




Article

Evaluating the Impact of Headstarting on the Critically Endangered Spoon-Billed Sandpiper *Calidris pygmaea*

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Abstract: Headstarting is a conservation approach that suggests offering an advantage to a population by improving egg production, survival of embryos and/or juveniles. In this article, we are providing the quantitative data obtained during 10 years for different stages of headstarting (production of eggs per pair, hatching and fledging rates) and the resulting impact (survival to maturity, philopatry rate, sex ratio, apparent survival, growth/decline rate) on the local population of the critically endangered spoon-billed sandpiper. We have shown that headstarting gains are reduced over time from fledging to long-term recruitment to the local breeding population. The possible reasons for this reduction are suggested and discussed. The unexpected finding was a drastic difference in sex ratios of the new recruits, which was about even for headstarting, but strongly male-biased for wild-reared birds. We suggest this happens due to increased mortality of female chicks in nature. We have also shown only headstarting could stop the global decline of the species, particularly once the suggested improvements are implemented and the number of pairs involved is scaled up. Headstarting also had a significant social effect due to the involvement of increasing numbers of people both in the local communities in Chukotka and from many countries on the flyway into searching for marked birds and learning about waders, raising awareness about ecological problems on the East Asian–Australasian Flyway. Thus, it has made the need for conservation actions on the flyway more obvious and sensible.

Keywords: artificial incubation; captive rearing; apparent survival; hatching rate; fledging rate; conservation



Citation: Loktionov, E.Y.; Digby, R.A.; Yakushev, N.N.; Shepelev, I.A.; Clements, J.P.; Tomkovich, P.S.; Jarrett, N.S.; Clark, N.A.; Green, R.E.; Lappo, E.G.; et al. Evaluating the Impact of Headstarting on the Critically Endangered Spoon-Billed Sandpiper *Calidris pygmaea*. *Diversity* **2023**, *15*, 584. <https://doi.org/10.3390/d15040584>

Academic Editors: Alexander Dvoretzky, Krivopalov Anton and Miguel Ferrer

Received: 23 January 2023

Revised: 5 April 2023

Accepted: 19 April 2023

Published: 21 April 2023



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1. Introduction

The population size of any species is driven by the balance between productivity and survival [1,2]. At present, species of long-distance migrant shorebirds are declining, especially on the East Asian–Australasian Flyway (EAAF) due to illegal hunting and habitat loss, both of which are reducing the survival rate of both juvenile and adult birds [3–6]. Although there has been some success in dealing with these threats, further work is needed. However, it may be possible to increase productivity in at least some of the most endangered local bird populations to reduce the chance of extinction and potentially aid recovery.

Headstarting (HS) is a conservation approach that can increase productivity by incubating eggs and raising chicks in captivity, avoiding predation at these very vulnerable

stages. A number of successful HS projects are known for reptiles [7], but there are far fewer examples amongst birds. However, HS has been used to increase productivity in the maleo (*Macrocephalon maleo*) [7], takahē (*Porphyrio mantelli*) [8], mangrove finch (*Camarhynchus heliobates*) [9], as well as of several species of waders, such as the American oystercatcher (*Haematopus palliatus*) [10], black-tailed godwit (*Limosa limosa*) [11], black stilt (*Himantopus novaezelandiae*) [12], piping plover (*Charadrius melodus*) [13] and snowy plover (*Ch. Nivosus*) [14]. Conservation actions in these cases ranged from eggs simply being moved to a safe place for parentless natural incubation (maleo) to a one-year-long captive-rearing process after artificial incubation (takahē).

In addition to improving egg and chick survival, HS can also increase egg production by stimulating production of a replacement clutch. It can also buffer unusually poor productivity in years with unfavourable environmental conditions, helping to protect against runs of severe conditions on breeding and non-breeding grounds, which can lead to population collapse [15]. For species with sex-biased chick survival, HS can help balance the sex ratio of first-breeders by reducing the effect of environmental drivers of this bias, and so assist faster population growth.

