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Survival estimates of GPS-tagged adult Golden Eagles (*Aquila chrysaetos*) breeding in Finland

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Adult survival estimates are important for assessing population status and viability and for investigating the role of different anthropogenic effects on their variation. Currently, the rapidly increasing wind power poses a new and severe threat to survival of large raptors. Between 2011–2024, we monitored 26 Golden Eagles (*Aquila chrysaetos*) using Global Positioning System tracking devices in Finland, on territories where wind-power plants are currently absent and eagles are not subject to increased mortality from wind power plant collisions. Using the accumulated tracking data, we constructed individual capture histories on a monthly basis and adult survival rates using known-fate models in program MARK. We also review published adult survival estimates of Golden Eagles reported throughout their range for relative comparison. Monthly adult survival in our study area was 0.9933 (0.9854–0.9970) which translates to annual survival of 0.924 (0.838–0.965). We found eight studies reporting survival estimates, which ranged from 0.860 to 0.975 with a mean of 0.928. Thus, adult survival rates of Golden Eagles breeding in northern Finland, that are not affected by wind power plants, are high as expected for a viable population and very close to the mean estimated from other Golden Eagle populations. Maintaining high adult survival rates will be key to Golden Eagle population stability with expanding wind energy development in Finland.

1. Introduction

Information about demographic rates is important for assessing the causes of population declines (*e.g.* Green 2002, Pakanen & Kylmänen 2023) and for assessing the potential impacts of human caused mortality due to persecution or environmental change on population viability (Whitfield *et al.* 2004, Carrete *et al.* 2009, Gauld *et al.* 2022). For example, recent developments in wind energy have increased potential negative impacts on wildlife (Santangeli *et al.* 2018), especially birds and bats that may suffer increased mortality due to collisions with wind turbines (Hunt *et al.* 2017, Katzner *et al.* 2017, Monti *et al.* 2023, Serratosa *et al.* 2024). Assessing overall contribution of wind energy-related impacts to wildlife requires baseline survival rates from natural conditions.

Large raptors have been suffering from anthropogenic effects such as persecution and poisoning in the last century (*e.g.* Whitfield *et al.* 2004), but recently these large species with reduced flight maneuverability are known to be affected by wind turbines, mostly through direct mortality and secondarily through habitat alteration and loss (Watson *et al.* 2018, Gauld *et al.* 2022). Golden Eagles (*Aquila chrysaetos*) are of conservation concern and are among the highest profile wildlife species killed at renewable-energy facilities in United States (Katzner *et al.* 2017). Information about adult survival is especially important from populations of these long-lived species in which surviving adults form the largest contribution to the population growth rates out of all demographic rates, and therefore increased adult mortality will have strong impacts on future population growth (Tack *et al.* 2017).

Unfortunately, survival estimates for medium to large sized raptors are rare because acquiring standard live-recapture data requires systems where the adults can be recaptured safely (Tolvanen *et al.* 2017), resighted using cameras (see *e.g.* Santangeli *et al.* 2020, Väli *et al.* 2021) or individuals identified through DNA (*e.g.* Nebel *et al.* 2023). However, these are often unfeasible leaving the estimation of large raptor survival to radio telemetry (Hunt *et al.* 2017), age ratio (Hernández-Matías *et al.* 2011) or dead recovery data (Millsap *et al.* 2022). Telemetry offers an option for estimating survival of large species, such as Golden Eagles, that may not suffer from transmitter-related impacts (*e.g.* Sergio *et al.* 2015, Crandall *et al.* 2019). Global Positioning System (GPS) transmitters specifically have been successfully used to study movements, habitat use and survival of eagles with no apparent ill effects (Harmata 2016, Nygård *et al.* 2016, Tikkanen *et al.* 2018a, 2018b).

