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Long-term impacts of the Smøla wind farm on a local population of white-tailed eagles (*Haliaeetus albicilla*)

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COVER PICTURE
Two white-tailed eagle chicks in nest at territory Høgøyan in 2023
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- Population modeling

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- Bestandsmodellering

Abstract

Stokke, B.G., Dahl, E.L., Kleven, O., May, R., Nygård, T., Pavón-Jordán, D. & Sandercock, B.K. 2024. Long-term impacts of the Smøla wind farm on a local population of white-tailed eagles (*Haliaeetus albicilla*). NINA Report 2333. Norwegian Institute for Nature Research.

In the period 2020–2023, a full annual inventory of white-tailed eagle territories at Smøla was undertaken. In addition, searches for collision victims at Smøla wind farm were conducted with standardized protocols. Feathers from nestlings and adults at nest sites, and tissue from collision victims were used in subsequent DNA analyses and population modelling procedures. The main aim was to obtain knowledge of the status of the local population of white-tailed eagles.

The results from the present study indicate that the breeding population of white-tailed eagles at Smøla has been rather stable in the period 1998–2023. There have been no obvious long-term changes in reproductive output or number of active territories. Two years with particularly low reproductive output were likely due to adverse weather conditions (2012) and an outbreak of avian flu (2022). Interestingly, exposure to avian flu did not seem to impact adult survival in 2022–2023.

The spatial distribution of territories, however, has changed after construction of the wind farm. The construction area used to hold many territories prior to construction, but in the period 2020–2023 there was only one nest located within the wind farm.

In the period 2005–2023, a total of 133 white-tailed eagles have been found killed by collision with turbine blades at the Smøla wind farm. In general, central areas of the wind farm have caused more collisions than peripheral turbines in the period 2020–2023. No collisions have occurred at the four turbines with rotor blades painted black to increase visibility, suggesting that the mitigation measure should be expanded to other turbines, especially locations that can be described as collision "hot-spots" with multiple collisions recorded in the last 4-year period. Furthermore, most collision victims were adult birds, probably in search for a vacant breeding territory.

Based on results from DNA analyses and population modelling, the white-tailed eagle population at Smøla seems to consist of a mix of transient and resident individuals. Furthermore, proximity to the wind farm had a pronounced effect on apparent survival of adult white-tailed eagles. The apparent survival of transient individuals declined from the centre of the wind farm. The pattern could be explained by many vacant territories near or within the wind farm, or more occupied territories at distances further away from the wind farm. In contrast, the apparent survival of residents showed the opposite pattern, with increasing survival with greater distance from the wind farm. The pattern might be expected if mortality rates are higher due to collisions at the wind farm, if mate loss leads to an increased probability of emigration, or because collision rates are low near nests because resident individuals learn to avoid nearby turbines.

We evaluated the status of the white-tailed eagle population at Smøla for two time periods with intensive monitoring effort that provided good quality DNA- and comparable inventory data (2006–2011 versus 2020–2023). We found no significant differences in the number of territories occupied, number of fledglings produced per occupied territory, or adult survival. We combined our new estimates of demographic rates in an age-structured matrix population model for female sea eagles.

In 2006–2011, the estimate of the finite rate of population change (λ) and 95% confidence interval (CI) of the estimate were both greater than one, and the eagle population was predicted to grow at ca. 3.1% per year. In 2020–2023, the estimate of λ was less than one and the population would be predicted to decline at ca. 1.1% year. However, the 95%CI included one so that the finite rate of population change was not significantly different from the rate predicted for a stationary population. Estimates of the net reproductive rate ($R0$) in the two time periods were > 1,

indicating that females were successfully replacing themselves each generation. The confidence intervals of *R0* were greater than one in 2006–2011 but included one in 2020–2023. Hence, it would be interesting to undertake a new investigation of the population status in approximately 15 years' time (one eagle generation).

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Sammendrag

Stokke, B.G., Dahl, E.L., Kleven, O., May, R., Nygård, T., Pavón-Jordán, D. & Sandercock, B.K. 2024. Langtidseffekter av Smøla vindpark på den lokale bestanden av havørn (*Haliaeetus albicilla*). NINA Rapport 2333. Norsk institutt for naturforskning.

I perioden 2020-2023 ble det foretatt årlige inventeringer av havørn-territorier på Smøla. I tillegg ble det gjennomført systematiske søk etter kollisjonsofre i Smøla vindpark. Fjær fra unger og voksne ved ulike reir samt vev fra kollisjonsdrepte individer ble benyttet i molekylære analyser og bestandsmodellering for å bedømme tilstanden til havørnbestanden på Smøla.

Resultatene indikerer at hekkebestanden hos havørn på Smøla har vært relativt stabil i perioden 1998–2023. Det har ikke vært noen store endringer i perioden hverken med hensyn til antall aktive territorier eller ungeproduksjon. To år med relativt lav ungeproduksjon skyldtes svært ugunstige værforhold (2012) og utbrudd av fugleinfluensa (2022). Resultatene tyder imidlertid på at overlevelsen til voksne fugler ikke ble påvirket av fugleinfluensa i 2022-2023 i noen betydelig grad.

Den romlige fordeling av havørnterritorier har derimot endret seg betydelig etter ferdigstillingen av Smøla vindpark. I årene før vindparken ble etablert var det mange territorier i dette området, men i perioden 2020–2023 ble det kun funnet ett aktivt territorium i vindparken.

Til sammen 133 havørner er blitt funnet drept grunnet kollisjon med vindturbinblader i Smøla vindpark i perioden 2005–2023. I perioden 2020–2023 ble det funnet flest kollisjonsofre i de sentrale delene av vindparken. Ingen kollisjoner ble påvist ved fire turbiner hvor ett av tre turbinblad var malt svart for å øke synligheten, noe som tilsier at dette avbøtende tiltaket bør benyttes også på andre turbiner i vindparken. Dette gjelder spesielt for de turbinene hvor man har påvist flest kollisjoner. Undersøkelsene viste også at det var flest voksne individer som ble funnet kollisjonsdrept. Dette var trolig individer som var på utkikk etter ledige territorier.

På bakgrunn av resultatene fra de molekylære analysene og bestandsmodelleringen består havørnbestanden på Smøla av en blanding av stasjonære (territorielle) og ikke-stasjonære individer. Det ble funnet at avstand fra vindparken hadde en tydelig effekt på voksenoverlevelsen. Overlevelsen til ikke-stasjonære individer avtok med avstand fra vindparken. Dette kan forklares med at det er mange potensielt ledige territorier i eller nær vindparken, eller mange okkuperte territorier lenger bort fra vindparken. Overlevelsen til stasjonære individer viste et motsatt mønster, med økende overlevelse med økende avstand fra vindparken. Dette kan forklares med høyere dødelighet i vindparken enn lenger unna, økt sannsynlighet for at stasjonære individer kan emigrere til andre områder dersom ett av individene i et par dør, eller lave kollisjonsrater ved reirområdene dersom stasjonære individer unngår å oppholde seg nær turbinene i vindparken.

Vi evaluerte statusen til havørnbestanden på Smøla i to tidsperioder der det eksisterer gode nok data til å gjennomføre bestandsmodellering (2006–2011 versus 2020–2023). Det ble ikke funnet noen statistisk signifikant forskjell hverken med hensyn til antall aktive territorier, antall unger produsert per aktivt territorium eller voksenoverlevelse.

I perioden 2006–2011 var bestandens vekstrate (λ), inklusive 95 % konfidensintervall, større enn 1, og bestanden var estimert til å vokse med ca. 3,1 % per år. I perioden 2020–2023 var vekstraten mindre enn 1, og estimert til å avta med 1,1 % per år. 95 % konfidensintervallet inkluderte imidlertid 1, noe som tilsier at bestandens vekstrate ikke er signifikant forskjellig fra det som er forventet for en stabil bestand. Estimatene for netto reproduksjonsrate (*R0*) i de to tidsperiodene var større enn 1, noe som indikerer at hunnene produserte nok avkom til å resultere i en stabil eller økende bestand. Konfidensintervallene for *R0* var høyere enn 1 i perioden 2006–2011, men inkluderte 1 i perioden 2020–2023. Det ville derfor vært interessant å gjenta havørninventering på Smøla om ca. 15 år (én ørnegenerasjon).

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Contents

Foreword

Construction of the Smøla wind farm was completed in 2005, and previous monitoring in the period 2005–2019 reported a total of 110 white-tailed eagles that were killed due to collision with turbine blades. Detailed mapping of white-tailed eagle territories at Smøla was conducted in two previous research projects (BirdWind and INTACT). In 2019, Statkraft AS contacted the Norwegian Institute for Nature Research (NINA) to carry out a new inventory of white-tailed eagle territories at Smøla. The aim of the project was to obtain an update on the current status of the local population. Knowledge about the state of the population is important because it is uncertain if mortality due to collisions with wind turbines have had negative long-term impacts on the local population of white-tailed eagles (Dahl et al. 2012, 2013). A new inventory of territorial eagles, in addition to DNA-sampling and search for dead birds, was conducted during the 4-year period of 2020–2023. The new demographic data were then synthesized in an age-structured population model to compare the status of the white-tailed eagle population in two periods with intensive monitoring in 2006–2011 (Dahl 2014) and 2020–2023 (this study).

