Science Advances
AAAS

advances.sciencemag.org/cgi/content/full/5/5/eaau2642/DC1

Supplementary Materials for

Unravelling migration connectivity reveals unsustainable hunting of the declining ortolan bunting

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Supplementary Texts 1 and 2
Fig. S1. Boxplot of average δ^2H_f in body coverts/scapulars of ortolan buntings captured during the breeding season by country where birds were captured (birds captured in Israel and Kuwait were spring migrants).
Fig. S2. Genetic assignment of breeding individuals to the eastern, western, and northern clusters following cross-validation.
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Other Supplementary Material for this manuscript includes the following:

(available at advances.sciencemag.org/cgi/content/full/5/5/eaau2642/DC1)

Data file S1 (Microsoft Excel format). Estimates of population sizes and trends.

Supplementary Text 1

Ring recoveries

Foreign ring recoveries of the French CRBPO database are available at www.crbpodata.mnhn.fr

We know that the origin and numbers of ortolan buntings ringed across Europe and further recovered in France is highly biased by heterogeneous ringing effort on breeding populations, and heterogeneous recapture efforts in France (concentrated in Les Landes). However, it is interesting to present here a summary of these ringing recoveries. Mapping these ringing recoveries indicate that most ortolans captured in Les Landes originated from western breeding populations.

Norway provided eight recoveries of birds all ringed in May or June, so during the breeding season. Indeed, the ringing effort was important in Norway where Svein Dale has monitored a breeding population during many years. Seven of these ring recoveries have been obtained between 1993 and 2005.

Sweden provided seven recoveries, of five individuals ringed during the breeding season, and two ringed at the end of August on islands known as migratory stopovers. These two birds probably came from farther north.

Of the nine recoveries from Finland, three have been recovered in the spring in Lot-et-Garonne and Gers. Eight of these recoveries were obtained before 1973, and only one later, in 1987. These Finnish recoveries indicate that some birds breeding in Finland do migrate by Les Landes i.e. the Atlantic route, though data from light loggers indicate that these are a minority of the total national population. This was also the case when the Finnish breeding population was far larger than nowadays, as it declined by ca. 90% during the last several decades. Furthermore, it is possible that a larger proportion of the Finnish population used the Atlantic flyway in the earlier decades.

One chick ringed in Estonia was caught two and a half months later in Les Landes in 1991.

Russia provided one ring recovery, of a bird ringed at Gumbaritsy, Leningrad region (60.68°N, 32.95°E), but late in August (26 August 1986) so that the bird was already in migration, before being captured on 21 September in Les Landes.

One bird ringed in Poland in May was recovered in Les Landes in September four years later, and three birds ringed in Germany in May-July were also captured in Les Landes in September of the same year (2) or the year after ringing (1).

Seven of the eight recoveries from Italy are birds ringed during the spring migration in Italy (end of April early May), and recovered another year in Les Landes. Only one bird was ringed during the autumn migration in Italy (23 August 1993), and captured three weeks later in Les Landes (14 September), suggesting that some individuals might sometimes switch from the Mediterranean to the Atlantic route.

The six recoveries from Belgium are of birds ringed there during the autumn migration, so of birds in migration along the Atlantic route.

Supplementary Text 2

National population sizes and trends using the flyways

To estimate the numbers and associated trends of ortolan buntings using the eastern and the western flyways, then also the Mediterranean and the Atlantic routes of the western flyway, we used estimates of population sizes as published in *(9)*, updated in a few cases as explained below.