Onshore wind power has increased enormously in Finland over the last decade, and it is predicted to grow from the current (the end of June 2024) over 7 GW (Renewables Finland 2024) potentially to 79 GW by 2045 (Fingrid 2023). In the future, the wind energy facilities will extend to the distribution of breeding Golden Eagles (Balotari-Chiebao *et al.* 2021). The predicted increase in risk requires collection of baseline information to fully assess impacts to Golden Eagles and help identify successful mitigation measures if needed (Allison *et al.* 2017). One important demographic component to maintaining population stability is adult survival. Currently, there is a lack of information on Golden Eagle adult survival in Finland, which could be used to inform demographic models in the future and to evaluate the potential impacts of future wind power plans. To help inform this information gap, we use GPS-tracking data from 26 adult Golden Eagles breeding in northern Finland to estimate adult survival probabilities. We also review scientific literature to assess the state of Golden Eagle adult survival from different areas across Finland.

2. Material and methods

2.1. Tracking data

We trapped 30 territorial adult Golden Eagles (17 males, 13 females) from carcass feeding sites using remote-controlled bow nets. Trapping was done during winter months from 2011 to 2023 at territories across the range of breeding Golden Eagles in Finland (Fig. 1). Survival of Golden Eagles followed on these territories was not affected by wind-power plants as wind power projects were absent from their home ranges. For individuals that died during the study, the distances from nest sites to the closest wind power project were at least 12 km, which exceeds Golden Eagle home ranges (mean distance to center of Minimum Convex Polygon 11.7 km, Tikkanen *et al.* 2018a). For individuals that are still followed, four home ranges contained wind turbines (the shortest distances to active nests were 3.5–9.1 km during monitoring).

We determined sex on the basis of mass and wing length tail feather coloration (Forsman 1980, Watson 2010). Seventeen individuals had been ringed as a chick before the GPS study began. At the start of GPS data collection, their age was on average 12 years (range 5–26 years calculated from those ringed as young, whose age is known).

