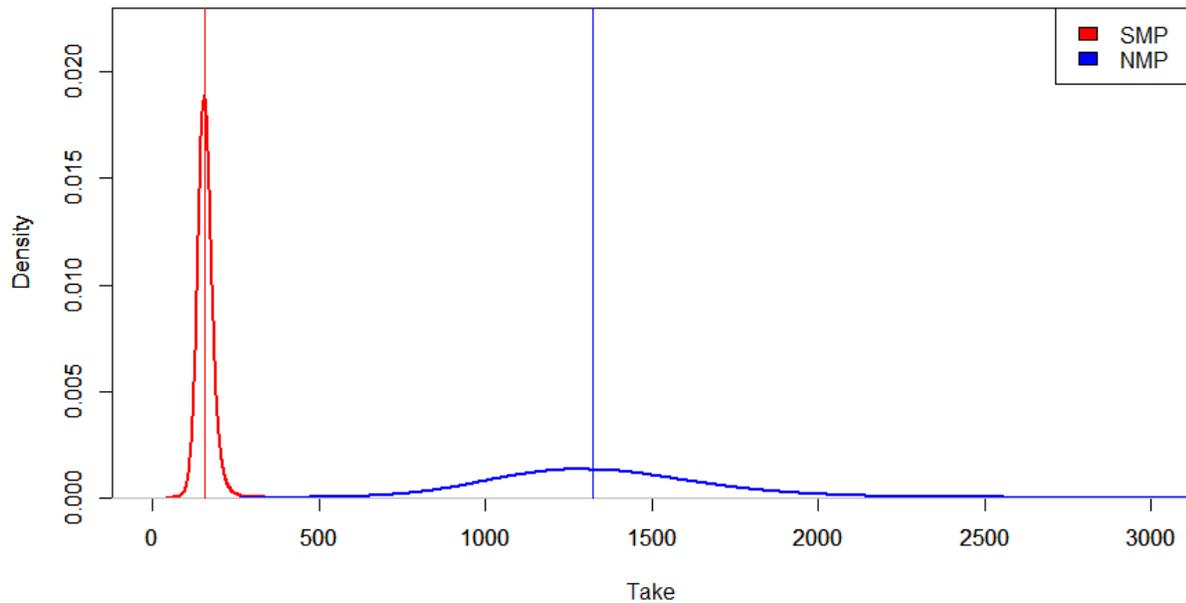
Figure 9. Posterior density distributions of expected maximum potential take (*H*) of first year (Y1) peregrine falcons from the southern (SMP) and northern (NMP) management populations under normalization. Median *H*, which is based on a maximum take rate of 5% of the Y1 population (i.e., a maximum Y1 take rate [*h*] of 0.05 from each management population), is estimated to be 158 for the SMP and 1324 for the NMP. Vertical lines represent medians, but a lower value of *H* (e.g., lower 20th quantile) could be selected by managers to buffer the risk of overharvest given uncertainty.

SUPPLEMENTAL INFORMATION

Table S1. Example for a 3-year study of cell probabilities (CP) used to analyze seasonal survival data. R = releases (number banded) by age class (Y1 = first year; AY1 = after first year), season (Su = summer; Au = autumn), and year. S and W represent seasonal survival rates in summer (Y1, 15 June–1 October; AY1, 1 May–1 October) and winter (1 October–1 May), respectively, by year (superscript 1, 2, or 3). r = recovery rate by year (superscript 1, 2, or 3).