The spoon-billed sandpiper (SbS) (*Calidris pygmaea*) (L., 1758) is a small wader species using the EAAF, with a breeding range restricted to the coast of the Chukchi Sea and the Asian side of the Bering Sea [16] and wintering grounds in Southeast Asia [17]. In 2008, this species was listed as critically endangered (IUCN 3.1) on the IUCN Red List due to a sharp population decline in recent decades [18–20]. The current global breeding population of the species is estimated from 120 [17] to 210–228 pairs [21,22]. There has been considerable international activity throughout the EAAF to conserve SbS and their habitat, aimed at reversing their negative population trend (e.g., [17,23–26]). This work has reduced the annual population decline from 26% in the 2000s [18] to 8–10% per year [21,27,28]. SbS were found breeding in the vicinity of Meinypil’gyno Village, Southern Chukotka, Russia, in 2001 [29], and, although it is still the largest known breeding population, it has declined from at least 80 pairs in 2003 [18] to no more than 12 pairs in 2022 [30].

Previous work on another northern breeding population [20,31–33] has shown that the SbS is a long-lived monogamous species, territorial in the pre-nesting period and highly site faithful. SbS normally breed at 2 years of age [34]. As in many other waders, juveniles generally migrate southward separately from adults [35], and thus do not need parents’ guidance to or from their natal area, which facilitates aviculture significantly.

In both 2011 and 2012, 20 eggs were collected for the “SbS Captive Breeding Programme” at the Wildfowl and Wetlands Trust centre at Slimbridge in the UK. The programme aimed to establish a captive breeding population as insurance against extinction and to reintroduce the species by transporting eggs to Chukotka, to be hatched there and the chicks released. To develop methods for this next step, the “SbS Headstarting Programme” was initiated in 2012 in Meinypil’gyno. Although no eggs have been supplied from the captive population, HS continues as a self-sufficient project.

This paper is the start of a series of articles on the headstarting results and procedures as a part of the long term project on saving the SbS. Here we report the impact of HS on the local SbS population over 10 years, and discuss the possible application of HS in relation to declining populations.

2. Methods

We have been monitoring the SbS breeding population in the vicinity of Meinypil’gyno Village (N 62.54°, E 177.05°), Chukotka Autonomous Okrug, in the far east of northern Russian since 2003, with intensive studies taking place from 2012 to 2022. The study site is a coastal area with diverse tundra vegetation and a varying landscape (coastal spits, coastal plain and moraine hills), which is situated between the Bering Sea, the mountains of the Koryak Highlands and two sizable lakes (Pelul’neyskoye and Vaamychgyn Lakes). Water from the catchments of these two lakes flows into the sea by two rivers that run along the coastal spit into a single river mouth, which is blocked by ice and gravel washed ashore by

autumn storms in some years. This causes spring flooding on the floodplains on the shores of the lakes, which are among the preferred habitats of SbS. The main survey area is about 40×12 km in size and is surveyed using ATVs, boats and on foot.

2.1. Ringing and Colour Marking

Individual colour-marking of SbS in the population started in 2012 using a combination of a metal ring from the Moscow Bird Ringing Centre (internal diameter 2.8–3 mm) on the right tibia and a plastic flag 10×5 mm² in size with a unique engraving of two alphanumeric characters. To distinguish between birds marked as adults and those marked as chicks, adult birds had the metal ring on the right tibia and the flag on the left tibia, with the opposite legs being used for chicks. Wild birds had lime (light green) flags and HS birds had white flags. SbS chicks were marked immediately after hatching when they already have well-developed legs. Colour-marking allowed them to be followed both on the breeding grounds and throughout the flyway.

Adult SbS were caught using “walk-in traps” (or occasionally, with a clap-net) mostly on their nests after the clutch had been taken for HS and replaced by dummy eggs. Some adults were caught during the brood rearing period when their chicks had hatched; they were attracted to the trap by playback of distress calls of chicks from a mobile phone placed into the trap. Sexes were assigned using plumage colouration (males are usually slightly brighter) and biometrics [36]. Sex can also be assigned in subsequent years using behavioural observations of pairs during the pre-nesting period. When the sex of one bird was known, we assumed that the partner(s) were of the opposite sex.