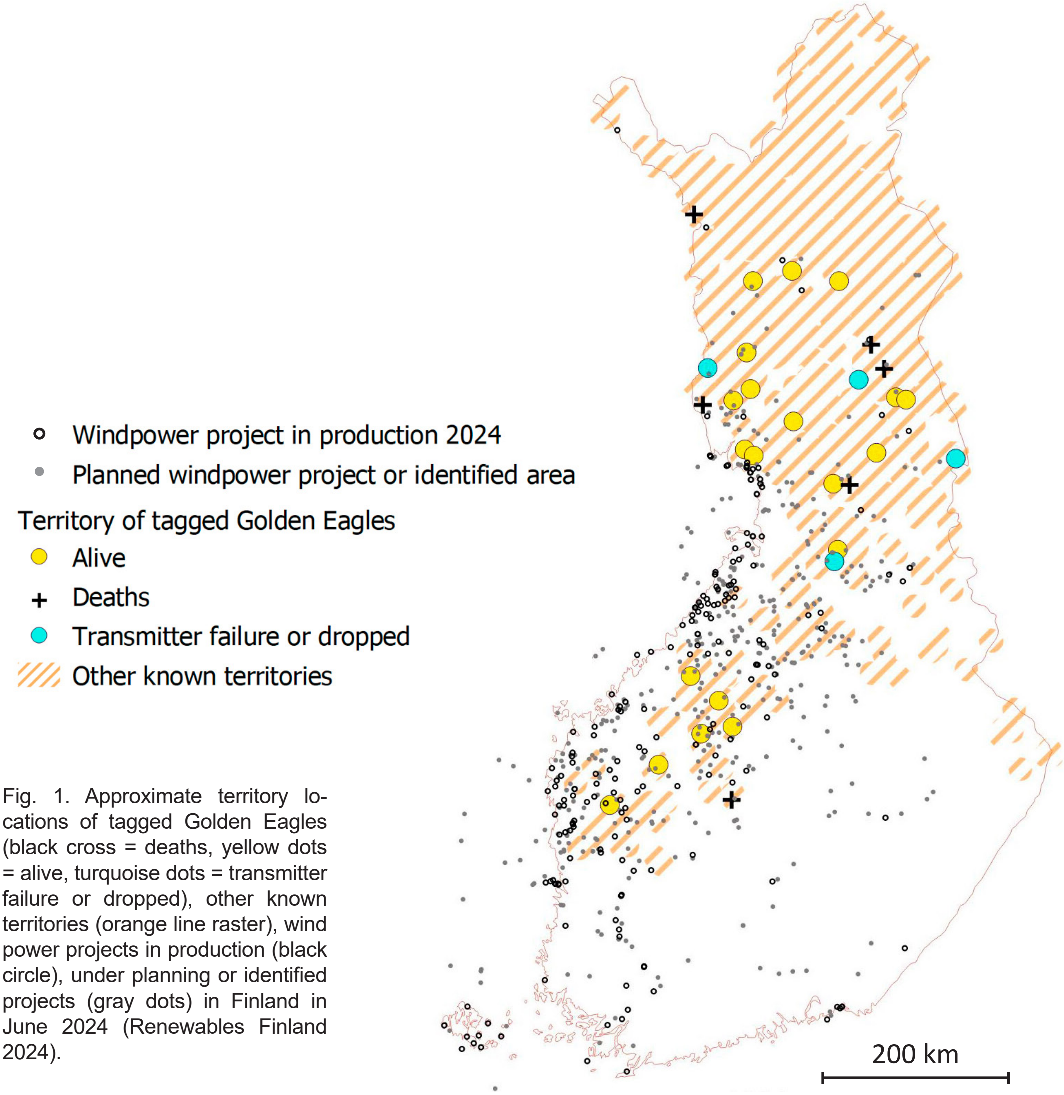

Fig. 1. Approximate territory locations of tagged Golden Eagles (black cross = deaths, yellow dots = alive, turquoise dots = transmitter failure or dropped), other known territories (orange line raster), wind power projects in production (black circle), under planning or identified projects (gray dots) in Finland in June 2024 (Renewables Finland 2024).

We ringed all previously unringed individuals with steel rings. All individuals were fitted with solar powered GPS transmitters (Cellular tracking ES-400-40-BKP; OrniTrack-50 - solar powered GPS-GSM tracker; Microwave telemetry Solar 50g PTT; Solar Argos GPS PTT-100 telemetry transmitter Microwave Telemetry, Inc.) using Teflon harnesses (not designed to fall off, see also Tikkanen *et al.* 2018a) with permission from the Centre for Economic Development, Transport and the Environment. The weights of these tracking devices were 50–70 g, which is at the maximum 2% of Golden Eagle mass as the smallest individual weighed 3.5 kg. These devices should therefore be a safe tracking method (Costantini & Møller 2013).

We followed tagged Golden Eagles until death, the device was shed, transmitter malfunction, or the study period was over in January 2024. The transmitters sent location data every 1 min – 1 hour in daylight depending on the programming of the transmitters. Those data were used to track the fate of each tracked individual eagle. Movement of individuals were followed closely so that deaths could be identified (Crandall *et al.* 2019). If the location remained stationary for

2 or more days, we visited (within 7 days at the latest) the site to determine if the Golden Eagle had died or if the tracking device had dropped (Crandall *et al.* 2019). If the Golden Eagle had died, we attempted to determine cause of death. If the tracking device stopped sending locations and was nowhere to be found at the latest location, the transmitter was concluded to have malfunctioned (Nygård *et al.* 2016).

2.2. Data analysis

We analyzed the data with program MARK using known fate models (White & Burnham 1999). We used the tracking information to construct individual capture histories that detailed for each month whether the individual stayed alive (10) or died (11), which allowed us to examine monthly survival. If the tracking device had dropped or failed and there was uncertainty in the fate of the individual, we removed the individual from the analysis (four individuals). If there were sighting information indicating that the bird was alive, we censored the history after the last month which the individual survived when the transmitter was still functioning (one individual). The dataset used in the final analysis included 908 monthly observations from 26 individuals (14 males and 12 females). We fit an intercept only model to derive an estimate of monthly survival. We derived an annual survival estimate by raising the monthly survival to the power of 12 (monthly survival^{12}).