Trondheim, January 2024
Bård G. Stokke, Project leader

1 Introduction

The Smøla wind farm consists of 68 wind turbines and is situated in the northwestern part of the island Smøla in Møre & Romsdal county, Central Norway (***Figure 1***). The wind farm was built in two stages and was fully operational from 2005 onwards. At the time of construction, the Smøla wind farm was the largest facility in Norway (Bevanger et al. 2010; May et al. 2013). Many studies have found that birds are at risk colliding with the turbine blades or towers, which is also the case at Smøla (Bevanger et al. 2010, 2016; Dahl 2014; May et al. 2020; Stokke et al. 2020b). Extensive searches for collision victims in the Smøla wind farm were conducted during the two research projects BirdWind (2006–2011) and INTACT (2013–2017) (May et al. 2020; Stokke et al. 2020b). In addition, Statkraft AS has carried out similar searches both before and after these projects, resulting in additional collision data from 2005 to the present. A total of 110 white-tailed eagles (*Haliaeetus albicilla*) were found killed due to collisions with turbine blades in the 15-year period of 2005–2019.In addition to searches for collision victims, complete inventories of the white-tailed eagle population on Smøla were undertaken during the breeding season. The latest year with a complete inventory before the start of the current project was 2013 (Dahl 2014; Bevanger et al. 2016). Long term impacts of the Smøla wind farm on the local population of white-tailed eagle were then investigated using a population modelling approach, entering data from the inventory and corresponding genetic data from sampling of feathers at nests and tissues from collision victims. The main finding of previous work was that the local sub-population within 5 km of the wind turbines was negatively influenced by the wind farm with a finite rate of population growth less than one, low replacement rate and a lower generation time (Dahl 2014). The current project "*Long term impacts of Smøla wind farm on the local population of white-tailed eagle (Haliaeetus albicilla)*" was completed during the 4-year period of 2020–2023 (Stokke et al. 2020a, 2021a). Our main aim was to determine the current status of the local white-tailed eagle population at Smøla by replicating the methods of the previous population study completed 10 years ago (Bevanger et al. 2010, Dahl 2014). Accordingly, a thorough inventory of all territories and nest sites were carried out in four years (2020–2023), accompanied by collecting feathers at the nests, and systematic search for collision victims at all turbines in the wind farm. Hence, based on genetic analyses of DNA from feathers and tissue materials that were collected with noninvasive methods, it was possible to determine the number of active territories of white-tailed eagles, and to assign collision victims to territories.
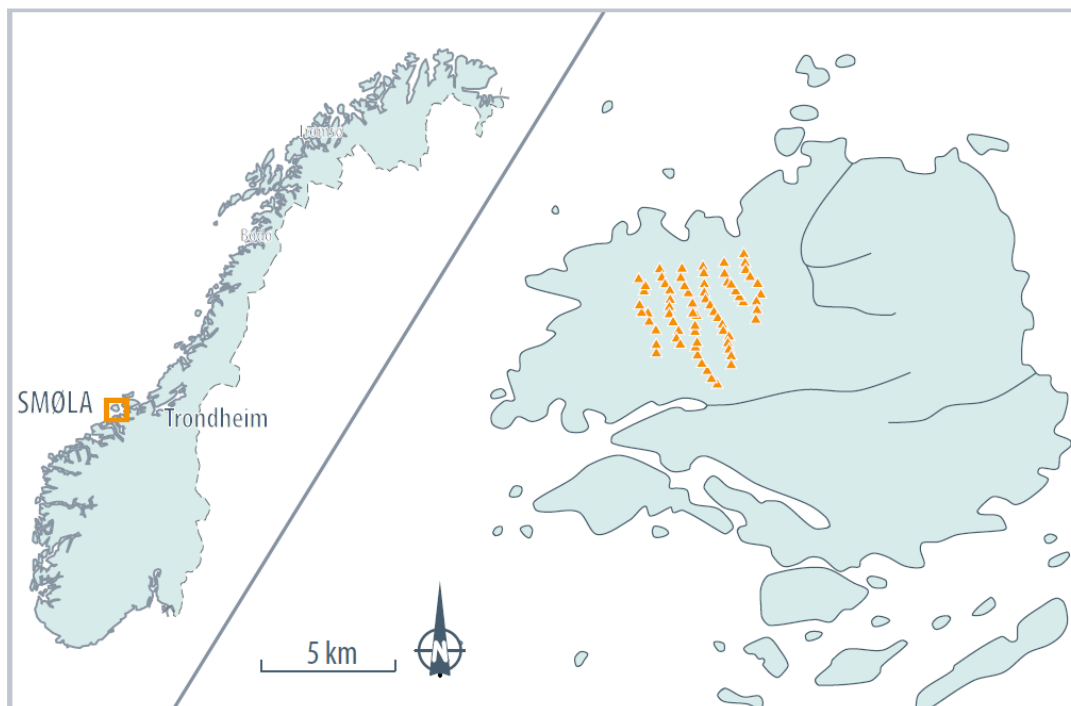

Figure 1. *The Smøla wind farm is situated in the northwestern part of the island Smøla, central Norway. From Bevanger et al. 2016.*

2 Methodology

2.1 Inventory of white-tailed eagle territories

The whole area of Smøla municipality, including all skerries and small islands off the coast of the main island, was searched systematically by experienced personnel for nests of white-tailed eagles from the end of May until end of June in four consecutive years (2020–2023). A Messenger-chat was used by the inventory team throughout the season for continuous sharing of observations, photos received from local inhabitants as well as updates of information from nest visits. Our methods proved to be highly efficient in assuring the quality of observations within the team as the season progressed. For each nest, GPS coordinates were taken, and territorial activity (detection of moulted feathers from adults), nest condition (fresh or old), nest contents (number of eggs, chicks or empty), and reproductive output (number of fledglings) were recorded at each visit. Feather samples from adults (moulted feathers) and chicks (feathers) in the nest were collected and subsequently used for DNA analyses (see **Chapter 2.3**).

2.2 Search for collision victims

Searches for collision victims at Smøla wind farm were conducted according to a standardized protocol at all turbines five times per year. On Smøla, no mammalian scavengers occur. A lack of scavenging, combined with the large body size of white-tailed eagles, means that any removal and detection biases are negligible. In 2020, searches were completed in April, May, June, August and October. In 2021, searches were completed in February, April, June, September and November, whereas in 2022 searches were performed in March, April, July, September and November. In 2023, one search was completed in May, and a second in October. All searches were carried out by a single person with a trained dog. The terrain outwards to 100 meters from each turbine was searched for carcasses of all bird species. Searches were conducted in favourable conditions with good visibility and mild weather. If a carcass was found, the GPS coordinates, turbine ID, distance from turbine, and species identity were recorded. Several carcasses of white-tailed eagles that died from collisions with turbines were found by hikers or Statkraft personnel outside of the systematic searches. These individuals were also included in the subsequent analyses. All eagle carcasses were collected and subsequently shipped to the NINA office in Trondheim for determination of age and sex, and tissue samples were collected for DNA analyses (see **Chapter 2.3**).

2.3 DNA analyses for individual identification and parentage

The tip (5–20 mm long) of the calamus of each collected feather was cut longitudinally and placed in a tube containing 470 µL ATL (Qiagen, Hilden, Germany) and 25 µL Proteinase K (Qiagen). From egg remnants, a small piece ($\approx 5{\times}5$ mm) of the egg membrane was placed in a tube containing 470 µL ATL and 25 µL Proteinase K. From muscle tissue samples, a small piece (≈ 25 mg) was cut off and placed in a tube containing 200 µL ATL and 20 µL Proteinase K. The samples were digested overnight at 56 °C and gently shaken in a shaking incubator during that period. *Table 1* provides an overview of the sample materials used and the sample size for each material type.

Table 1. An overview of the sample materials and sample sizes included in the DNA-based monitoring of white-tailed eagles at Smøla during the years 2020–2023.

	Year of breeding season			
	2020	2021	2022	2023
Sample materials				
Moulted feathers	167	160	113	158
Pulled feathers from nestlings	27	21	15	19
Egg membranes	1	1	1	0
Tissue or feathers from dead individuals	2	10	7	5
Total samples	**197**	**192**	**136**	**182**

Genomic DNA was extracted using a semi-automated system (Maxwell® 16 Research Instrument, Promega, Madison, WI, USA) and the Maxwell 16 tissue DNA Purification Kit following the manufacturer's protocol.

All samples were genotyped with 15 microsatellite loci and one locus for sex determination (**Table 2**). The markers were amplified in three multiplex sets by polymerase chain reaction (PCR) and using fluorescently labelled forward primers. The alleles were separated by capillary electrophoresis on an ABI3500xl Genetic Analyzer and the sizes determined with the software Gene-Mapper. Each sample was genotyped three times and a consensus genotype was constructed from the replicates by applying the following two criteria: markers with a heterozygote result had to show the same pattern in two independent PCRs whereas markers with a homozygote result had to be confirmed in three independent PCRs. Consensus genotypes containing at least ten microsatellite loci were included for individual identification.

Table 2. *Characteristics of genetic markers used for sex determination, individual identification and parentage analysis for white-tailed eagles at Smøla.*

Locus	Reference	A	Allele size range (bp)	H_O	H_E	P_{ID}
Age2	Topinka & May 2004	21	167-229	0.89	0.91	0.01
Hal01	Hailer et al. 2005	6	130-140	0.74	0.73	0.12
Hal04	Hailer et al. 2005	4	155-161	0.42	0.38	0.44
Hal05	Hailer et al. 2005	2	104-107	0.50	0.47	0.39
Hal06	Hailer et al. 2005	3	174-182	0.51	0.57	0.27
Hal09	Hailer et al. 2005	7	132-146	0.67	0.70	0.13
Hal13	Hailer et al. 2005	6	148-164	0.76	0.79	0.07
Hal14	Hailer et al. 2005	7	175-236	0.66	0.68	0.13
Hle01	Tingay et al. 2007	6	163-175	0.69	0.73	0.12
Hle04	Tingay et al. 2007	5	230-238	0.68	0.71	0.13
Hvo03	Tingay et al. 2007	6	172-192	0.59	0.57	0.21
IEAAAG04	Busch et al. 2005	4	200-216	0.50	0.51	0.31
IEAAAG05	Busch et al. 2005	11	132-170	0.69	0.69	0.12
IEAAAG12	Busch et al. 2005	5	96-112	0.75	0.73	0.12
IEAAAG15	Busch et al. 2005	3	121-129	0.48	0.51	0.36
Z37B	Dawson et al. 2015	1 (males)	98	0	0	
Z37B	Dawson et al. 2015	2 (females)	94,98	1	1	

Notes: A, number of alleles; H_O, observed heterozygosity; H_E, expected heterozygosity; P_{ID}, probability of individual identity. The data are based on genotypes from 140 presumably unrelated adult individuals analysed with GenAlEx v6.501 (Peakall & Smouse 2012). The combined probability of identity for the 15 autosomal loci was 5.6×10^{-13}. The locus Z37B was used to determine sex of individual birds.