As a summary for figures not given in the main text, the eastern flyway drains breeding populations from Russia and all countries east of the migration divide, representing 4,283,250 pairs (range 2,907,250 to 6,310,500) and their offspring down to winter across highlands of Ethiopia and Eritrea. This represents 90% of European ortolan buntings *(9)*, with a recent (2000-2014) population trend estimated between -10% and -20%. Contrastingly, only ~468,700 pairs (354,622 to 619,479) breed west of the migration divide *(9)*, representing the remaining 10% of the European population, with a recent decline between -10% and -20% (2000-2014). The western flyway thus drains birds breeding mainly in Fennoscandia, the Baltic States, Poland and Germany, Italy, France and the Iberian Peninsula. They winter in West Africa (Sierra Leone to Guinea, also Senegal and southern Mauretania), while an unknown part of these western populations follows a third central flyway down to Italy and Tunisia/Libya to winter across highlands of northern Nigeria. Along the western flyway, birds carrying loggers revealed the use of two distinct routes. The more western a breeding population, the more Atlantic its migration route, and only western breeders use an Atlantic route crossing the Pyrénées at their western end. Less western breeders (e.g. most Finnish and Baltic ortolan buntings) use a western by Mediterranean route, flying over eastern Poland to northern Italy, then following the Mediterranean coast before reaching Africa; they do not visit southwest France.

Eastern flyway

By summing the breeding population sizes from European countries where ortolan buntings use the eastern flyway, we obtain a breeding population size of 4,283,250 pairs (2,907,250 to 6,310,500 pairs). The main contributing countries are Russia, Turkey, Romania, Bulgaria, and Azerbaijan. The global European population size is estimated at 4,754,440 breeding pairs (3,262,000 to 6,930,000 pairs), so the eastern flyway is used by 90% of European ortolan buntings.

By comparing the current population estimates to those published earlier, recent average trend of these eastern flyway populations gives a small increase by 10.6%, though comparing the sums of the upper and lower limits of previous and current national population sizes gives a range of -4% to +27%. This eastern population could be either in small decline, or increasing. However, it should be noted that the main trend comes from the Russian population, for which comparison of previous vs current estimates gives +7% (-14% to+33%), while Russian experts generally agree that the population has declined by 15 to 30%. As Russia holds two thirds of this eastern flyway European population, it is wiser to consider that the eastern flyway population is decreasing, probably by 10 to 20%.

Western flyway

Note 1: here we considered that birds from the western side of the species range use the western flyway, though there are certainly some populations included here using a central flyway to winter in Nigeria – probably populations from Italy, countries around the Adriatic Sea, Austria and Hungary, and possibly part of the populations breeding in Poland, in other central European countries and in Finland. The values given for the western flyway are therefore highly conservative in the sense that the real population size using the western flyway is lower. It is however possible that some breeders of western Belarus (500-1000 pairs) use either the western or the central flyway, though we have no evidence for this in this study, and it would concern only small numbers not likely to change the global picture.

Note 2: compared to *(9)*, we have actualized the breeding population size for Poland. Two different sources (the recent atlas of breeding birds, and an analysis of densities conducted by Jakub Kosicki) are congruent in estimating the national population size of ortolan bunting in Poland to 154,000 pairs (140,000 to 171,000 pairs). The values published previously of 197,000 to 298,000 are therefore overestimates, as even Polish experts do not understand where this estimate comes from. In our work, we now consider these updated estimates for Poland (in the following calculations). References to be consulted are *(19,20,21)*.

Note 3: methods to obtain estimates of population trends. We used two ways to calculate average multi-national population trends. First, we calculated the geometric mean of the lower and upper values of a national population size range estimates, and summed these means among countries. We further compared the trend of this summed geometric mean between 2000 and the most recent year considered (generally 2012 or 2014). We did the same for the lower values of the national population size range, and the same for the upper values. Second, we calculated the mean of national trends weighted by national population size (the weights being the geometric means of national upper and lower values, or the lower values, or the upper values). The recent national trends are those reported by each country, which are not a direct comparison of current and previous population sizes, but come from dedicated monitoring of breeding birds, such as breeding bird surveys (in most countries; France, Spain, Poland, Finland, Sweden, Norway), or comparison of densities found on sampled sites (Russia, Germany). Trend values have been rounded to the nearest unit on a percentage scale.

Global western and central flyways

By summing the national population sizes of all countries lying west of the identified migration divide, we obtain an estimate of 468,701 breeding pairs (354,622 to 619,479). This represents ca. 10% of the European breeding population size.

The post-2000 trend of these populations is:
- comparison of geometric means: -10% (-13% for the lower values, -6% for the upper values);
- weighted means of national trends: -18% (-18% for the lower values, -17% for the upper values).