2.3. Review of adult survival rates

We used information available in previous reviews of large raptors (Newton 2016, Tack *et al.* 2017) and the Golden Eagle (Watson 2010), and searched for published adult survival estimates for the Golden Eagle using Google Scholar with search words "Golden Eagle" or "*Aquila chrysaetos*" and "survival" or "mortality" with words indicating methods "capture-recapture", "dead recovery", "CJS-model", "age ratio", "GPS", "known fate". We had no spatial or temporal restrictions in the search. See Appendix 1 for a prisma figure outlining the review process.

3. Results

Individuals were followed from two to 94 months. Out of 26 individuals, 19 were still alive and tracked at the end of January 2024 (Table 1). Six individuals died during the study. Causes of death were starvation (n = 1) and unknown (n = 5). One of these individuals was found injured (probably in a collision with a power line) and would have died without treatment at an animal hospital. After treatment, the bird was released without GPS tracking. One transmitter had dropped. Four transmitters stopped working. Of these, one individual was resighted after the transmitter failure and confirmed to be alive (identified by a ring). This individual was censored after the last observation received from the GPS-device. The remaining three birds and the one that dropped its transmitter were removed from the data before the survival analysis. Monthly survival estimated from the intercept model was 0.9933 (0.9854–0.9970), which translates to annual survival of 0.924 (0.838–0.965).

3.1. Review

We found eight publications that reported nine survival estimates for adult Golden Eagles with varying methods (Table 2). Millsap *et al.* (2022) used joint dead recovery (3,128 individuals) and satellite tagging data (512 individuals) collected from western parts of the United States together with an integrated population model (Schaub & Kéry 2021) to model impacts of survival and other demographic rates on population growth rates. Another study from Sweden estimated adult survival using accumulated dead recovery data from Golden Eagles ringed as chicks from 1990 to 2015 (Daouti 2017). Daouti (2017) used the Seber parametrization (Seber 1970) assuming that juveniles and adults have equal recovery probabilities.

Hunt *et al.* (2017) followed 257 Golden Eagles from four life-stages (132 juveniles, 64 subadults, 21 floaters and 41 adult) in California United States using radio telemetry. Using information on cause-specific mortality, they were able to separate different sources of mortality.

Table 1. Information about GPS-tagged Golden Eagles.

