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Article

Mitigating Acute Climate Change Threats to Reintroduced Migratory Northern Bald Ibises

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Abstract: For the past 20 years, reintroduction efforts have been underway to reestablish a migratory population of Northern Bald Ibises (*Geronticus eremita*) in Central Europe, which now consists of more than 250 birds. They breed both north and south of the Alps and migrate to a common wintering ground in Tuscany. Recently, the start of autumn migration is increasingly delayed, which correlates with extended warm periods in autumn. Later in the year, however, the birds no longer find sufficient thermals to cross the Alps and remain in the northern Alpine foothills. In order to save their lives, we had to capture the affected birds before onset of winter, which is not a sustainable solution. A new approach to solving the problem is the establishment of a second migration route to a wintering area in Andalusia, Spain, connecting our population with a sedentary population there. The new migration route bypasses mountain barriers and allows the birds to reach the wintering grounds also later in the year. The modelling of a pan-European population will provide the birds with high ecological and spatial flexibility. Our project exemplifies the consequences of advancing global warming for animal populations and the associated challenges for conservation projects.

Keywords: northern bald ibis; conservation; climate change; translocation; bird migration

1. Introduction

Conservation translocation has been developing into a well-established and diverse discipline of animal and plant conservation [1]. Due to the increasing anthropogenic influence on all habitats, translocations of endangered species or reintroductions of extinct in the wild species are becoming more and more the last remaining options to prevent the extirpation of a species [2]. The progressively clear influence of climate change is intensifying and accelerating this development [3]. Therefore, the need for creative and innovative methods in species protection is becoming ever greater and more urgent [4].

Historically, the Northern Bald Ibis (*Geronticus eremita*; Figure 1) inhabited extensive areas around the Mediterranean. Wintering sites were known along the African west coast down to Mauritania and Senegal and along the east coast down to Eritrea and Ethiopia [5–7]. Human influence and climate change caused the extinction of the Egyptian population already by the end of the third millennium BC and the European population in the early 17th century [7]. Subsequently, the species went extinct in most of the remaining regions during the 20th century, except for a small population with two colonies on the Moroccan Atlantic coast, which, however, have transitioned to a sedentary lifestyle [8–10]. Due to the massive population decline the species was listed as critically endangered on the IUCN Red List for 24 years before being downlisted to endangered in 2018, due to successful conservation efforts in Morocco and elsewhere.

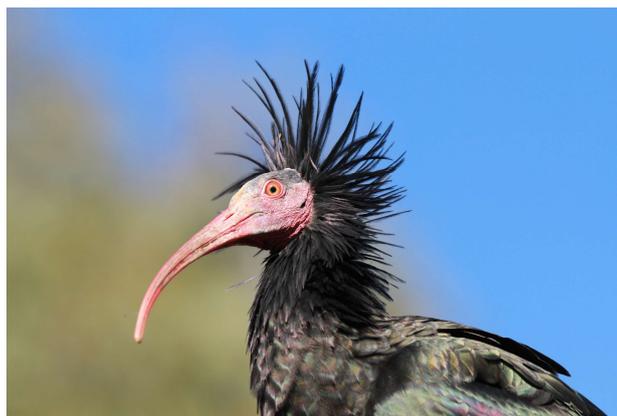


Figure 1. Northern Bald Ibis portrait, J. Fritz.

Since the early 1950s, approximately 100 juveniles have been imported from former breeding colonies in the Moroccan Atlas to European zoological gardens. These individuals served as founders of the captive population, which grew over time to several thousand individuals [11]. Thus, the Northern Bald Ibis is an outstanding example of the increasingly important role of zoological gardens in species conservation [12]. Well-managed zoo populations provide the opportunity to conduct research and ultimately transfer individuals back into the wild. In 2018, a comprehensive study on Northern Bald Ibis genetics was published indicating that despite the relatively small number of founding individuals the European zoo population is genetically highly structured and, thus, forms a good basis for translocation measures [13].

As a migratory species, the Northern Bald Ibis exhibits genetically determined migratory restlessness [14], strong navigation skills and persistent, energy-efficient flight techniques [15–19]. These traits persist even after generations of captivity in zoos, where they cannot perform migratory behaviour. However, juveniles rely on experienced conspecifics during their first autumn migration to reach a suitable wintering region. Therefore, the spatial orientation of migration and its destination are primarily socially learned traditions passed down through generations [7]. However, the historic migratory traditions have been lost with the extinction of all wild migratory populations.