Individuals identified through the DNA-based monitoring during the years prior to 2020 were also included when identifying unique individuals and in the list of candidate parents because white-tailed eagles are long-lived birds. According to the Norwegian Bird Ringing Centre, the oldest ringed white-tailed eagle in Norway became at least 32 years old. The birds from the previous inventory period were genotyped with five additional microsatellite loci to match the panel of markers applied to the birds from the current inventory project. Unique genotypes were identified using the program *allelematch* (Galpern et al. 2012) in R 4.3.1 (R Core Team, 2023). Parents of the genotyped nestlings were identified using the program *COLONY* (Jones & Wang 2010).

2.4 Estimation of apparent survival

Encounter histories. Our DNA analyses of feathers collected at nest sites and tissue samples from collision mortalities provided information on detections of individual eagles for the 4-year period of 2020–2023. Feathers from nest sites were collected from adult birds at least 5+ years old and did not include nestlings at the nest, young or subadults (E.L. Dahl, pers. obs.). We used the DNA detections to create individual encounter histories for each bird where each year was coded as detected (1) or not detected (0). For each detection, we recorded the distance from the

location where the sample was collected to the centroid of the wind farm (63.406°N, 7.920°E). The summary file included a 4-year encounter history (e.g., 1011), a sex determination, and individual covariates for estimates of distance from the wind farm in each year that the bird was detected within the study area.

Mark-recapture analyses. Survival analyses were conducted in an R environment (R Core Team 2022) with the package RMark as an interface to Program Mark (White and Burnham 1999, Laake 2013). We used Cormack-Jolly-Seber (CJS) mark-recapture models to estimate annual rates of apparent survival (ϕ) corrected for the probability of detection (p). Apparent survival is the product of true survival and site fidelity, and the complement includes losses to mortality or emigration. The probability of detection is the probability of detecting an individual with the standardized field methods where the complement can include birds that were missed because they skipped breeding or avoided detection. The annual survival of long-lived birds is often affected by annual conditions and by demographic variation among different sex or age-classes. We included annual variation as a time-dependent effect and sex as a group effect. Inspection of the encounter histories showed that a high proportion of individuals were detected in only one year. To model the potential effects of transience on apparent survival, we used 'time-since-marking' models that separate apparent survival in the interval after first detection ($\phi1$) from apparent survival in subsequent intervals for birds that were detected in multiple years ($\phi2+$). We opted to start with a global model that included the effects of year, sex and time-since-marking in apparent survival and the effects of year and sex in the probability of detection ϕ(tsm*time*sex), p(time*sex). We also modelled apparent survival as a function of distance to the centre of the wind farm where distance was an individual covariate that could change from year to year. We predicted a positive relationship between apparent survival and distance if exposure to wind turbines increases mortality or reduces site fidelity. We tested goodness-of-fit to the global model without individual covariates with the Fletcher's c-hat procedure within Mark. We then incorporated our estimate of the variance inflation factor (c-hat) into our model selection procedures and used quasi-AICc values to rank alternative models. We used Akaike weights to identify the subset of models with the greatest support from the data and used them to obtain parameter estimates.

2.5 Population modelling

We compared population status of white-tailed eagles at Smøla for two time periods with intensive monitoring: the six seasons from 2006–2011 (Dahl 2014) and the four seasons from 2020-2023 (this study). We developed an age-structured matrix population model based on pre-breeding censuses for females only. Following Dahl (2014), we assumed juveniles, subadults and adults differed in annual survival and that white-tailed eagles started breeding as 7-year-olds in areas with high population density. Fecundity rates of adults were calculated as the average number of fledglings produced in occupied territories, which was a function of clutch size and the probability of breeding success (*Table 3*). We parameterized the model with our separate estimates of fecundity and adult survival for the two different time periods. We used published estimates for the survival of juveniles and subadults to complete the model. Estimates of survival of juveniles from fledging until the following summer were based on a sample of 59 birds marked with GPS tags at Smøla during 2006–2011 (Dahl 2014). Estimates of survival for the six year-classes of subadults were based on 184 ring recoveries from 3,434 eagles ringed in Norway during 1974–2000 (Nygård et al. 2009). Estimates of the finite rate of population change (λ), net reproductive rate (R0, female offspring per breeding female per generation) and generation time (T, years) were calculated with functions in the popbio package in Program R (Stubben & Milligan 2007). A stationary population should have a finite rate of population change of $\lambda = 1$ and a net reproductive rate of R0 = 1 for replacement. We use parametric bootstrapping to calculate the 95% confidence interval (CI) for each of the matrix properties. We first took a random draw for fecundity from a normal distribution and random draws for each probability of survival from the beta distribution, combined the set of random draws in the age-structured projection matrix and then calculated the three matrix properties. In the next step, we repeated the same steps for 10,000 iterations to generate bootstrap distributions for the matrix properties and then calculated the mean estimate, standard error and 95% CI from the quantiles of each bootstrap distribution.

3 Results and discussion
3.1 Number of territories, spatial distribution and reproductive output

The white-tailed eagle population at Smøla was closely monitored in the 16-year period of 1998–2013 (**Table 3**). Monitoring took place in parts of the municipality also in the following 3-year period of 2014–2016, but no data were collected during the period 2017–2019. The entire population was monitored intensively thereafter during the last four years of 2020–2023.

Table 3. *Long-term results from population monitoring of white-tailed eagles at Smøla municipality during the 26-year study period of 1998–2023. Pulli = total number of nestlings, Nests = number of nests containing nestlings, Clutch = clutch size for pairs with successful fledgling production, Territories = number of occupied territories, Reproductive success = number of fledglings produced per occupied territory, Coverage = monitoring effort.*

Year	Pulli	Nests	Clutch	Territories	Reproductive success	Coverage
1998	20	11	1.82	42	0.48	Good
1999	20	13	1.54	39	0.51	Good
2000	22	16	1.38	48	0.46	Good
2001	14	11	1.27	47	0.30	Good
2002	17	14	1.21	53	0.32	Good
2003	17	11	1.55	49	0.35	Good
2004	14	10	1.40	41	0.34	Good
2005	19	15	1.27	50	0.38	Good
2006	23	17	1.35	49	0.47	Good
2007	30	22	1.36	47	0.64	Good. DNA-data
2008	21	14	1.50	50	0.42	Good. DNA-data
2009	27	21	1.29	52	0.52	Good. DNA-data
2010	36	23	1.57	45	0.80	Good. DNA-data
2011	17	15	1.13	42	0.40	Good. DNA-data
2012	6	5	1.20	41	0.15	Good
2013	39	27	1.44	42	0.93	Good
2014	34	22	1.55	32	1.06	Incomplete
2015	30	20	1.50	35	0.86	Incomplete
2016	32	19	1.68	40	0.80	Incomplete
2017	-	-	-	-	-	No data
2018	-	-	-	-	-	No data
2019	-	-	-	-	-	No data
2020	31	23	1.35	45	0.69	Good. DNA-data
2021	31	23	1.35	51	0.61	Good. DNA-data
2022	18	13	1.38	47	0.38	Good. DNA-data
2023	34	22	1.55	49	0.69	Good. DNA-data

The number of active territories and reproductive output on Smøla varied from year to year (**Table 3**), but without any obvious long-term changes (**Figure 2** and **3**). Two years had particularly low reproductive success. Reproductive output was extremely low in 2012 due to unfavourable weather conditions during the breeding season (**Figure 3**). Output was also low in 2022, when several nests were found with dead chicks. One of the dead chicks was tested for avian flu

(H5Nx) and was confirmed to have a positive response. Hence, the low reproductive output in 2022 was likely due to an outbreak of avian flu (***Figure 3***).
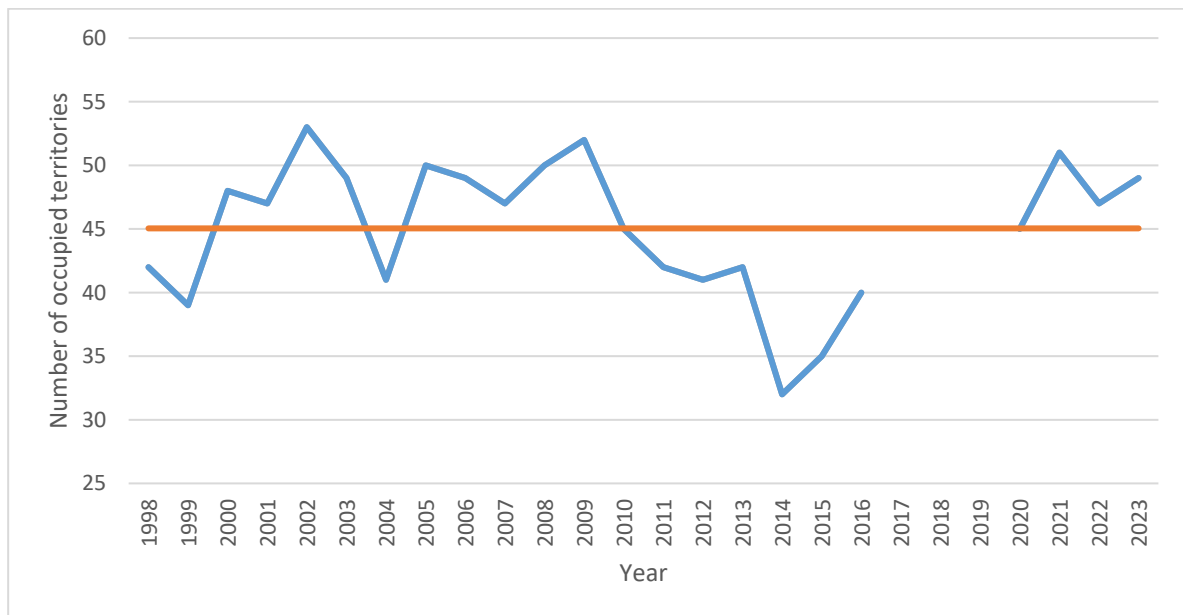