Bird ID	County	Transmitter	Sex	Year	Months	End status
#1	Perho	OrniTrack-50 - solar powered GPS-GSM tracker	Male	2021	25	Alive
#2	Ylitornio	Microwave telemetry Solar 50g PTT	Male	2016	33	Dead
#3	Muonio	Microwave telemetry Solar 50g PTT	Male	2011	30	Dead
#4	Salla	Microwave telemetry Solar 50g PTT	Male	2051	25	Dead
#5	Kyyjärvi	Cellular tracking ES-400-40-BKP	Female	2018	52	Dead
#6	Pudasjärvi	OrniTrack-50 - solar powered GPS-GSM tracker	Female	2022	17	Dead
#7	Salla	Cellular tracking ES-400-40-BKP	Male	2016	28	Dead
#8	Kemijärvi	Microwave telemetry Solar 50g PTT	Male	2013	7	Transmitter dropped
#9	Sodankylä	Microwave telemetry Solar 50g PTT	Male	2014	77	Transmitter failure; seen alive
#10	Rovaniemi	Cellular tracking ES-400-40-BKP	Female	2019	59	Alive
#11	Lestijärvi	Cellular tracking ES-400-40-BKP	Female	2019	58	Alive
#12	Utajärvi	OrniTrack-50 - solar powered GPS-GSM tracker	Male	2021	34	Alive
#13	Utajärvi	OrniTrack-50 - solar powered GPS-GSM tracker	Male	2021	3	Transmitter failure
#14	Kuusamo	Microwave telemetry Solar 50g PTT	Female	2013	25	Transmitter failure
#15	Kaustinen	Microwave telemetry Solar 50g PTT	Male	2016	94	Alive
#16	Pello	Microwave telemetry Solar 50g PTT	Male	2017	17	Transmitter failure
#17	Sodankylä	Cellular tracking ES-400-40-BKP	Female	2018	62	Alive
#18	Kuusamo	Cellular tracking ES-400-40-BKP	Male	2020	39	Alive
#19	Posio	Cellular tracking ES-400-40-BKP	Female	2020	38	Alive
#20	Ranua	OrniTrack-50 - solar powered GPS-GSM tracker	Female	2020	38	Alive
#21	Pudasjärvi	OrniTrack-50 - solar powered GPS-GSM tracker	Female	2018	70	Alive
#22	Kittilä	OrniTrack-50 - solar powered GPS-GSM tracker	Female	2021	26	Alive
#23	Simo	OrniTrack-50 - solar powered GPS-GSM tracker	Female	2022	26	Alive
#24	Kauhajoki	OrniTrack-50 - solar powered GPS-GSM tracker	Male	2022	25	Alive
#25	Seinäjoki	OrniTrack-50 - solar powered GPS-GSM tracker	Female	2022	13	Alive
#26	Alajärvi	OrniTrack-50 - solar powered GPS-GSM tracker	Male	2023	2	Alive
#27	Simo	OrniTrack-50 - solar powered GPS-GSM tracker	Male	2023	3	Alive
#28	Ylitornio	OrniTrack-50 - solar powered GPS-GSM tracker	Female	2021	27	Alive
#29	Taivalkoski	OrniTrack-50 - solar powered GPS-GSM tracker	Male	2023	11	Alive
#30	Ylitornio	OrniTrack-50 - solar powered GPS-GSM tracker	Male	2023	3	Alive

Table 2. Published adult survival rates for Golden Eagles with confidence intervals or standard errors (SE) in parenthesis.

Survival	Method	Years	Country	Reference
0.860 (SE 0.132)	Satellite tracking	2011–2015	USA	Harmata 2016
0.890 (0.820–0.940)	Dead recovery data	1990–2015	Sweden	Daouti 2017
0.935 (0.892–0.979)	Radio telemetry	1994–1999	USA	Hunt *et al.* 2017
0.925	Disappearance of individuals		Germany	Bezzel & Fünfstück 1994 (in Watson 2010)
0.924 (0.838–0.965)	Satellite tracking	2011–2024	Finland	This study
0.930 (0.814–0.976)	Satellite tracking	2010–2017	Montana, USA	Crandall *et al.* 2019
0.940 (0.900–0.980)	Dead recovery data & satellite tracking	1997–2016	USA	Millsap *et al.* 2022
0.942 (0.923–0.955)	Age ratios	1982–1992	Scotland	Whitfield *et al.* 2004
0.958 (0.935–0.982)	Age ratios	1982–1992	Scotland	Whitfield *et al.* 2004
0.975	Disappearance of individuals		Scotland	Crane & Nellist 1999 (in Watson 2010)

They used known fate models to estimate adult survival with all causes of mortality (0.905), when wind power caused mortalities were censored (0.920) and when all human caused mortalities were censored (0.935).

Two studies used satellite telemetry to follow Golden Eagles in Montana, United States. Crandall *et al.* (2019) followed 16 adults using satellite transmitters that were mounted using a Teflon ribbon with a cross-chest breakaway harness. They used a multistate model with three states (alive, dead and unknown) to estimate adult survival. Harmata (2016) estimated adult survival by following 25 Golden Eagles equipped with tail-mounted satellite transmitters.