Numbers and trends over France

Within the national populations breeding west of the migration divide, we then considered that birds breeding in Portugal, Spain, Italy, Andorra, Slovenia and Croatia do not migrate over France. Therefore, the population size susceptible to be migrating over France is estimated at 194,070 pairs (165,598 to 227,435).

The post-2000 trend of these populations is:
- comparison of geometric means: -32% (-17% for the lower values, -45% for the upper values);
- weighted means of national trends: -25% (-24% for the lower values, -26% for the upper values).

Given the similarity of the estimates obtained with the two methods, we are confident that the global trend of these populations is between -25% and -32% (a decrease by one quarter to one third).

Numbers and trends over southwest France

There are 15 countries holding ortolan bunting breeding populations likely to migrate over France. Geolocators have revealed that the majority of Finnish breeders use a Central European/Mediterranean route, and do not visit southwest France, and some of them even use a central flyway. In Sweden, 3 out of 11 used this Mediterranean route while all German tracks used the Atlantic route, thus over southwest France. In Poland, one track follows a Mediterranean route, another bird migrated southwards along the third central flyway, while one Polish bird with a logger was caught by a hunter in 2014 in Les Landes. To be able to obtain an estimate of how many birds do visit southwest France during migration, we therefore propose three scenarios, considering that only a part of some national populations use the Atlantic route, while another part uses a Mediterranean route (or even the central flyway). Typically, birds using the Atlantic route enter France between Nord and Alsace departments, while birds using the Mediterranean flyway enter France – if they do - at the Alps or along the coast from Italy. In all three scenarios, we considered that most of the French breeding population uses the Mediterranean route, while the 100-200 pairs breeding in central and western France (mainly in Poitou-Charentes) use the Atlantic route.

Map explaining how we shared the French breeding population between the Atlantic and the Mediterranean routes of the western flyway. Background map from the recent Atlas of birds of France *(22)*:
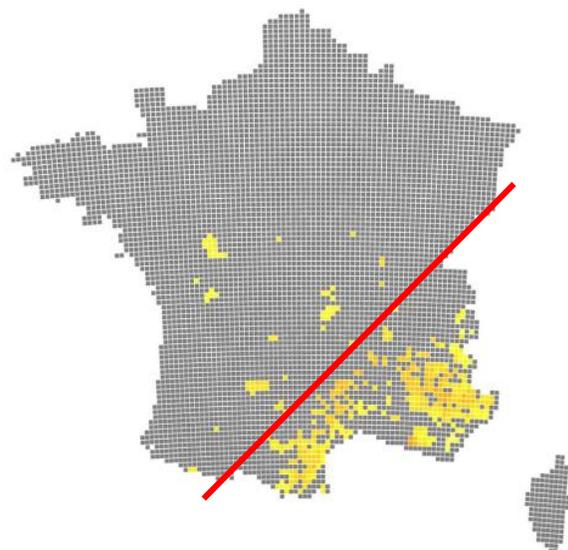
The three scenarios considered that the following proportions of national population sizes were migrating by the Atlantic route:

Scenario 1:   Finland and Baltic states (Estonia, Latvia and Lithuania) 0%
Sweden 60%
Poland 20%
Germany, Norway, Czech Republic, Austria, Switzerland 100%
France 100-200 pairs

This scenario applies if there is a confirmed central flyway used by birds from Poland, and in normal years, or years of western winds, when Finnish, Baltic and eastern Polish birds all use the Mediterranean route.

In this scenario 1, the population size susceptible to migrate over southwest France is estimated at 46,446 pairs (40,254 to 53,591). The post-2000 trend of these populations is:
   - comparison of geometric means: -11% (+8% for the lower values, -26% for the upper values);
   - weighted means of national trends: -17% (-17% for the lower values, -16% for the upper values).

Scenario 2:   Finland and Baltic states 20%
Sweden 80%
Poland 40%
Germany, Norway, Czech Republic, Austria, Switzerland 100%
France 100-200 pairs

This scenario considers that ringing recoveries from Finland attest that some Finnish birds do migrate by les Landes, at least in some years, despite the light loggers we retrieved did not confirm this is the usual route. For Sweden, this scenario reflects the proportions of the tracks obtained with light loggers, while for Poland it considers that less than half of the breeding birds do use the Atlantic route, which is very conservative given the geolocation data obtained in this study.