The position and colour of a flag provides preliminary information about of a bird to a cohort. Such individual recognition of SbS was necessary for various purposes: local population monitoring, obtaining demographic parameters, behavioural observations and learning about local and flyway movements of the birds. Information about records of colour-marked SbS was obtained from the flyway due to a network of observers created by the SbS Task Force of the EAAFP.

2.2. Collection of Eggs and Artificial Incubation for HS

HS aims to increase productivity by preventing predation of eggs and chicks, while allowing pairs to produce a replacement clutch. Data for birds headstarted between 2012 and 2021 have been analysed if not otherwise specified. The HS protocol is described below in brief, but has been subject to minor modifications to improve the outcome as the project has developed. Detailed description of the HS protocol is a topic for a separate article to be published. Here we presented only details essential for the results understanding. Egg collection and bird handling were carried out under annual permits issued by the Russian Ministry of Natural Resources and Ecology.

From the arrival of the first SbS on 30 May–6 June (median 2 June, $n = 14$), we surveyed the area for territories of SbS males and home ranges of pairs. During these ca. 7 days, birds were rather vocal and thus were easier to locate. Once found, their behaviour was monitored to establish the time of nest cup scraping, nest location and first egg dates.

The nests were only visited when necessary to minimise any additional predation risk. Nest sites were initially visited about once a week, increasing to almost daily during the estimated hatching date. For reference, we have monitored the fate of other wader species nests in the area in the same way. In most cases, at least one SbS partner had been individually colour-marked, allowing us to know whether we were dealing with a first or replacement clutch. Nests were lost as a result of flooding ($n = 7$) or predation of a part-completed first clutch ($n = 8$), resulting in reduced clutch size of the rest of the eggs in another nest cup. We considered these to be the first clutches still. A few pairs were observed early in the season, but their eggs hatched late. These were assumed to be replacement clutches, even though the first clutches had not been located ($n = 9$).

Collecting eggs from newly completed clutches reduces the risk of nest loss due to predation or flooding, although there is an increased risk of embryo damage during

transportation, and therefore a reduced hatch rate [37]. The eggs were collected for HS at the earliest opportunity (including collecting incomplete clutches, with eggs being replaced by dummies), taking into consideration the distance of the nest from the incubation facility and the intervening terrain. Eggs were transported to the rearing station in the village using portable incubators (AB Newlife Houbara and AB Newlife Toolbox) running between 35–36 °C and ca. 45% relative humidity (RH) running from a 12 V battery. These were transported on foot, by boat or using an ATV driven cautiously between 5–10 km/h within a time frame not exceeding 4 hrs. The farthest delivery was 27.0 km (geodesic), while the mean was 11.1 ± 8.5 km (min. 2.2 km, median 10.5 km, $n = 73$; here and below mean values are provided with \pm SD).

Eggs arriving at the rearing station Figure 1a were immediately marked and weighed (for individual monitoring through incubation), then measured and candled to ascertain age if not already known. They were then placed into a standard parameter incubator.



Figure 1. (a) Incubator at the rearing station and (b) the aviary.

The incubation period estimated for the last egg in a clutch in the northern population was 21.5–23 days (22.43 ± 0.61 , $n = 7$) [32], while for artificially incubated eggs collected for HS with known laying date, it was 20.5–23 days (21.9 ± 0.9 , $n = 11$) and 21–22 days (21.6 ± 0.5 , $n = 5$) for wild ones.

2.3. Chick Rearing and Release

After hatching, the chicks were weighed and fitted with a split plastic colour ring on the left or right tarsus for identification purposes before being placed in the brooder, usually for 18–24 h.