	Bands	Summer Year 1	Winter Year 1	Summer Year 2	Winter Year 2	Summer Year 3	Winter Year 3	Not Recovered
Spring	$R^1_{Y1,Su}$	$(1-S^1_{Y1})r^1$	$S^1_{Y1}(1-W^1_{Y1})r^1$	$S^1_{Y1}W^1_{Y1}(1-S^2_{AY1})r^2$	$S^1_{Y1}S^2_{AY1}W^1_{Y1}(1-W^2_{AY1})r^2$	$S^1_{Y1}S^2_{AY1}W^1_{Y1}W^2_{AY1}(1-S^3_{AY1})r^3$	$S^1_{Y1}S^2_{AY1}S^3_{AY1}W^1_{Y1}W^2_{AY1}(1-W^3_{AY1})r^3$	$1-\sum \text{Row CP}$
Spring	$R^2_{Y1,Su}$			$(1-S^2_{Y1})r_2$	$S^2_{Y1}(1-W^2_{Y1})r^2$	$S^2_{Y1}W^2_{Y1}(1-S^3_{AY1})r^3$	$S^2_{Y1}S^3_{AY1}W^2_{Y1}(1-W^3_{AY1})r^3$	$1-\sum \text{Row CP}$
Spring	$R^3_{Y1,Su}$					$(1-S^3_{Y1})r^3$	$S^3_{Y1}(1-W^3_{Y1})r^3$	$1-\sum \text{Row CP}$
Autumn	$R^1_{Y1,Au}$		$(1-W^1_{Y1})r^1$	$W^1_{Y1}(1-S^2_{AY1})r^2$	$S^2_{AY1}W^1_{Y1}(1-W^2_{AY1})r^2$	$S^2_{AY1}W^1_{Y1}W^2_{AY1}(1-S^3_{AY1})r^3$	$S^2_{AY1}S^3_{AY1}W^1_{Y1}W^2_{AY1}(1-W^3_{AY1})r^3$	$1-\sum \text{Row CP}$
Autumn	$R^2_{Y1,Au}$				$(1-W^2_{Y1})r^2$	$W^2_{Y1}(1-S^3_{AY1})r^3$	$S^3_{AY1}W^2_{Y1}(1-W^3_{AY1})r^3$	$1-\sum \text{Row CP}$
Autumn	$R^3_{Y1,Au}$						$(1-W^3_{Y1})r^3$	$1-\sum \text{Row CP}$
Spring	$R^1_{AY1,Su}$	$(1-S^1_{AY1})r^1$	$S^1_{AY1}(1-W^1_{AY1})r^1$	$S^1_{AY1}W^1_{AY1}(1-S^2_{AY1})r^2$	$S^1_{AY1}S^2_{AY1}W^1_{AY1}(1-W^2_{AY1})r^2$	$S^1_{AY1}S^2_{AY1}W^1_{AY1}W^2_{AY1}(1-S^3_{AY1})r^3$	$S^1_{AY1}S^2_{AY1}S^3_{AY1}W^1_{AY1}W^2_{AY1}(1-W^3_{AY1})r^3$	$1-\sum \text{Row CP}$
Spring	$R^2_{AY1,Su}$			$(1-S^2_{AY1})r^2$	$S^2_{AY1}(1-W^2_{AY1})r^2$	$S^2_{AY1}W^2_{AY1}(1-S^3_{AY1})r^3$	$S^2_{AY1}S^3_{AY1}W^2_{AY1}(1-W^3_{AY1})r^3$	$1-\sum \text{Row CP}$
Spring	$R^3_{AY1,Su}$					$(1-S^3_{AY1})r^3$	$S^3_{AY1}(1-W^3_{AY1})r^3$	$1-\sum \text{Row CP}$
Autumn	$R^1_{AY1,Au}$		$(1-W^1_{AY1})r^1$	$W^1_{AY1}(1-S^2_{AY1})r^2$	$S^2_{AY1}W^1_{AY1}(1-W^2_{AY1})r^2$	$S^2_{AY1}W^1_{AY1}W^2_{AY1}(1-S^3_{AY1})r^3$	$S^2_{AY1}S^3_{AY1}W^1_{AY1}W^2_{AY1}(1-W^3_{AY1})r^3$	$1-\sum \text{Row CP}$
Autumn	$R^2_{AY1,Au}$				$(1-W^2_{AY1})r^2$	$W^2_{AY1}(1-S^3_{AY1})r^3$	$S^3_{AY1}W^2_{AY1}(1-W^3_{AY1})r^3$	$1-\sum \text{Row CP}$
Autumn	$R^3_{AY1,Au}$						$(1-W^3_{AY1})r^3$	$1-\sum \text{Row CP}$

Table S2. Candidate models for testing age class (a; first year, after first year), season (s; su = summer, wi = winter), year (*t*), and management population (p; northern management population, southern management population) effects on survival (*S*) and recovery (*r*) rates. Survival probabilities were estimated monthly so that seasonal rates could be directly compared, and then expanded to the appropriate time period for each age and management population to include in cell probabilities when analyzing the band and recovery data.