In this scenario 2, the population size estimated to migrate over southwest France is 81,325 pairs (70,255 to 94,140).

The post-2000 trend of these populations is:
   - comparison of geometric means: -22% (-5% for the lower values, -35% for the upper values);
   - weighted means of national trends: -21% (-20% for the lower values, -21% for the upper values).

Scenario 3:   Finland and Baltic states 40%
                      Sweden 100%
                      Poland 60%
                      Germany, Norway, Czech Republic, Austria, Switzerland 100%
                      France 100-200 pairs

This scenario considers that in some exceptional years, strong eastern winds could force most of the western breeding populations to use the Atlantic route.

In this scenario 3, the population size likely to migrate over southwest France is estimated at 116,289 pairs (100,255 to 134,888). The post-2000 trend of these populations is:
  - comparison of geometric means: -25% (-10% for the lower values, -38% for the upper values);
  - weighted means of national trends: -22% (-22% for the lower values, -23% for the upper values).

We propose to consider the mean estimate of the medium scenario as the average population size, and the mean estimates of the lower and upper scenarios (1 and 3) as the lower and upper values of population sizes. As a consequence, the population size of ortolan buntings migrating by southwest France is estimated at 81,000 pairs (range 46,000-116,000). In our calculations, ~75% of these birds do come from Poland, so Poland is the main country contributing to this route. All three scenarios are congruent in estimating the recent decrease of these breeding populations by one fifth to one quarter (-20% to -30% during the last 14 years).

A further way to estimate the recent trend of the populations migrating over southwest France is to use the genetic assignments (1/3 of Nordic individuals, 2/3 of central/western individuals), and to weight the regional trends of these northern and central/western populations by these proportions. The regional trend for [Finland, Sweden, Norway, Estonia, Latvia and Lithuania] is -53% since 2000 (national trends weighted by national population sizes). The regional trend for [France, Germany, Poland, Czech Republic, Austria] is -19%. Then the average recent trend of the populations migrating over south-west France would be estimated as -30%, which is consistent with the estimates obtained by comparing population sizes.