Whitfield *et al.* (2004) estimated two adult survival rates for populations in Scotland by comparing age groups. They generated survival estimates where persecution did not affect the results. One estimate was derived for the whole of Scotland (with multiple areas called zones included) using a regression model where the number of subadults for every 100 adults was explained by the density of poisoning incidents. The persecution free survival estimate was taken from the intercept as 0.942. In one completely persecution free zone (Western Seaboard), the estimate was 0.958. Watson (2010) reported studies from Germany (0.925) and Scotland (0.975) where estimates were drawn by using the disappearance of individuals from their territories as a cue for mortality.

Adult survival rates from all the published estimates ranged from 0.860 to 0.975 with a mean of 0.928 when using estimates that do not include human caused mortalities such as persecution or wind turbine collisions (Table 2).

4. Discussion

Using data from GPS-tagged individuals, we estimated annual survival probability of breeding Golden Eagles in Finland to be 0.924. In our review, we found only eight studies reporting adult survival estimates for Golden Eagles. These studies used varying methods, including three studies that did not use marking or tagging of individuals as a source of survival estimation indicating that there are a limited number of robust adult survival estimates available for Golden Eagles. Estimates from previous studies ranged from 0.860 to 0.975 and the mean Golden Eagle survival across all studies was on average 0.928. Thus, our estimate for the Finnish Golden Eagle population is close to this mean. This level of adult survival is within expected levels of a healthy population in Scotland (Whitfield *et al.* 2004).

Our study is among the first to examine adult survival of Golden Eagles in Northern Europe. A previous study from Sweden estimated mean annual survival (0.890) using dead recoveries (Daouti 2017). This study did not control for age differences in the recovery parameter, which may have affected the results if the assumption of equal recovery rates between juveniles and adults was not met by the data. Another study from Finland examined turnover rates from breeding Golden Eagles using chick DNA as a source of information (Kylmänen *et al.* 2023). Given our survival estimate, annual mortality of Golden Eagles is 0.076. Hence, the turnover rate (0.23) estimated by Kylmänen *et al.* (2023) likely reflects additional factors such as site fidelity.

Juvenile survival rates among Golden Eagles are clearly lower than those of adults (*e.g.* McIntyre *et al.* 2006: 1. year survival 0.19–0.34; Nygård *et al.* 2016: 1. year survival 0.58, 2. year survival 0.50; Millsap *et al.* 2022: 1. year survival 0.73, 2. year survival 0.87; Hunt *et al.* 2017: 1. year survival 0.84; Murphy *et al.* 2017: 1. year survival 0.79). Despite that this strong spatial variation may be caused by methodological differences between the above studies, large differences in juvenile survival warrant studies examining it also in Finland.

Our approach, the use of GPS-tracking data to estimate survival of adult Golden Eagles in Finland, facilitates estimation of adult survival from territories that are not yet subject to potential impacts from wind turbine collisions. Given the known importance of adult survival to Golden Eagle population stability, our relatively high estimated annual adult survival is likely a primary contributor to the observed population growth rate in Finland based on territories (1.02 SE 0.01; Tikkanen *et al.* unpublished). Therefore, this population may be vulnerable to increased mortality from expanding wind energy development. Further modelling efforts to quantify effects of future lost Golden Eagle habitat (Tikkanen *et al.* 2018a) from expanding wind energy development and collision risk models (Band *et al.* 2007) joined with subsequent modelling of their impacts on population viability (Wiens *et al.* 2017) are needed in order to guide responsible siting of wind power plants in Finland.

GPS-merkittyjen pesivien aikuisten maakotkien (*Aquila chrysaetos*) selviytymisarviot Suomessa

Aikuislintujen selviytymisarviot ovat tärkeitä arvioitaessa populaation tilaa ja elinkelpoisuutta sekä tutkittaessa ihmisen aiheuttamien vaikutusten roolia arvioiden vaihtelussa. Tällä hetkellä nopeasti lisääntyvä tuulivoima muodostaa uuden ja vakavan uhan suurten petolintujen selviytymiselle.