Since 2002, a European conservation translocation project, co-funded by the European Union's LIFE-program, aims at re-establishing a self-sustaining migratory Northern Bald Ibis population in Europe. This endeavour marks the world's inaugural attempt to reintroduce a migratory bird species that had gone continentally extinct.

However, a recent trend towards a progressively delayed onset of autumn migration has emerged. This shift towards an ever later migration has no noticeable negative effects on birds breeding south of the Alps, they migrate later in the year but reach the common wintering area in Tuscany safely. However, it does cause increasing problems for birds breeding north of the Alps, where an ever-larger number fails to cross the Alps during the autumn migration despite repeated attempts. Ultimately, they remain north of the Alps, which poses a threatening situation since these birds hardly survive the winter in this region.

In view of this development, we were required to take emergency measures in order to avoid serious losses. This involves capturing the birds remaining in the north in time before the first onset of winter, transferring them with cars across the Alps, and releasing them at the southern foothills. It saves their lives, but it was clear that this elaborate management cannot be a sustainable strategy. Therefore, we came up with a mitigation measure to ensure the sustainable, independent survival of the population in the face of progressive climate change. Together with our Spanish partners from Proyecto Eremita who are establishing a sedentary Northern Bald Ibis colony in Andalusia [11,20] we aim for a migratory tradition from the northern Alpine foothills towards Andalusia. This route does not involve any mountain barriers and therefore enables birds from the breeding grounds in the northern Alpine foothills to reach their wintering grounds even late in the year.

In this paper we report on the Northern Bald Ibis reintroduction so far, we address the increasing impact of climate change to the migratory Northern Bald Ibis population, and outline the measures implemented to mitigate this growing adverse effect on the population.

2. Materials and Methods

Project implementation

The reintroduction of the Northern Bald Ibis started in 2002 with a feasibility study according to the IUCN guidelines for reintroductions and other conservation translocations [50]. From 2014 to 2019 a first European LIFE-project was successfully implemented (LIFE+12-BIO_AT_000143) and in 2022, a second LIFE-project started with a duration of seven years (LIFE20 NAT/AT/000049; www.waldrapp.eu). It is implemented by ten European partners under leadership of Zoo Vienna (www.zoovienna.at). The private company Waldrappteam Conservation & Research (www.waldrappteam.at) is in charge of the overall management and implements the human-led migrations.

Human-led migration

The human-led migration is the main translocation method used. Its objective is to establish a new social tradition using founder birds from zoo origin (F0) [21,22]. The method involves hand-raising of up to 36 chicks per season by two human foster parents. We practice socially involved hand-raising [23], where the foster parents are engaged in intensive interactions with the birds without the use of disguises or dummies. This ensures a close social bond between the foster parent and each of the birds, which is a crucial requirement for the human-led migration. Contact of the birds to any other human is strictly prohibited to avoid general habituation to humans. Birds raised in this manner establish a long-lasting close relationship with the foster parents while remaining shy and reserved towards other humans.

After fledging, the birds undergo a comprehensive step-by-step training program designed to teach them to follow double seated microlight aircraft, called paraplanes (Figure 2), with a foster parent on the back seat. These aircraft are equipped with a large parachute, allowing them to fly speeds of 40-45 km/h, matching the birds' flight speed.



Figure 2. Human-led migration; H. Wehner.

In early August, the birds enter a state of migratory readiness, reaching their maximum body weight and increasing the level of corticosterone, the main regulatory hormone for bird migration [14,24,25]. Soon after, the human-led migration begins, dependent on appropriate weather conditions. The journey is divided into flight stages with intermediate stopover days. During stopovers the birds stay in a spacious aviary, cared for and fed by their foster parents.

Upon arrival at the wintering site, the birds remain in an aviary for several weeks to acclimate before they are released. They typically return to their breeding area by their third year when they reach sexual maturity. However, some of the subadults make explorative flights for a part of the route or even return to their breeding area.

Biologging and monitoring

Since 2016, the majority of birds are equipped with solar-powered commercial GPS devices [26]. Due to significant aerodynamic and health issues caused by fixation of the devices on the upper back via a wing-loop harness [27,28], all tags are now positioned on the lower back and fixed via a leg-loop harness made of Teflon tube. The data is automatically transferred to the open-source animal movement platform *Movebank* and the freely accessible App *Animal Tracker*.