Figure 2. *Number of occupied white-tailed eagle territories at Smøla in the period 1998–2023. Orange horizontal line = mean for the whole period (45). See **Table 3** for more information.*
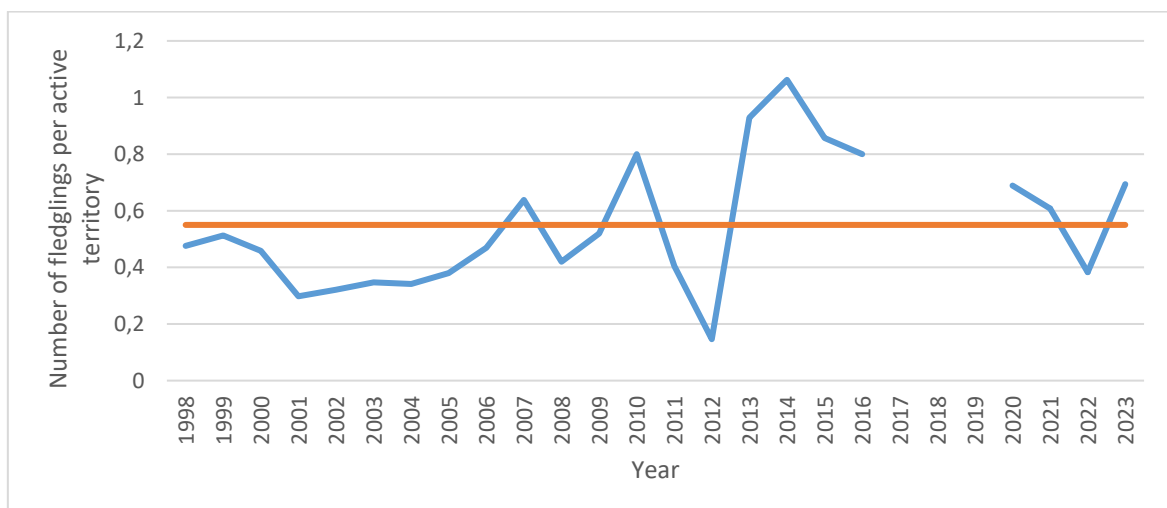

Figure 3. *White-tailed eagle fledgling production per occupied territory at Smøla in the period 1998–2023. Orange horizontal line = mean for the whole period (0.55). Reproductive output was low in 2012 due to adverse climatic conditions and in 2022 due to an outbreak of avian flu. See **Table 3** for more information.*

In the periods 2007–2011 and 2020–2023, feather samples were collected from both nestlings and adults at nests (moulted feathers from both adults if possible), and tissue from collision victims in the wind farm. DNA profiles from collision mortalities have been used to identify the territory where the individuals originated from. DNA from both feathers and carcasses is important to analyse cause- and age-specific survival rates, and also allows an accurate estimate of the actual number of territories (Dahl 2014). If feathers of a particular adult individual are obtained from two nests in the same year (one or both empty), one can conclude that both nests belong to the same territory.

Interestingly, the mean reproductive output measured as the number of fledglings per active territory in the two periods with intensive sampling was quite similar (2007–2011: 0.56 versus 2020–2023: 0.59), even when including the unusually low output in 2022 caused by the avian flu outbreak. The mean reproductive output prior to these periods (1998–2006) was 0.40. The estimate for the early period is likely to be an underestimate due to differences in field methodology. Individuals were not identified because DNA-data were unavailable and nests from the same breeding pair might have been assigned to different territories. Nevertheless, both the number of territories (*Figure 2*) and the reproductive output per active territory (*Figure 3*) seem to have been rather stable over time at Smøla from prior to wind energy development until present (1998–2023).

Regarding long-term changes in spatial distribution of territories, however, there has been a marked decrease in number of territories inside the wind farm area over time. Prior to 2005, there was a high density of eagle territories in the area where the wind farm was developed (*Figure 4*, Bevanger et al. 2010). Only a few years after the wind farm was operational, the densities of territories in the wind farm area had declined (*Figure 5*, Bevanger et al. 2010).
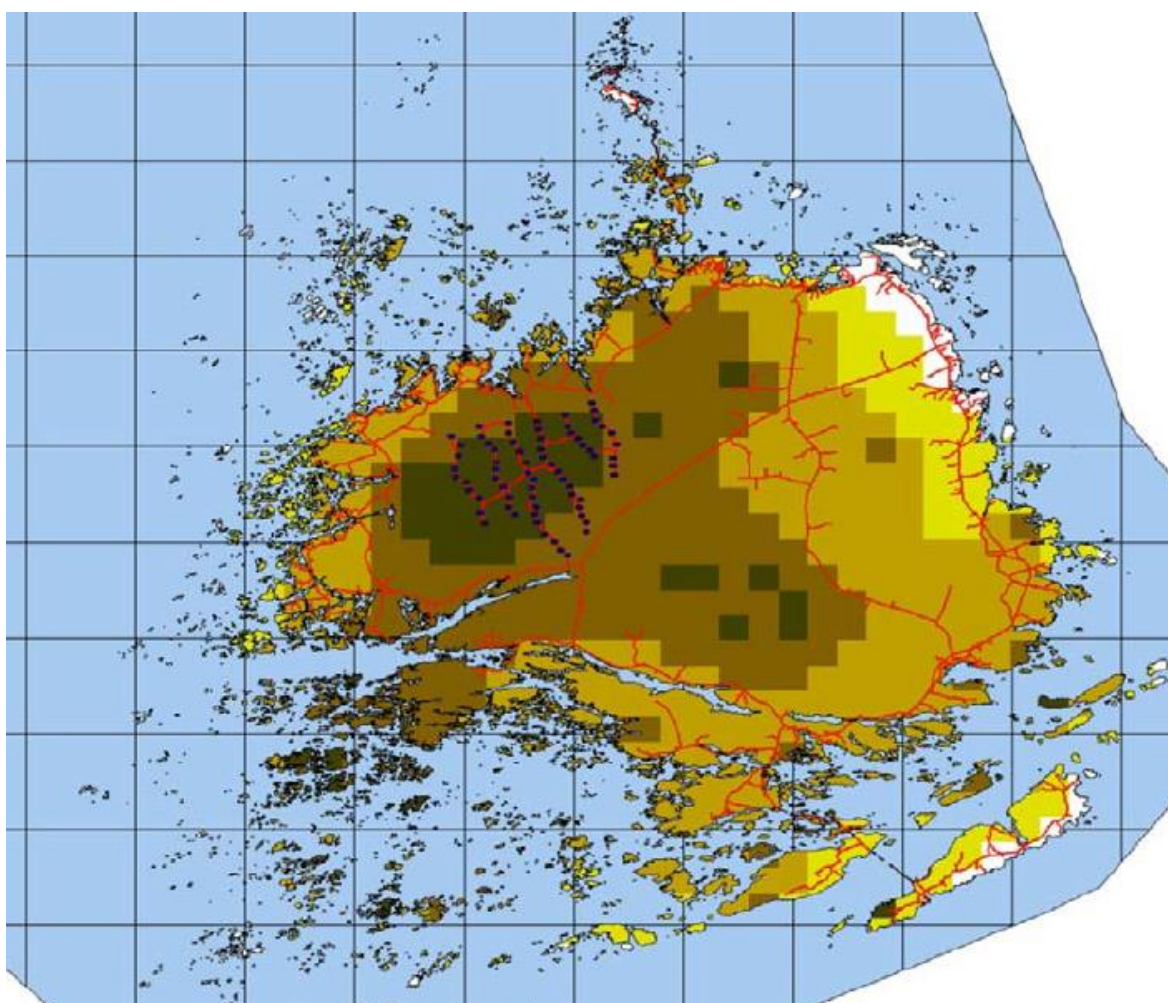

Figure 4. Densities of occupied white-tailed eagle territories on Smøla in 2000 and 2001. Darker colours indicate higher densities of eagle territories. From Bevanger et al. (2010).