Model No.	Model parameters	No. of parameters	Model description
1	$S_a, r_.$	3	*S* varies by age; *r* is constant
2	$S_{a,s}, r_.$	5	*S* varies by age and season; *r* is constant
3	$S_{a,s}, r_t$	6	*S* varies by age and season; *r* varies by year
4	$S_{a,s}, r_{s,t}$	8	*S* varies by age and season; *r* varies by season and year
5	$S_{a,s}, r_{s,t,p[su]}$	10	*S* varies by age and season; *r* varies by season and year, and by management population only during summer
6	$S_{a,s}, r_{s,t,p}$	12	*S* varies by age and season; *r* varies by season, year, and management population
7	$S_{a,s}, r_{t,p}$	8	*S* varies by age and season; *r* varies by year and management population
8	$S_{a,s}, r_{t[wi],p[su]}$	8	*S* varies by age and season; *r* varies by year only during winter and by management population only during summer
9	$S_{a,s,p}, r_{t,p}$	12	*S* varies by age, season, and management population; *r* varies by year and management population
10	$S_{a,s,t}, r_{t,p}$	12	*S* varies by age, season, and year; *r* varies by year and management population
11	$S_{a,s,t,p}, r_{t,p}$	20	*S* varies by age, season, year, and management population; *r* varies by year and management population

Table S3. Model selection results for estimating peregrine falcon survival and recovery rates for candidate models in the survival submodel. The model in bold and shaded grey represents the model used in the integrated population models.

Model No. [a]	Model parameters[a]	DIC	ΔDIC	Deviance
6[b]	$S_{a,s}, r_{s,t,p}$	4971	0	4959
9	$\boldsymbol{S_{a,s,p}, r_{t,p}}$	**4984**	**13**	**4972**
7	$S_{a,s}, r_{t,p}$	5047	76	5038
11	$S_{a,s,t,p}, r_{t,p}$	5062	91	4937
10	$S_{a,s,t}, r_{t,p}$	5123	152	4994
5[b]	$S_{a,s}, r_{s,t,p[su]}$	5459	488	5448
8	$S_{a,s}, r_{t[wi],p[su]}$	5627	656	5618
4[b]	$S_{a,s}, r_{s,t}$	6041	1070	6032
3	$S_{a,s}, r_{t}$	6430	1459	6386
2	$S_{a,s}, r_{.}$	6769	1798	6763
1	$S_{a}, r_{.}$	6844	1873	6841

[a] See Table S2 for model numbers and descriptions of model parameters.
[b] Model appeared to be biased based on unrealistic reporting rate estimates near 0.80.

Table S4. Model selection results for estimating peregrine falcon abundance from migration counts in the northern management population. λ = mean count; i = site; t = year; T = count minutes; β_0 = common intercept; $\varepsilon_{\text{site}}$ = site random effect; $\varepsilon_{\text{year}}$ = year random effect; $noise_{i,t}$ = overdispersion term that accounts for site by year variation.

Model	DIC	ΔDIC
$\log(\lambda_{i,t}) = 1 \times \log(T_{i,t}) + \beta_0 + noise_{i,t}$	2097	0
$\log(\lambda_{i,t}) = 1 \times \log(T_{i,t}) + \beta_0 + \varepsilon_{\text{year}} + noise_{i,t}$	2097	0
$\log(\lambda_{i,t}) = 1 \times \log(T_{i,t}) + \beta_0 + \varepsilon_{\text{site}} + \varepsilon_{\text{year}} + noise_{i,t}$	2104	7
$\log(\lambda_{i,t}) = 1 \times \log(T_{i,t}) + \beta_0 + \varepsilon_{\text{site}} + noise_{i,t}$	2107	10
$\log(\lambda_{i,t}) = 1 \times \log(T_{i,t}) + \beta_0 + \varepsilon_{\text{site}}$	17931	15834
$\log(\lambda_{i,t}) = 1 \times \log(T_{i,t}) + \beta_0$	220498	218401
$\log(\lambda_{i,t}) = 1 \times \log(T_{i,t}) + \beta_0 + \varepsilon_{\text{year}}$	1231075	1228978

Table S5. Summary of peregrine falcon productivity data used in the integrated population models for the northern (NMP) and southern (SMP) management populations.