Data analysis and statistics

All analyses were carried out using data from our internal database. Statistical analysis was done with the freeware statistical software R (<https://www.R-project.org/>).

Ethical note

Bird care, keeping, training, and release follow well-established standards in accordance with the legal framework and under the supervision of Waldrappteam Conservation & Research experts. Translocation and management measures were implemented in the framework of European LIFE-projects (LIFE + 12-BIO_AT_000143 & LIFE20 NAT/AT/000049, LIFE NBI). National approvals were provided by the provinces of Salzburg (21302-02/239/352-2012) and Carinthia (11-JAG-s/75-2004), as well as by Baden-Württemberg (I1-7.3.3_Waldrapp), Bavaria (55.1- 8646.NAT_03-10-1), and Italy (0027720-09/04/2013).

3. Results

3.1. Reintroduction of a Migratory Population

From 2004 to 2022, a total of 15 human-led migrations from different sites in the northern foothills of the Alps to the WWF Oasis Laguna di Orbetello in southern Tuscany, Italy (42.425484°N, 11.232662°E), as the common wintering site, were carried out. The mean duration of the migration journeys was 25 ± 10 days, with a mean of 8.5 ± 4.7 flight stages. The mean total distance was 927 ± 215 km with a mean of 139 ± 56 km per flight stage. In the frame of these migrations, we released a mean of 18.5 ± 9.1 juveniles per season, 277 juveniles in total. The released birds are descended from nine European zoo breeding colonies, with the majority of 74% coming from Rosegg Zoo in Carinthia, Austria (<https://www.rosegg.at>).

Since 2011, a steadily increasing number of wild living birds are migrating between the wintering site in Tuscany and four breeding areas, Kuchl (country of Salzburg, AUT; 47.633790°, 13.160413°), Burghausen (Bavaria, GER; 48.156356°, 12.825322°), Ueberlingen (Baden-Wuerttemberg, GER; 47.780569°, 9.128938°) and Rosegg (Carinthia, AUT; 46.585935°, 14.021097°). Since 2011, birds breed successfully in the wild. So far, 324 birds fledged in the wild (2011-2023), with 74 fledglings in 2023 (Figure 3). Detailed demographic data have been available since 2014. Since then, the survival rate from hatching to fledging is 86 ± 5 percent (2014-2023). The mean fecundity is 2.46 ± 0.45 fledglings per nest (2014-2023). Breeding success tends to increase with a fledging rate of 2.96 in 2023.

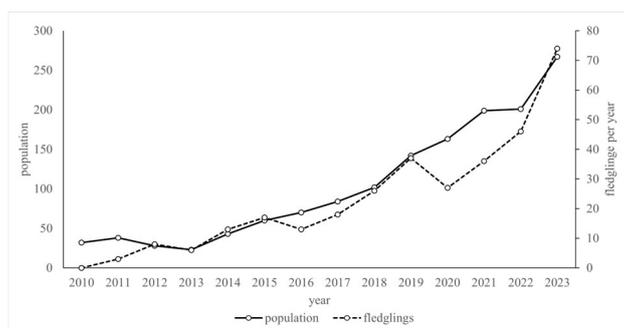


Figure 3. Demography and Reproduction. Solid line: size of the Central European Northern Bald Ibis population; dashed line: number of fledglings per year. By end of 2023 the population comprised 256 individuals, including the fledglings of that year.

Since 2014, extensive remote monitoring by use of GPS devices has enabled a detailed analysis of mortality. For $55 \pm 17\%$ of the losses (2014-2023) the cause of mortality could be identified. Main

mortality causes are electrocution on medium voltage power poles ($36\pm 16\%$), collision and injuries ($25\pm 20\%$) and illegal bird hunting in Italy ($17\pm 7\%$). The proportion of collision and injuries varies greatly over the years depending on stochastic events such as storms and severe weather, with an annual proportion ranging from 7% to 78%.

End of 2023, the population comprised 256 individuals (Figure 3), with 54% of the birds raised by human foster parents and released (founders; F0) and 46% raised by their biological parents in the wild (successors; F1-F3).