Vuosina 2011–2024 seurasimme 26 maakotkaa (*Aquila chrysaetos*) Suomessa käyttämällä satelliittipaikannusjärjestelmän seurantalaitteita alueilla, joilla ei ole tuulivoimaloita, eikä kotkien kuolleisuus ole lisääntynyt törmäysten vuoksi. Kerättyjen seurantatietojen avulla rakensimme yksilöllisiä havaintosarjoja kuukausitasolla ja arvioimme aikuisten selviytymisprosentit käyttämällä tunnetun kohtalon malleja MARK-ohjelmassa. Tarkastelimme myös julkaistuja aikuisten maakotkien selviytymisarvioita niiden levinneisyysalueella vertailevaa analyysia varten.

Tutkimusalueellamme kuukausittainen aikuisten selviytymisprosentti oli 0.993 (0.985–0.997), mikä tarkoittaa vuosittaista selviytymisprosenttia 0.924 (0.838–0.965). Löysimme kahdeksan tutkimusta, jotka raportoivat selviytymisarvioita, ja niiden vaihteluväli oli 0.860–0.975, keskiarvon ollessa 0.928. Näin ollen Pohjois-Suomessa pesivien maakotkien, jotka eivät ole tuulivoimaloiden vaikutuksen alaisia, aikuisten selviytymisprosentit ovat korkeat, kuten elinkelpoisessa populaatiossa odotetaan, ja hyvin lähellä muiden maakotkakantojen keskiarvoa. Korkeiden aikuisten selviytymisprosenttien ylläpitäminen on avainasemassa maakotkien populaation vakauden säilyttämisessä, kun tuulivoimarakentaminen Suomessa lisääntyy.

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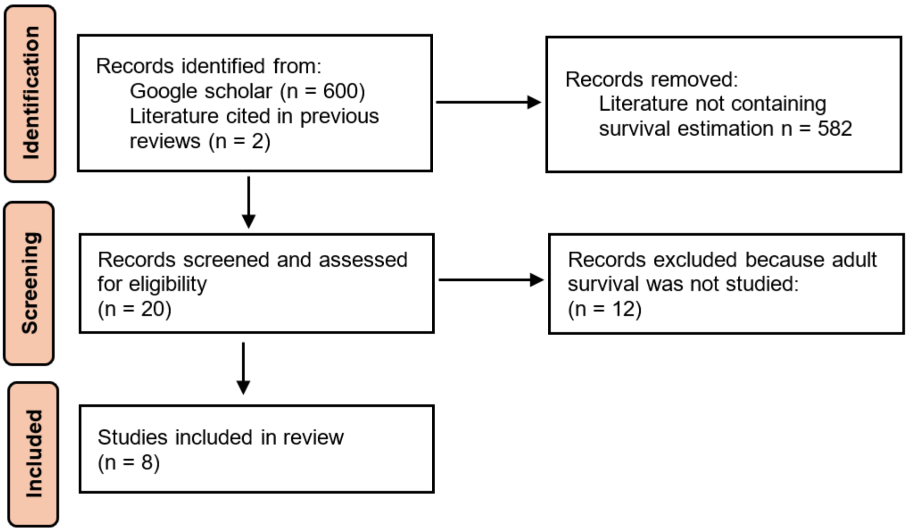
Appendix 1

A prisma figure for steps of the review. We used two sources. First, we searched for records on published adult survival estimates for the Golden Eagle from Google scholar with search words “Golden Eagle” or “*Aquila chrysaetos*” and “survival” or “mortality” with words indicating methods “capture-recapture”, “dead recovery”, “CJS-model”, “age ratio”, “GPS”, “known fate”. From these, we examined the first 600 hits and removed those not including survival estimation. The second source of information was previous reviews of large raptors (Newton 2016, Tack *et al.* 2017) and the Golden Eagle (Watson 2010), which provided 2 records not included in the Google scholar search.



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