In the period 2020–2023, there was only one active territory located inside the wind farm area. The territory, «Mellomvatnet Nord», was situated in the northeastern corner of the wind farm close to wind turbines 63 and 64. Eggs were laid, but no chicks hatched in 2020 and 2021. Both in 2022 and 2023, one chick was produced in this nest (*Figure 6*).
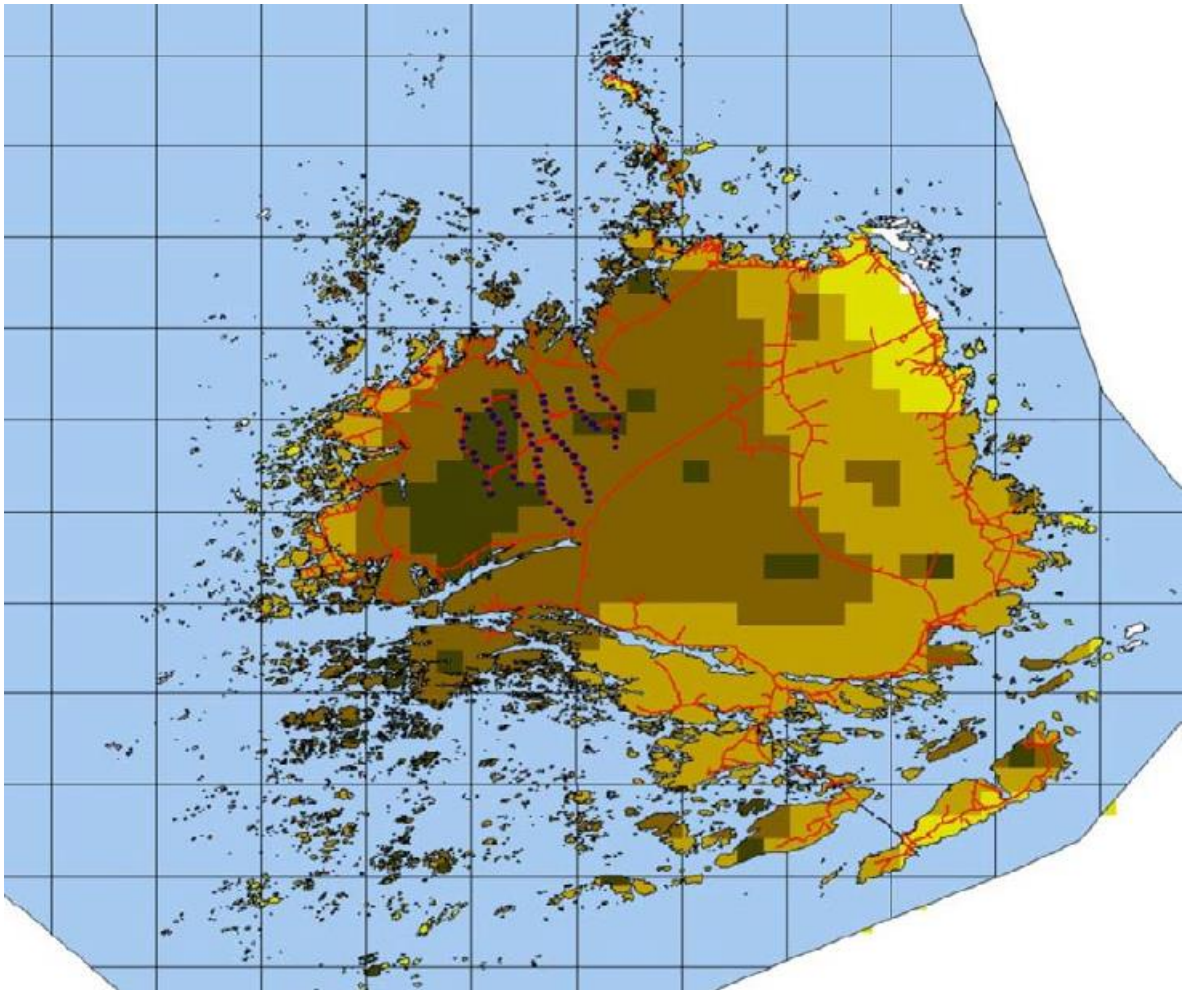
Figure 5. *Densities of occupied white-tailed eagle territories on Smøla in 2008 and 2009. Darker colours indicate higher territory densities. From Bevanger et al. (2010).*

Figure 6. *A small nestling white-tailed eagle in the territory «Mellomvatnet Nord» inside the wind farm. This eagle territory was the only site producing chicks inside the wind farm area during the period 2020–2023. © Espen Lie Dahl.*

In the period 2020–2023, a total of 114 white-tailed eagle nestlings were documented in Smøla municipality (***Table 3***), and white-tailed eagle activity was confirmed in 60 territories. About half of the active territories (47%) have been in use in all four years (***Figure 7***). In total, 45 territories produced one or more nestlings, but as many as 42% of the nestlings were raised in 20% of these territories (***Figure 8***).
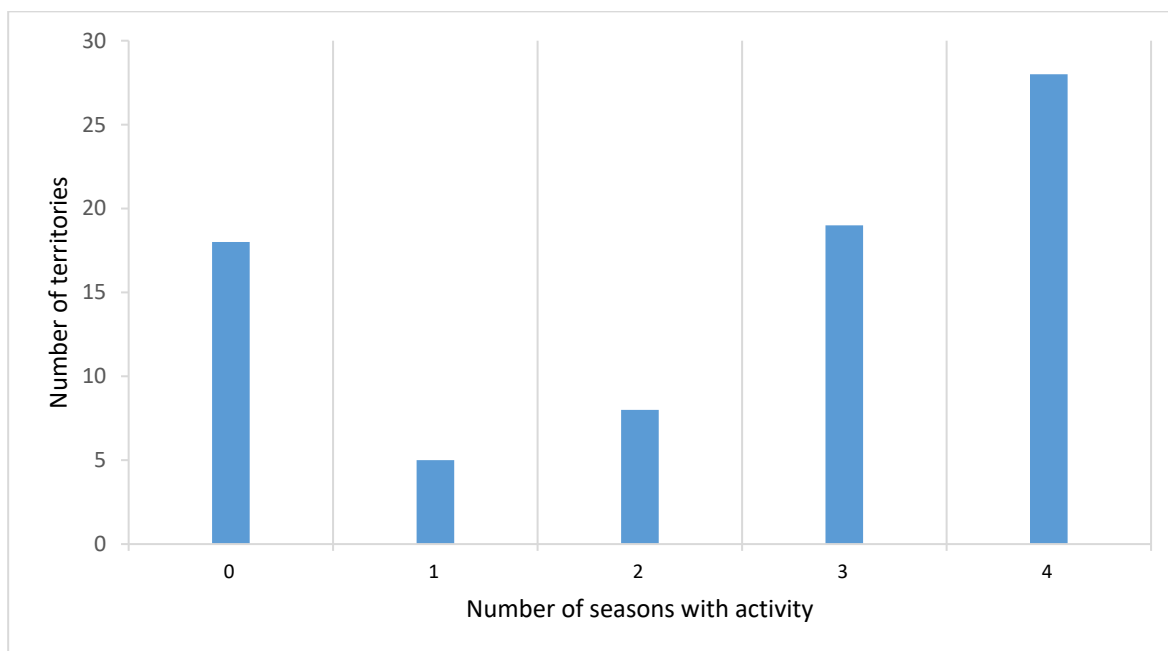

Figure 7. *Number of seasons with white-tailed eagle activity in the territories visited during 2020–2023.*
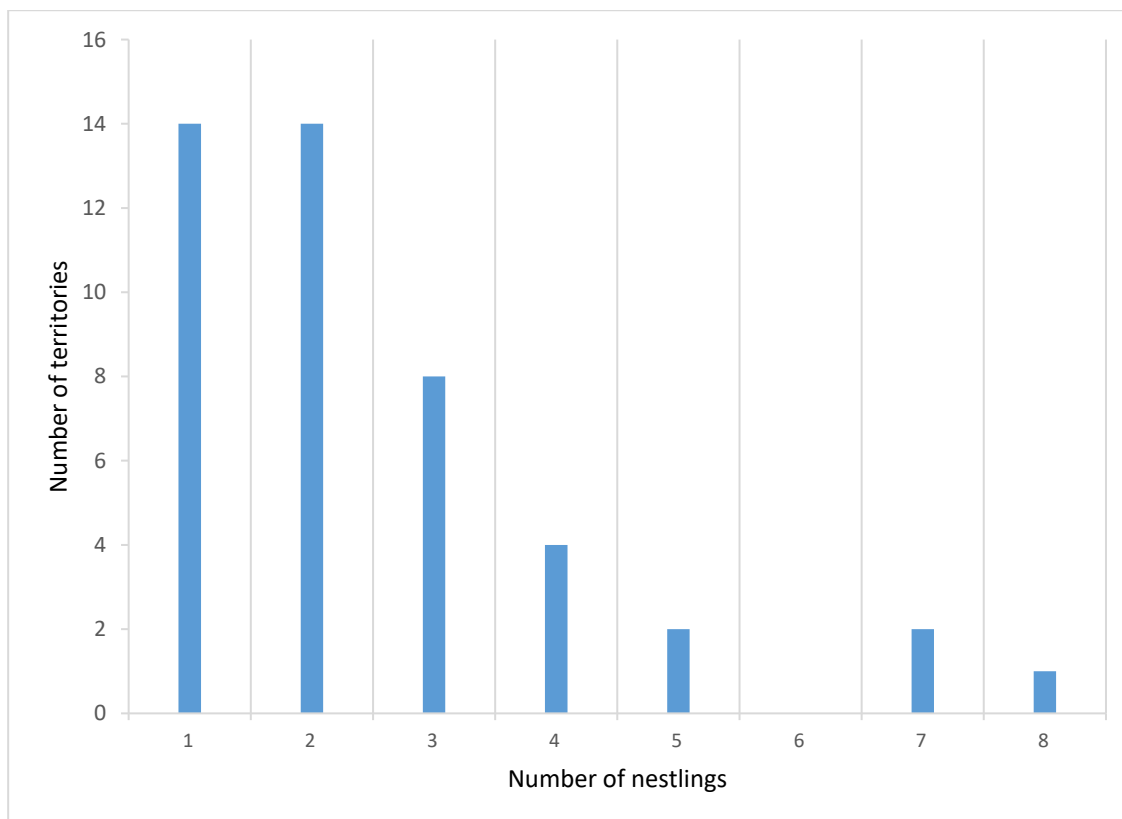

Figure 8. *Total number of white-tailed eagle nestlings in 2020–2023 in the 45 territories successfully producing at least one chick.*

3.2 Collision mortality events

In the study period 2020–2023, a total of 23 white-tailed eagle carcasses were found within the wind farm (***Table 4***), bringing the tally for the 19-year period of 2005–2023 to 133 individuals (***Figure 9***). Most individuals found during the last four years were adults (76%, 16 of 21 birds with age information). Two birds had been previously ringed as nestlings and were 3 and 8 years old at death. The sex ratio was similar to a 1:1 ratio, with 9 males and 11 females (binomial test, P = 0.82). The central part of the wind farm proved to be a collision "hot-spot", while no dead birds were found at turbines with rotor blades painted black as part of a previous investigation on mitigating measures to reduce risk of collisions (***Figure 10***, May et al. 2020).