3.2. Timing of the Autumn Migration and Immediate Emergency Measures

Over a span of 12 years, from 2012 to 2023, the onset of the autumn migration for birds of the three breeding colonies in the northern Alpine foothills has shifted significantly by more than a month (Linear Model, multiple $R^2=0.5757$, $t=3.68$, $p=0.0042$; Figure 4).

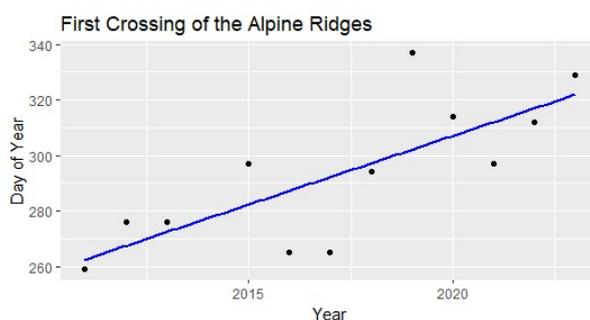


Figure 4. Shift of the autumn migration. The diagram shows the respective day of the year, when the Northern Bald Ibises of the Central European population first attempted to cross the Alps during autumn migration from the years 2011 to 2023. The trend line indicates a strong shift into the later part of the year.

As the number of birds lingering on the northern edge of the Alps at the onset of winter increased, we were compelled to implement an adaptive emergency measure. This involves capturing the birds remaining in the north in time before the first onset of winter. The capture process involves the use of a remote-controlled feeder and an enclosure with a drop gate (Figure 5). The birds are immediately placed in individual boxes and transferred in a car across the Alps. On the southern edge of the Alps, they are released. Most of the released birds immediately fly further south on a direct course toward the wintering area. In this way, a total of 211 birds have been rescued during the years 2017 to 2023, with 40 birds alone in 2023.



Figure 5. Caching of remaining Northern Bald Ibises in the Alps; remote-controlled mealworm dispenser in a fence with remotely controlled trap-door, J. Fritz.

3.3. Initial Human-Led Migration to Andalusia

On August 21 in 2023, a human-led migration with 35 hand-raised and trained Northern Bald Ibises started from the airfield Binningen near the breeding colony in Ueberlingen at Lake Constance. The journey of 2.319 kilometres was covered in 19 flight stages with an average stage length of 122 kilometres and a total duration of 43 days (Figure 6). Three birds were lost during flight stages in

Spain. On October 2, the team reached the final landing site in Barbate, Andalusia, with the remaining 32 birds. After habituation in a large aviary the birds were finally released in early December.

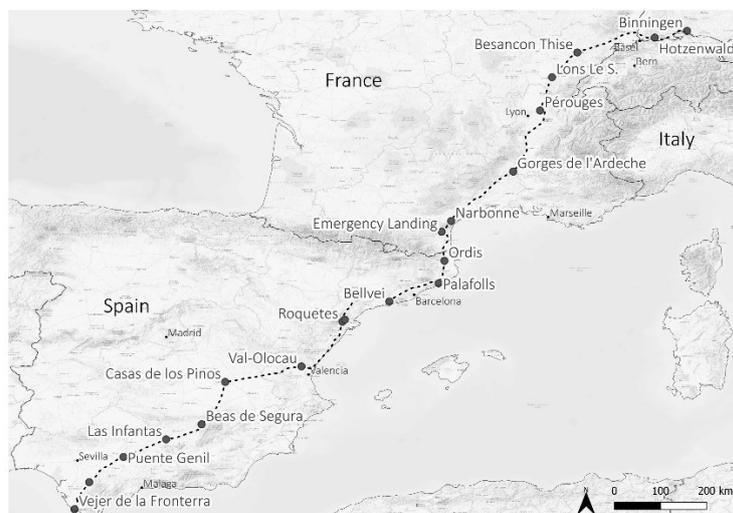


Figure 6. Route of the human-led migration from Baden-Württemberg to Andalusia in 2023; a route of 2.300 km was covered with 19 flight stages.

Before and during the entire journey, the birds were weighed every morning. They were accustomed to this procedure. During the journey, the body weight of the birds decreased significantly from 1.351 ± 110 gram before onset of the migration to 1.318 ± 108 gram at arrival in Andalusia (Wilcoxon signed rank test; $N=31$, $U=428$, $p=0.00043$). However, this decrease was marginal (4%) and in general the birds showed no impairment due to the long duration and distance of the migration.