Indeed, the recent trend of these populations can be estimated between -20% and -30% (2000-2014). This represents an average decrease of nearly 1.4% to 2.1% each year. This means that the population size using the Atlantic route of the western flyway is on average currently decreasing by ~1,500 pairs (3,000 mature adults) each year.
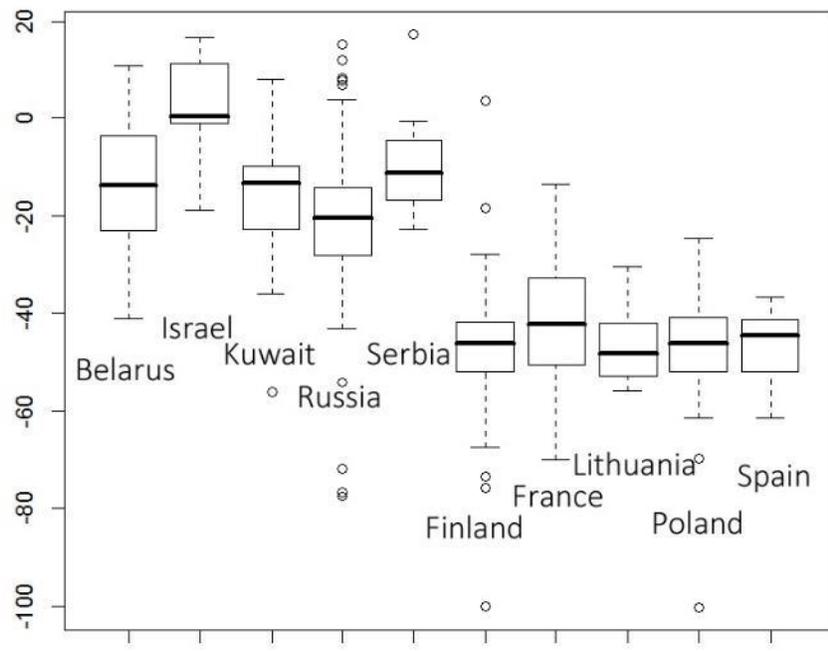
Fig. S1. Boxplot of average δ^2H_f in body coverts/scapulars of ortolan buntings captured during the breeding season by country where birds were captured (birds captured in Israel and Kuwait were spring migrants).
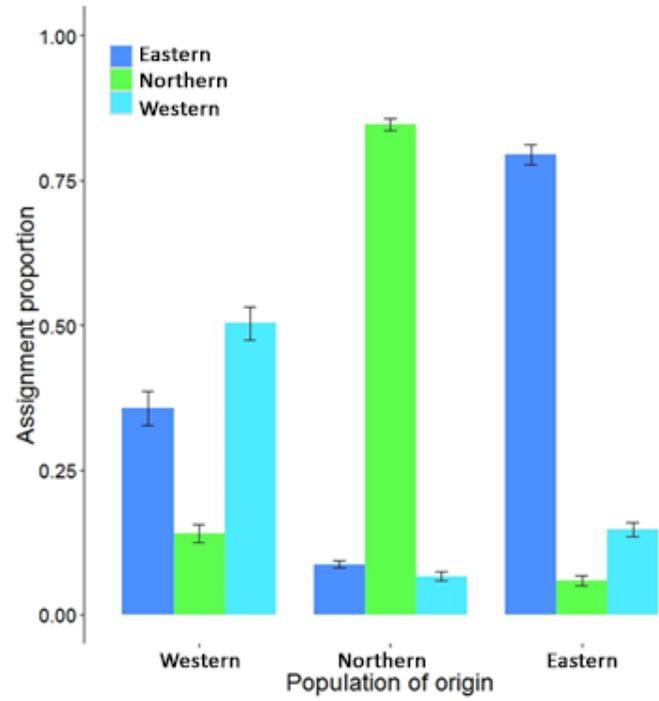
Fig. S2. Genetic assignment of breeding individuals to the eastern, western, and northern clusters following cross-validation.
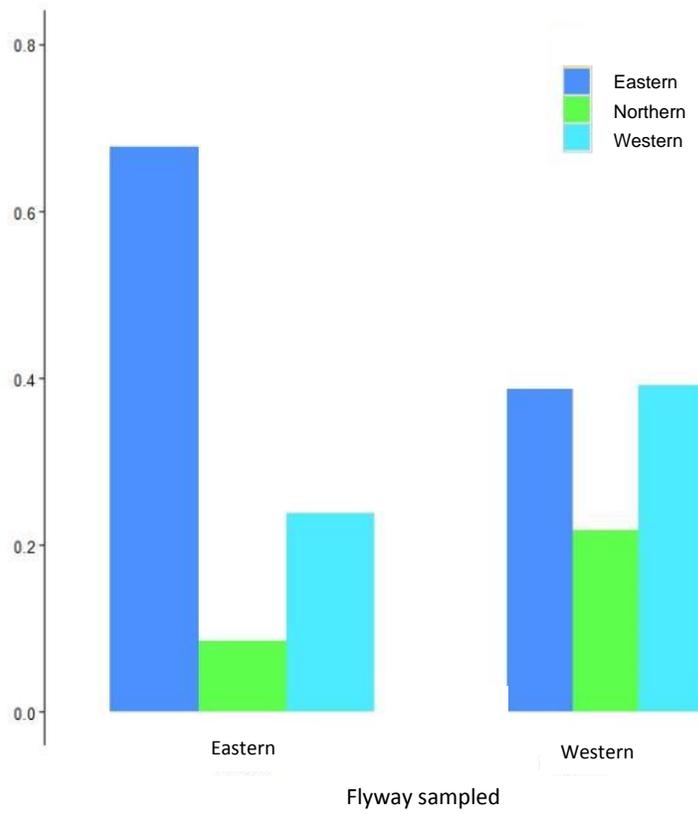
Fig. S3. Genetic assignment of individuals sampled during migration along the eastern and western flyways to a breeding population.
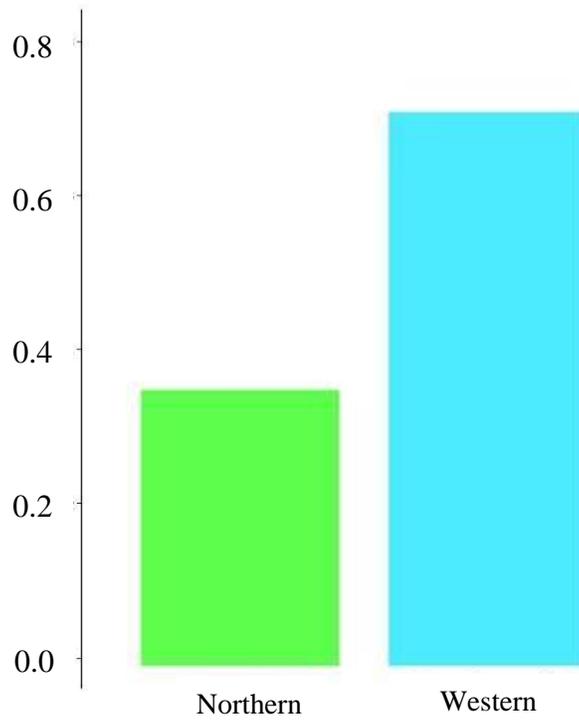