Table 4. *White-tailed eagle collision victims found at the Smøla wind farm in the period 2020–2023. Dead eagles were sexed by necropsy and aged by plumage coloration and wing moult as young (1 year), subadult (2-4 years) or adults (5+ years). Data were not available for badly decomposed specimens.*

| Date	Turbine	Sex	Age	Comment
11.04.20	46	Male	Adult	Ringed as nestling, 15.06.12, Sandøy, Møre og Romsdal
11.04.20	47	Female	Subadult	Ringed as nestling, 13.06.17, Frøya, Trøndelag
11.03.21	46	Female	Adult	
15.03.21	47	Male	Adult	
22.04.21	49	Male	Adult	
08.05.21	52	Female	Adult	
09.05.21	24	Female	Adult	
07.06.21	53	Female	Adult	
08.06.21	24	Female	Adult	
02.07.21	36	No data	No data	
09.03.22	56	Female	Adult	
13.03.22	36	Female	Young	
13.03.22	35	Female	Adult	
21.04.22	42	Male	Adult	
21.04.22	50	Male	Young	
23.04.22	35	Male	Adult	
20.07.22	46	Female	Adult	
05.09.22	64	Female	Adult	
20.02.23	5	No data	No data	
08.05.23	45	No data	Subadult	
09.05.23	33	Male	Adult	
09.05.23	24	Male	Adult	
06.06.23	2	Male	Subadult	
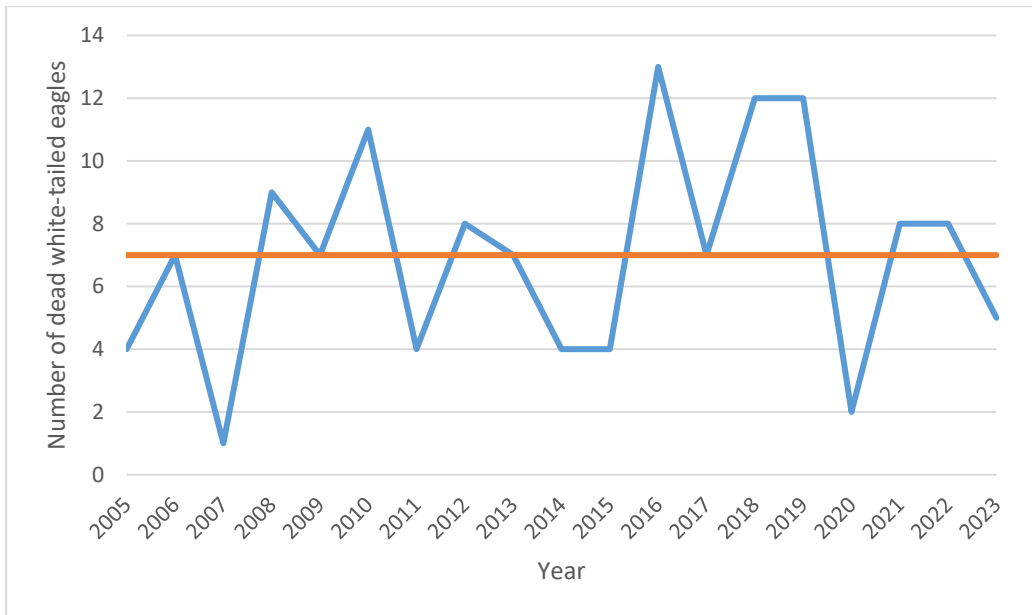
Figure 9. *Annual variation in the number of dead white-tailed eagles found at the Smøla wind farm in the period 2005–2023 (n = 133). Orange horizontal line = mean for the whole period (7).*
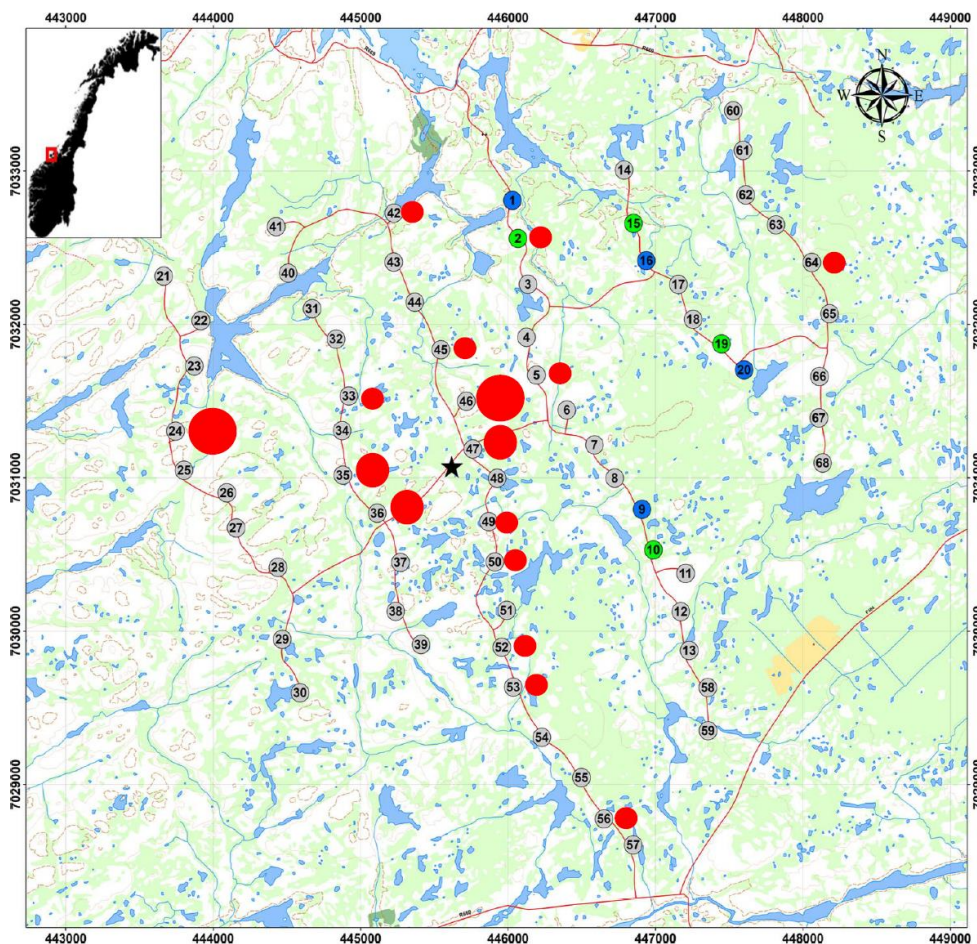

Figure 10. *Overview of the Smøla wind farm with white-tailed eagle carcasses found in the period 2020–2023. Wind turbines are in numbered grey circles and locations of carcasses of white-tailed eagles in red circles where size of circles denotes the number of individuals found (1-3). Four turbines had rotor blades painted black (blue circles) with adjacent control turbines (green circles). See also May et al. (2022). Map modified from May et al. (2020).*

3.3 DNA analyses for individual identification and parentage

During the years 2020–2023, a total of 598 moulted feathers from adult, 82 feathers collected from nestlings, three egg membranes and 24 samples of muscle tissue or feathers from dead individuals were genotyped. Successful genotyping was completed for 90% (536/598) of the moulted feathers, 96% (79/82) of the pulled feathers, 67% (2/3) of the egg membranes and 79% (19/24) of the tissue samples from dead individuals. Successful genotypes contained information from 10-15 microsatellite loci. The 536 successfully genotyped moulted feathers represented 156 different adult individuals (86 females and 70 males). Based on the parentage analyses, we further identified two additional males that were not detected through analysis of moulted feathers. The two males were detected first time as breeders in 2006 and 2012 during the previous period of DNA-based monitoring.

3.4 Encounter histories based on DNA detections

A total of 158 individual eagles were identified with the DNA-based monitoring at Smøla in the 4-year period of 2020–2023. All eagles were identified from DNA extracted from shed feathers, body tissue samples or from parentage analysis, and were therefore in an age-class of 5+ years old. The sex ratio of detected eagles was not significantly different from a 1:1 sex ratio with a total of 86 females and 75 males (binomial test, $P = 0.43$). We compiled the detection information into encounter histories for each bird. A subset of 21 of 158 individuals (13%) were first detected in the last year of the study in 2023 (0001). Thus, estimation of demographic parameters was based on 137 individuals first detected in in 2020-2022. The probability of detection was imperfect with our noninvasive methods because many individuals were overlooked in one or more years and had gaps in their encounter histories. Nevertheless, encounter histories included 34 of 137 individuals (25%) that were detected in both 2020 and 2023 and were therefore alive in all four years of the study (1111, 1101, 1011, 1001), and birds detected in multiple years were likely territorial individuals (**Table 5**). A high proportion of eagles (45%, 61 of 137) were only detected in a single year (1000, 0100, 0010) which would be expected if the population also included transient floaters. Only one eagle in the sample was confirmed as a mortality from the wind farm; a male that was detected in 2020 and 2021 but then found dead in 2022 (Havorn0100). In the encounter histories, the mortality event was coded as not available for detection in 2023.