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

4. Discussion

In 1994, the Northern Bald Ibis was listed as *critically endangered* on the IUCN Red List. At that time, it was among the rarest birds in the world. Only one population on the Atlantic coast in Morocco was remaining, with 65 breeding pairs and a total of about 200 birds in two colonies [29]. Meanwhile the species has been downlisted to endangered. Due to effective management, the Moroccan population has grown to over 700 individuals [30]. And the species returned to European nature, where it was previously widespread until it was eradicated in the early 17th century [5,31].

The European LIFE-project has made a significant contribution to the improved conservation status of this species, especially because they are the only migratory Northern Bald Ibises in the world. The species was migratory all over its historic range, with breeding areas in Northern Africa, the Middle East and Europe and with different wintering sites, especially along the west and east coast of Africa [7,9,32]. From the European population, which was eradicated already in the 17th century, it is known that the birds have left their breeding grounds over the winter, but not where they migrated to and overwintered [5,31]. In 2013, with disappearance of the last bird of a relict population breeding in Syria and wintering in Ethiopia [7,33], the Northern Bald Ibis with its species-typical migratory lifestyle has completely disappeared throughout the entire former distribution area. The only remaining wild population has adopted a sedentary lifestyle and lives year-round at the Atlantic coast of Morocco [9,11].

In the frame of the LIFE-project migratory Northern Bald Ibises returned to their historic breeding sites in Europe. It is the first attempt to reintroduce a continentally extinct migratory bird species, and the results are promising. End of 2013, the population consisted of 256 individuals, where 46% of them belong to successor generations (F1-F3), growing up in the wild and naturally learning

the wintering area from their conspecifics. This proves that the migration tradition established within the framework of the project is preserved across generations. In addition, a number of studies has shown that the birds of this released population display complex and efficient migratory behaviour in terms of energetics [34,35], flight technique [15,17,36] and navigation [16], consistent in detail with the migratory behaviour of other species. Through a population viability analysis, the threshold for self-sustainability is set at a total population size of 314 individuals [37]. The authors anticipate achieving this threshold by the period of 2026/2027.

The project's innovative use of the human-led migration, where microlight aircraft guide hand-raised ibises to their wintering grounds, has proven to be a highly effective method for establishing new migratory patterns. In 1988, Bill Lishman became the first man ever who used a microlight plane to fly with a group of human-imprinted Canada Geese (*Branta canadensis*) [21]. In the frame of a 12-year feasibility study the method was adopted for the Northern Bald Ibis, with several challenges to overcome. In contrast to geese this species is altricial, which shortens the period of training until the onset of migration. Its active flight speed is relatively slow with about 45 km/h, which poses a technical challenge. And the species practices different flight techniques during migration, mainly formation flight, thermal soaring/gliding and intermittent flight [17,23,38–40]. It requires experienced pilots to adapt to the variable flight behaviour of these birds during migration. Over the years, however, these challenges have been overcome and the reliability and efficiency of the method has been optimized. Meanwhile, detailed protocols for hand-raising, imprinting, training and the human-led migration ensure efficient implementation of the method. In the frame of 15 human-led migrations a total of 277 chicks were guided to Tuscany and released at the wintering site, with a maximum of 30 released juveniles per season (2017) and a maximum daily flight stage of 360 km (2011). The human-led migration also offers unique opportunities for scientific research on the physiology, energetics, aerodynamics and technology of bird flight [18,19,41].

The northern Alpine foothills are known as the centre of the historical Northern Bald Ibis distribution in Europe [5,7]. And it is still a region with outstanding reproductive successes. The actual mean fecundity is 2.96 fledglings per nest, which is far above the rate of other populations [37]. A recent study combining GPS data with Earth sense data identified an abundant availability of suitable foraging habitats along the northern Alpine foothills, implying a great potential for habitat expansion for existing colonies [26]. Thus, the availability of the northern Alpine foothills as a breeding range is considered essential for the sustainable survival of a European population. However, an adequate migratory behaviour is a prerequisite for colonies which breed north of the Alps, as these birds can hardly survive the winter in this region.

However, in recent years the birds have shown significant changes in their migration behaviour in response to climate change. In particular, the increasingly pronounced and longer warm periods in autumn cause a shift of the birds' departure from their breeding grounds from September to November. This change in the birds' timing is aligning with general evidence for extensive and diverse effects of climate change on the migratory behaviour of various bird species [42–46].