Geographic Area	No. of Years[*]	No. of Broods	No. of Fledglings
NMP			
US State			
Alaska	11	895	1246
Canadian Territory			
Nunavut	11	376	374
Country			
Greenland	11	112	179
Total		1383	1799
SMP			
US State			
Arizona	3	89	63
California	11	518	969
Colorado	12	258	313
Connecticut	12	103	174
Delaware	2	2	8
Georgia	12	34	41
Idaho	4	85	151
Illinois	10	176	332
Indiana	8	117	239
Iowa	12	77	142
Kansas	5	7	21
Kentucky	12	164	359
Maine	11	256	199
Maryland	2	10	31
Massachusetts	2	6	14
Michigan	8	181	365
Minnesota	8	415	918
Missouri	6	66	164
Montana	10	638	1332
Nebraska	12	29	76
Nevada	2	6	5
New Hampshire	2	7	13
New Jersey	12	334	633

|			
New Mexico	6	280	375
New York	2	28	59
North Carolina	12	137	152
North Dakota	6	9	23
Ohio	7	71	173
Oregon	2	35	52
Pennsylvania	2	2	6
Rhode Island	2	2	5
South Carolina	9	9	18
Tennessee	2	2	4
Texas	1	3	1
Utah	12	186	266
Vermont	12	548	760
Virginia	2	16	38
Washington	2	40	67
West Virginia	4	14	17
Wisconsin	12	545	1189
Wyoming	11	219	324
Canadian Province			
Alberta	3	37	101
Manitoba	12	70	130
Ontario	6	220	211
Total		6051	10533

* Number of years of data from 2009–2020.
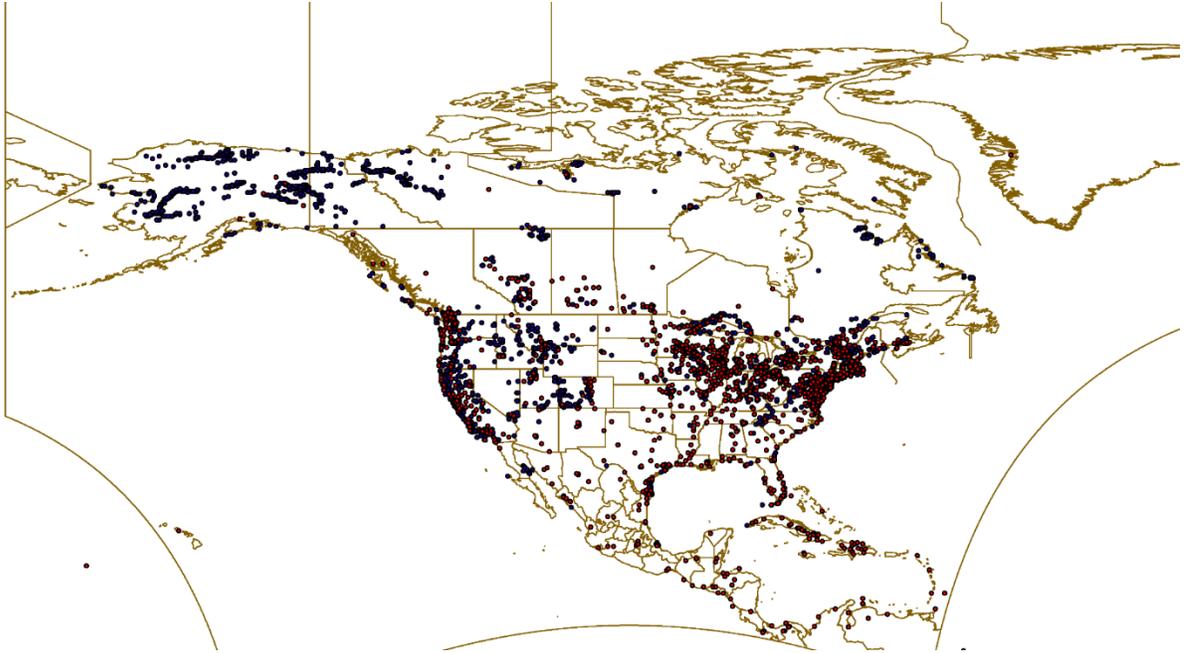
Figure S1. Banding (blue dots) and recovery (red dots) locations of peregrine falcons throughout North America, 1980–2019.