Table 5. *Encounter histories for white-tailed eagles detected with DNA methods at Smøla in the 4-year period 2020–2023. Histories were coded as 1 = detected by DNA or 0 = not detected during the study year. Encounter histories where eagles were detected in a single year were relatively common in the dataset (1000, 0100, 0010).*

Encounter history	Females	Males	Total
1111	13	12	25
1110	3	3	6
1101	1	1	2
1100	8	5	13
1010	2	4	6
1001	4	1	5
1000	15	9	24
0111	2	3	5
0110	2	1	3
0101	1	3	4
0100	13	14	27
0011	4	1	5
0010	5	5	10
0001	12	9	21
Total	**86**	**72**	**158**

The centroid for the 68 wind turbines in the Smøla wind farm was located at 63.406°N, 7.920°E. The nesting and roosting sites where feather samples of eagles were collected for DNA analyses were located at distances between 1.2 to 18 km (median = 10.2 km) from the centroid of the wind farm. Sample locations that were < 5 km from the centroid were within the footprint and areas adjacent to the wind farm whereas locations > 5 km from the centroid had less exposure to the wind turbines.

3.5 Estimation of adult survival

The global model ϕ(tsm*time*sex), p(time*sex) was a good fit to the encounter histories for the 158 eagles that were detected with DNA sampling. The estimate of the variance inflation factor from Fletcher's c-hat procedure indicated moderate levels of overdispersion (c-hat = 2.30). Thus, we incorporated the estimate of c-hat into our model selection procedures and ranked models based on quasi-Akaike's Information Criterion adjusted for small sample sizes (QAICc, *Table 6*). Models with sex effects or annual variation in the probability of detection were ranked low and the best fit models indicated that a constant probability of detection was the best fit to the data. Models with time-since-marking effects in apparent survival were strongly supported by the data and the standard CJS model without these effects ϕ(time*sex), p(time*sex) received no support (delta-QAICc > 17, wi < 0.001). Initial inspection of the encounter histories and the parameter estimates from the best fit models indicated that the population of white-tailed eagles was likely to be a mixture of transient and resident individuals. Time-since-marking models revealed that apparent survival after first detection was much lower compared to apparent survival of returning birds. Thus, we expected that apparent survival after first detection (ϕ1 or Phi1) was likely measuring survival and site fidelity of transient birds whereas apparent survival in later years (ϕ2+ or Phi2+) was primarily based upon the resident territorial breeders. Transient birds could have been subadults or nonterritorial adults that were unmated, given the fact that only feathers from adult birds were collected at nest sites the latter is most likely, confirming the findings from Dahl (2014) that nonterritorial adults (floaters) are a considerable proportion of the total adult population and play an important role in the population dynamics in white-tailed eagle in the Smøla population.

Table 6. Model selection for alternative Cormack-Jolly-Seber (CJS) models fit to the encounter histories for white-tailed eagles at Smøla in the 4-year period 2020–2023. The two demographic parameters included apparent survival (ϕ) and probability of detection (p). Model factors included constant (con), sex, time-since-marking (tsm), and distance to the centre of the wind farm (dist). Model fit was assessed by the deviance (QDev), number of parameters (K) and quasi-AIC (QAICc). Models were then ranked by delta-QAICc values and model weights (wi).

Model	QDev	K	QAICc	Delta-QAICc	wi ≤
ϕ(tsm*year) *p*(con)	172.8	6	185.2	0.00	0.406
ϕ(tsm) *p*(con)	180.7	3	186.8	1.67	0.176
ϕ(tsm*year) *p*(sex)	172.7	7	187.2	2.07	0.144
ϕ(tsm*year) *p*(year)	172.7	7	187.2	2.08	0.144
ϕ(tsm) *p*(sex)	180.7	4	188.9	3.71	0.064
ϕ(tsm*dist) *p*(con)	179.7	5	190.0	4.86	0.036
ϕ(tsm*sex) *p*(con)	180.7	5	190.9	5.79	0.023
ϕ(tsm*sex) *p*(sex)	180.6	6	193.0	7.80	0.008
ϕ(tsm*sex*year) *p*(sex*year)	171.7	14	201.6	16.48	0.001
ϕ(sex*year) *p*(sex*year)	181.4	10	202.4	17.27	0.001

Estimates of the probability of detection from the best fit models indicated a weak effect of sex where males had a slightly higher probability of detection (0.747) than females (0.718, *Table 7*). Imperfect detection could have been due to several causes including intermittent breeding by adults, failure to collect shed feathers from an individual, or feathers in poor condition where

efforts to amplify the degraded DNA in a PCR reaction were unsuccessful. Estimates of apparent survival from the best fit models with time-since-marking effects showed a strong difference between the year after first detection (ϕ1) compared to later years (ϕ2+, **Table 7**). The complement of apparent survival includes losses to mortality and to emigration. Thus, apparent survival after first detection is expected to be low if transients are detected while prospecting for vacant territories but then emigrate from the study area. The estimate of ϕ1 was high in 2020–2021 because all birds were newly detected in the first year of the 4-year study period. However, ϕ1 was consistently lower than ϕ2+ in the years 2021–2022 and 2022–2023 when new birds could be distinguished from returning birds. Our estimates of ϕ1 (range = 0.335 to 0.455) were low compared to estimates of survival for subadult birds based on ring recoveries (range = 0.79 to 0.90, Nygård et al. 2009), and the difference was likely explained by permanent emigration of birds from the study area in our sample. Thus, we conclude that the population of eagles at Smøla likely includes a mixture of transient and resident individuals. Moreover, our two estimates of apparent survival are likely to be specific to the transient (ϕ1) and resident subsets of the population (ϕ2+). Avian flu was detected in 2022 and confirmed to cause mortality of juvenile eagles but did not appear to affect adults because the apparent survival of residents was actually higher during the year of the outbreak (2022–2023) than a year without exposure (2021–2022, **Table 7**). The overall estimate of apparent survival of adults at Smøla during the time period of 2020–2023 was 0.857 ± 0.076SE (range = 0.787 to 0.942).

Table 7. *Estimates of demographic parameters from the best fit models in the candidate set (Table 4). The three parameters include apparent survival of transients during the year after first detection (ϕ1) apparent survival in later years among resident birds (ϕ2+), and the annual probability of detection (p) with methods based on DNA sampling of feathers.*

Year	ϕ1 ± SE	ϕ2+ ± SE	Sex	p ± SE
ϕ(tsm*year) p(sex)				
2020–2021	0.769 ± 0.087	---	Male	0.747 ± 0.093
2021–2022	0.335 ± 0.123	0.787 ± 0.107	Female	0.718 ± 0.095
2022–2023	0.455 ± 0.256	0.942 ± 0.150		
ϕ(tsm) p(con)				
All	0.625 ± 0.077	0.857 ± 0.076	All	0.720 ± 0.074

We also tested for the effects of distance from the wind farm on the apparent survival of transients (ϕ1) and residents (ϕ2+). The model ϕ(tsm*dist) p(con) was lowly ranked (delta-QAICc > 4.8, wi < 0.04, **Table 6**) because the confidence intervals for the estimated relationships were relatively wide (**Figure 11**). Nevertheless, proximity to the wind farm had a clear effect on the average survival of white-tailed eagles at Smøla. The difference between transients and residents was negligible near the centroid of the wind farm but increased with distance from the wind farm. The apparent survival of transients (ϕ1) declined from 0.753 at 0 to 0.598 at 18 km (green line in **Figure 11**). A negative relationship between apparent survival and distance would be expected if territories within or near the wind farm were more likely to be vacant, or conversely, if territories outside of the wind farm were more likely to be occupied and defended by a breeding pair of white-tailed eagles. In contrast, the apparent survival of residents (ϕ2+) showed the opposite pattern and increased from 0.732 at 0 km to 0.985 at 18 km (blue line in **Figure 11**). Lower estimates of apparent survival at distances < 5 km would be expected if exposure to the wind turbines increased the mortality rates or probability of emigration among resident birds. The two demographic processes might also be linked because white-tailed eagles breed as monogamous pairs and surviving birds might be more likely to disperse after the death of a mate. Conversely, apparent survival of territorial birds might be higher at distances > 5 km because most eagle territories are now located outside the footprint of the wind farm (see **Chapter 3.1**) and territorial individuals may learn to avoid nearby turbines because collision rates are lower < 0.5 km from nest sites (Dahl et al. 2015).
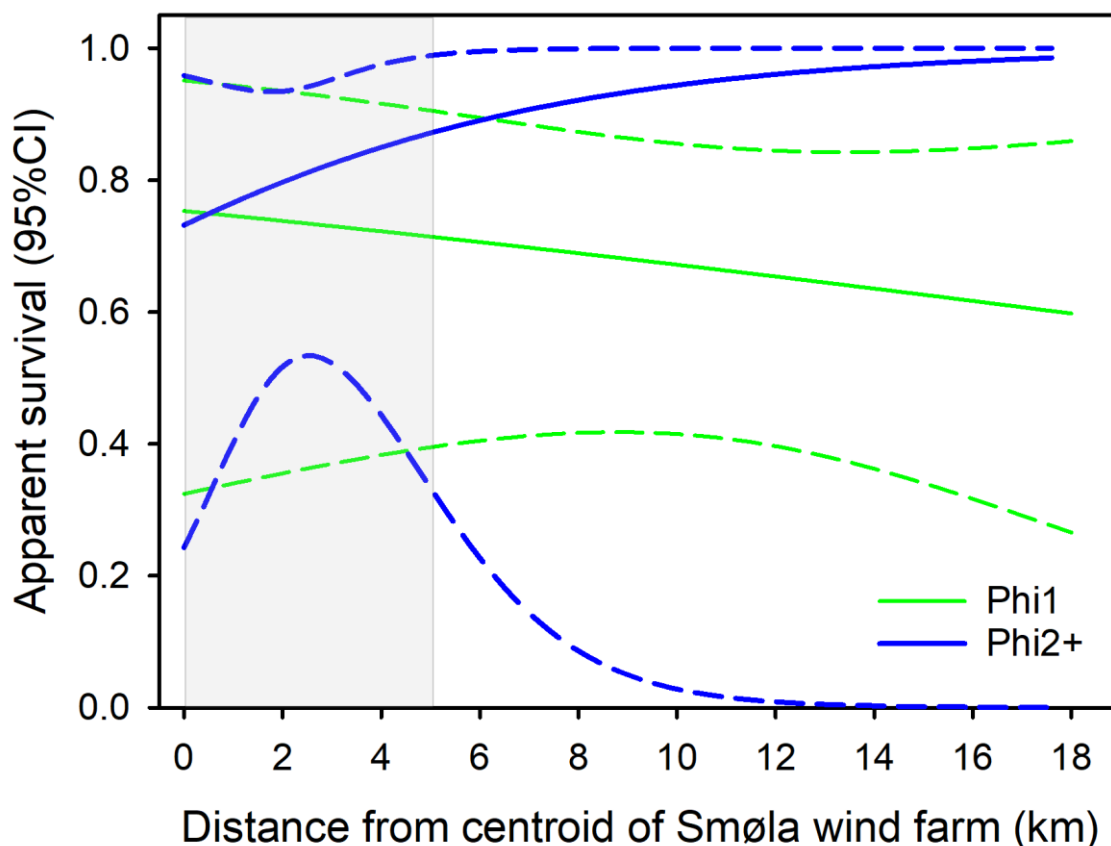
Figure 11. *Relationships between annual rates of apparent survival of white-tailed eagles and distance from the Smøla wind farm in the period 2020–2023. Parameter estimates of apparent survival (solid line) with 95%CI (dashed lines) are reported separately for the transition after first detection for transients (ϕ1, green lines) and later years for territorial birds (ϕ2+, blue lines). Parameter estimates were taken from the model ϕ(tsm*dist) p(con). The grey box from 0-5 km indicates the footprint of the Smøla wind farm and adjacent areas.*