The progressively failed attempts of birds to cross the Alps later in the year seem to be related to their flight technique. In alpine areas, Northern Bald Ibises soar in thermal updrafts to reach sufficient flight altitudes [17]. GPS data of unsuccessful attempts indicate that the birds when approaching mountain slopes search for thermals and soar, but with a low climbing rate, they finally fail to reach the required altitudes. These observations are in accordance with the fact, that thermal activity in alpine regions gradually decreases in autumn and early winter due to the changed inclination of the sun and the accumulation of cold air in the valleys. These observations among wild birds during migration in the Alps also correspond to experiences during human-led migration. In Alpine regions birds and accompanying aircraft use thermals to gain altitude up to 3000 meters above sea level. Attempts to lead the birds over Alpine passes without suitable thermals mostly fail.

With a western detour the Northern Bald Ibises could overcome the barrier of the Alps to reach the wintering area in Tuscany. However, there is evidence for this detour for only one adult bird. Instead of a detour, Northern Bald Ibises preferably navigate on the shortest direct route to their wintering area. They only deviate from this path when facing barriers, but once successfully passed,

they again continue along the shortest line. This *direttissima navigation* results in the birds approaching the Alps in the same region each year and encountering the same barriers. The birds lack of adaptive adjustments to the behaviour so far is in correspondence with meta-analysis indicating that the adaptive responses to ongoing climate change are insufficient and may already be threatening the persistence of species [3,47,48].

The current objective of the project to establish a new migration route to Andalusia gained impetus from the flight of a juvenile male Northern Bald Ibis named *Ingrid*. During the human-led migration 2022 to Tuscany this hand-raised bird lost contact to the group and returned to the northern Alpine foothills. From there he headed along the Alpine Arc towards the West and thereafter strictly to South-West until it reached a site near Malaga where he remained. During winter, Ingrid was captured and transferred to the nearby sedentary release population of Proyecto Eremita, which he immediately joined. But after more than a year of companionship in the sedentary colony, *Ingrid* set off on a remarkable flight in April 2023. For three consecutive days, the male flew almost 1000 km across Spain on a straight northeast course, with the bird's breeding grounds in the northern Alpine foothills as the obvious destination. His behaviour thus corresponds to the *direttissima navigation* of birds when approaching the Alps. Unfortunately, close to the French border the bird died due to predation.

In 2023, a first human-led migration over 2,300 kilometres from southern Germany to Andalusia was performed with a group of 32 juveniles. At least an additional four migrations from the northern foothills of the Alps to Andalusia are planned to release a total of about 150 birds. They should become the founders of a new migration tradition which connects the breeding areas north of the Alps with a wintering area in Andalusia. This new migration path connects the European migratory population with the sedentary Spanish population and thus also two well established European conservation projects, the European LIFE-project and the Spanish *Proyecto Eremita*. The symbiosis of the two European projects aims at forming a population which covers an area of about 5,000 km² extending from Andalusia to southern Germany and central Italy. This population includes migratory breeding colonies north and south of the Alps and a sedentary colony in Andalusia. Another two semi-wild sedentary colonies, one in Friuli, Italy, and the other one in Gruenau im Almtal, Upper Austria [49], also increasingly interact with the migratory colonies. Experience to date has shown that adult migratory birds are generally not deterred from flying to their traditional breeding grounds by sedentary birds in the wintering area or along the migration route. This is a basic prerequisite for the intended establishment of this second migration route.

The future will show what dynamics will result from the diversity and large-scale distribution of migratory and sedentary colonies. We assume that it results in increased ecological flexibility, which helps the population to adapt to the constantly changing environment. The project is highlighting the importance and potential of translocations also in the light of mitigating climate change. Moreover, it is also an example of efficient cross-border cooperation between previously independent projects. Transnational cooperation is becoming increasingly important due to the ever-larger number of threatened migratory animal species. In particular, however, the project has become an example of how immediate and significant the consequences of climate change can be for species and what challenges this can pose for ongoing species conservation measures.

Author Contributions: All authors conceived the ideas and designed methodology; JF, BG and HW collected and analysed the data; JF led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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Conflicts of Interest: The authors declare no conflicts of interest.

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