Fig. S4. Genetic assignment of individuals sampled during migration in France (western flyway) to a breeding population other than the eastern cluster (as stable isotopes and archival light loggers excluded an eastern breeding origin for western migrants).
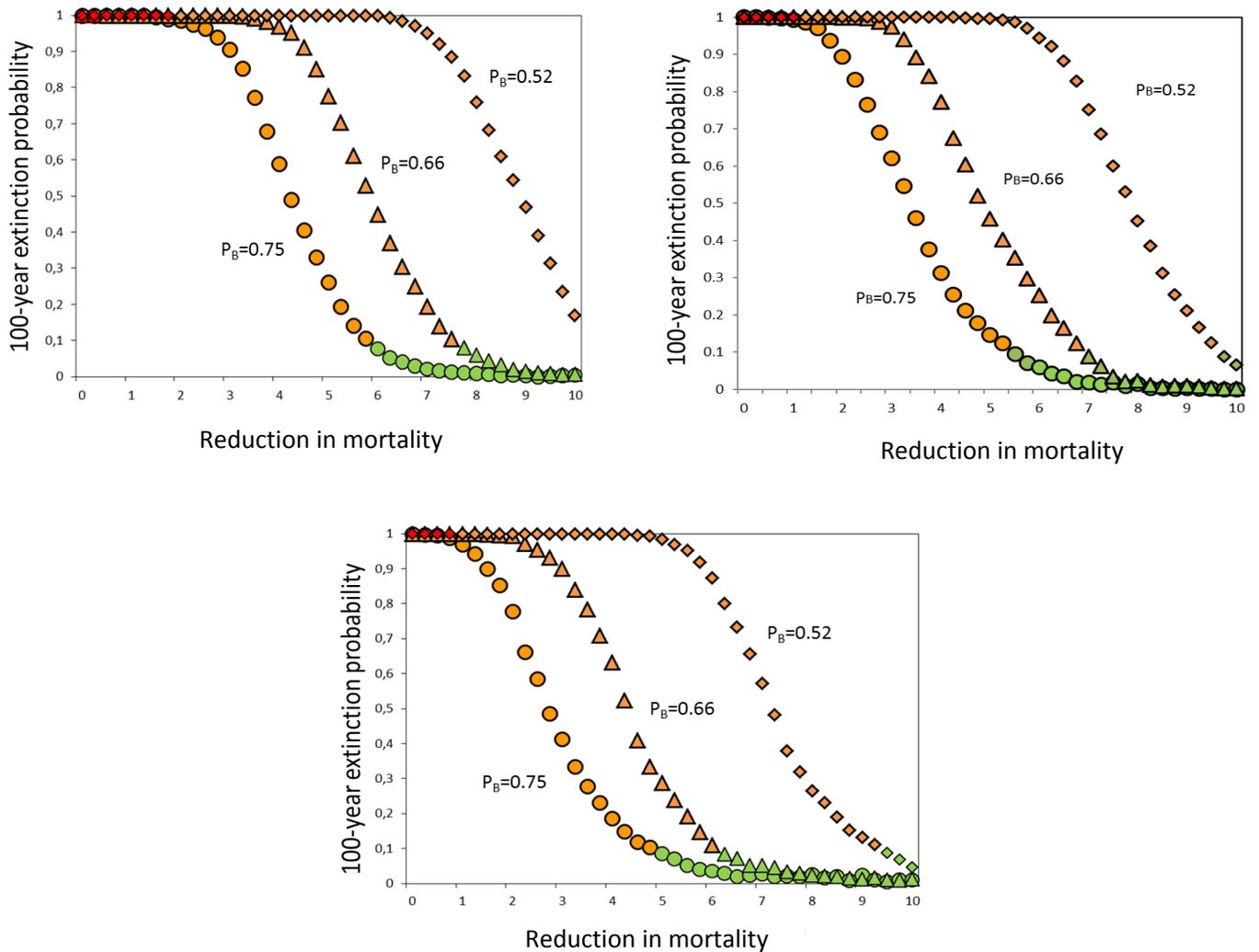
Fig. S5. 100-year extinction probability for various demographic and hunting scenarios. Effect of mortality reduction on the projected 100-year extinction probability for various scenarios of operational sex-ratio (diamonds, PB=0.52; triangles, PB=0.66; circles, PB=0.75) and clutch size (upper left panel, CS=4.25; upper right panel, CS=4.57; lower panel, CS=4.9). The absolute decrease in mortality probabilities of adults and juveniles (X-axis) is expressed in points of the mortality percentage. Colors indicate the IUCN red list status of the population based on criterion E estimated from extinction probabilities after 10, 20, 100 years, 3 generations and 5 generations (green: Least Concern; orange: Vulnerable; red: Endangered). See Material and Methods for further details.