3.6 Population modelling

We developed an age-structured matrix population model to combine our estimates of demographic parameters and to calculate the matrix properties to determine the population status of white-tailed eagles at Smøla. The matrix model included separate nodes for six year-classes of subadults and a single age-class for adults (**Figure 12**). In a matrix model with prebreeding censuses, the fecundity arc is a product of the average number of female fledglings per occupied territory and then the survival of the juvenile birds until the start of the next breeding season ($F/2*S_{juv}$). The remaining arcs and self-loops were age-specific estimates of survival for subadults (S_{1-6}) and adults (S_{ad}). We parameterized the model with estimates of demographic parameters for the two separate time periods of intensive monitoring during 2006–2011 and 2020–2023. From our intensive monitoring of white-tailed eagle territories and non-invasive monitoring of breeding pairs, we obtained independent estimates of territory occupancy, fecundity (F) and adult survival (S_{ad}) for the two time periods (**Table 8**). The two time periods did not differ in the number of territories occupied (47.5 vs. 48.0, $t = -0.25$, $P = 0.805$), number of fledglings produced per occupied territory (0.541 vs. 0.593, $t = -0.53$, $P = 0.614$), or adult survival (0.94 vs. 0.857, $\chi^2 = 1.2$, $P = 0.279$). We did not have original estimates of survival for either juveniles (S_{juv}) or subadults (S_{1-6}) and instead used published estimates based on ring recoveries and birds marked with GPS tags. It is unknown if juvenile and subadult survival changed between the two time periods and we opted to use the same estimates for both periods. We used functions for deterministic matrix models without density-dependence and a parametric bootstrapping procedure to estimate the finite rate of population change (λ), the net reproductive rate (R0) and generation time (T, years).
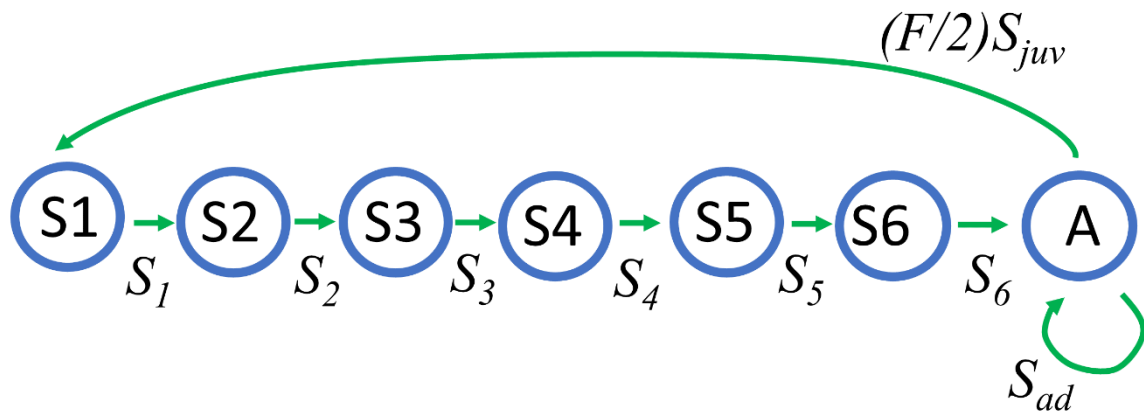
Figure 12. *Life-cycle diagram for a matrix population model based on pre-breeding surveys for white-tailed eagles. Nodes include six age-classes for subadults (S1 to S6) and adults (A) are assumed to start breeding as 7-year olds at Smøla. Age-specific demographic rates include the fecundity rates (F) measured as the number of fledglings produced per occupied territory, a constant based on a 1:1 sex ratio (½), and the age-specific survival rates of juveniles (S_{juv}), subadults (S_{1-6}) and adults (S_{ad}).*

We evaluated the population status of white-tailed eagles at Smøla for the two time periods of 2006–2011 and 2020–2023. We parameterized the model with our demographic estimates and then used functions for a deterministic population model without density-dependence to obtain estimates of the matrix properties. We then used parametric bootstrapping to obtain confidence intervals for each of the matrix properties. In 2006–2011, the estimate of λ = 1.031 and 95%CI for the finite rate of population change (1.006–1.053) were both greater than one, and the white-tailed eagle population was predicted to grow at ca. 3.1% per year (***Table 8***, Dahl 2014). In 2020–2023, the estimate of λ = 0.989 was less than one and the population would be predicted to decline at ca. 1.1% year. However, the 95% CI (0.899–1.059) included one so that the finite rate of population change was not significantly different from the rate predicted for a stationary population. Estimates of the net reproductive rate were $R0$ = 1.87 and 1.21 during the same two time periods and values of $R0$ > 1 indicate females were successfully replacing themselves each generation. The confidence intervals of $R0$ were greater than one in 2006–2011 (95% CI: 1.16–2.88) but included one in 2020–2023 (95% CI: 0.34–3.93). White-tailed eagles are long-lived birds and the estimates of generation time ranged from T = 19.9 years in 2006-2011 and 14.7 years in 2020-2023.

Table 8. *Estimates of demographic parameters for white-tailed eagles at Smøla from two time periods with intensive monitoring effort and estimates of population status from an age-structured projection matrix (see **Figure 14**).*

Population parameters	2006–2011	2020–2023	Sources
Demographic parameters (mean ± SE)			
Number of occupied territories	47.5 ± 1.5	48.0 ± 1.3	1
Number of fledglings produced per occupied territory (F)	0.541 ± 0.062	0.593 ± 0.073	1
Juvenile survival (S_{juv})	0.84 ± 0.05		2
Subadult survival (S_1)	0.90 ± 0.02		3
Subadult survival (S_2)	0.93 ± 0.02		3
Subadult survival (S_3)	0.93 ± 0.02		3
Subadult survival (S_4)	0.89 ± 0.03		3
Subadult survival (S_5)	0.88 ± 0.03		3
Subadult survival (S_6)	0.79 ± 0.05		3
Adult survival (S_{ad})	0.94 ± 0.01	0.857 ± 0.076	2, 4
Matrix properties (mean ± SE, 95%CI)			
Finite rate of population change (I)	1.031 ± 0.012 (1.008–1.052)	0.988 ± 0.043 (0.896–1.058)	
Net reproductive rate ($R0$)	1.87 ± 0.45 (1.16–2.88)	1.21 ± 1.14 (0.34–3.93)	
Generation time (T, years)	19.9 ± 1.6 (17.0–23.3)	14.7 ± 4.1 (9.5–25.2)	

Sources: 1 = Table 3 of present report, 2 = Dahl 2014, 3 = Nygård et al. 2009, 4 = Table 7 of present report.

3.7 Conclusions

In conclusion, the white-tailed eagle population at Smøla has been rather stable over the last decade. However, although not statistically significant, the finite range of population change was lower in 2020–2023 compared to 2006–2011. Both the net reproductive rate and generation time were lower in 2020-2023 than 2006-2011 but extensive overlap in the 95%CI indicated that the differences were not significant. Furthermore, both in 2006–2011 (Dahl 2014) and 2020–2023 the apparent survival of resident birds declined with closer proximity to the wind farm. Looking at the spatial distribution of nests, it is clear that the area in the vicinity of the wind farm has changed from a good breeding area to a poor one, with only a single nest in the period 2020–2023.

It has also been stated that negative effects at a single farm do not represent a threat to the regional or national white-tailed eagle population (Bevanger et al. 2016), which has been increasing (Stokke et al. 2021b). Cumulative effects in case of many such developments in prime white-tailed eagle habitats along the Norwegian coast, however, have the potential to cause negative impacts at a larger geographical scale (Bevanger et al. 2016).

4 References

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