Table S1. Number of geolocators deployed and retrieved by country (region) and year when data were retrieved from the logger and logger model.

Country	Year	SOI loggers	INTIGEO loggers
Belarus	2016	1	1
Finland	2016	5	3
Finland	2017		1
France	2015	1	
Germany	2014		1
Germany	2015		17
Lithuania	2016		1
Norway	2014	1	
Poland	2016	2	
Russia – Vladimir	2016		1
Russia – Vladimir	2017		3
Russia – Belgorod	2016		5
Russia – Volgograd	2016	4	2
Spain	2016	2	
Sweden	2013	1	3
Sweden	2014		6
Sweden	2015		2

Table S2. Summary of base demographic parameters values for Vortex population viability analysis.

Parameter	Value or option
Mating system	Monogamous
Age at first reproduction	1 year for both sexes
Age at last reproduction	20 years for both sexes
Maximum clutch size	6
Sex ratio at birth	1:1
Percent breeding	52.4 (SD = 4.5)
Exact distribution of clutch size within the population	1 = 0%; 2 = 2%; 3 = 14%; 4 = 43%; 5 = 41%; 6 = 0%
Juvenile (0-1 year) mortality probability for both sexes[1]	82.4 (SD = 6.3)
Adult mortality rate for both sexes	36 (SD = 7.1)
Males in breeding pool	100%
Initial population size	400
Carrying capacity	2000

1: includes both pre- and post-fledging mortality

Table S3. Best model structures for survival analyses. Model selection was based on the Akaike's Information Criterion (AICc). AICc differences between the best model and the next candidate model (ΔAICc), deviances and number of parameters (np) are reported.

Model	ΔAICc	deviance	np
Φ(i) Psi(f) P(f+t) A(f)	0	2613.18	18
Φ(f) Psi(f) P(f+t) A(f)	2.06	2613.16	19
Φ(f.t) Psi(f.to.t) P(f.t) A(f)	43.1	2567.07	59