Once ca. 8 days old, chicks were moved to the aviary located on the shore of Pekul'neyskoye Lake about 3 km from the village (Figure 1b). This is a slightly brackish lake with similar vegetation to that where adult SbS are often found to breed and rear chicks. It provides a good example of a habitat to which they should return.

Chicks were released around the 25–31 July, the youngest ones 18–30 days old, depending mostly on the breeding schedule of SbS and related egg collection. The age at release was very important for the subsequent survival, i.e., the earlier the better [38]. Post-release monitoring was performed twice a day for around two weeks, or until no more sightings had been recorded for a period of at least three days.

Subsequent observations of HS birds came from the flyway (Kamchatka Peninsula in Russia, South Korea, Japan, China, Taiwan, Thailand, Myanmar and Bangladesh) and from the vicinity of Meinypil'gyno once they returned for breeding.

2.4. Calculations

We used the following formulae to estimate the annual number of fledged chicks per pair (E):

$$E_{HS} = C_{HS} \times H_{HS} \times F_{HS} + R_{HS} \times C_r \times S_{w,r} \times H_w \times F_w,$$

$$E_w = (C_f \times S_{w,f} + (1 - S_{w,f}) \times R_w \times C_r \times S_{w,r}) \times H_w \times F_w,$$

where C is average clutch size, H is hatch rate (ratio of the number of eggs hatched to the total number of eggs), F is fledge rate (ratio of the number of chicks fledged to those hatched), R is replacement probability and S is nest safety rate (ratio of the number of nests with at least one egg hatched to the number of nests found); subscripts designate HS as headstarted, w as wild, f as first and r as replacement. To estimate annual output of hatched chicks, fledge rates are not meaningful, so taken as $F_{HS} = F_w = 1$. For egg production (number of eggs survived to hatching), hatch rates are taken as equal to unity, too. Gain at some stage of the life cycle is evaluated as the ratio of HS output parameters (including induced output from replacement clutches) to the relevant natural one.

Recruitment to the breeding population was estimated as the number of chicks reaching maturity per pair (G):

$$G_{HS} = C_{HS} \times H_{HS} \times F_{HS} \times M_{HS} + R_{HS} \times C_r \times S_{w,r} \times H_w \times 0.9 \times M_w,$$

$$G_w = (C_f \times S_{w,f} + (1 - S_{w,f}) \times R_w \times C_r \times S_{w,r}) \times H_w \times 0.9 \times M_w,$$

where 0.9 is the proportion of wild chicks surviving from hatching to marking (mean 2.6 days old, $n = 75$ in 2013–2016) and M is maturity rate calculated as the ratio between the number of birds observed on the breeding grounds, or at the age of at least 23 months elsewhere, to the number of marked birds in the relevant cohort. Headstarting recruitment rate is a ratio of pairs involved whose eggs were collected to the total number of pairs in the local population. In our case, it was 50% on average (range 40–67%).

3. Results

3.1. Nest Fate

Most of the SbS clutches found in the beginning of a breeding season, in relatively easily accessible sites, were collected for HS. This in total provided slightly less than half of all eggs found in 2012–2022 (Figure 2). Since those were early clutches, most of them were from the first pairs to breed each season. First clutches consisted of a mean of 3.85 ± 0.04 SE eggs (range 2–4, $n = 97$). In general, replacement clutches contained fewer eggs—mean 3.13 ± 0.11 SE (1–4, $n = 52$).

The rate of nest predation varied between years (Table 1), with reasons for the differences being unclear. Overall, 37.9% of eggs from first clutches were lost (Figure 3), and for all replacement clutches this rate is similar (38.4%). Survival of SbS nests is usually slightly lower than generalised values for other local waders (Table 1; Ref. [39]).

Table 1. Percentage of monitored wader nests that survived to hatching in the vicinity of Meinypil'gyno in 2013–2022.

Year Species	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total
Spoon-billed Sandpiper <i>Calidris pygmaea</i>	66.7% ($n = 6$)	62.5% ($n = 8$)	50.0% ($n = 10$)	50.0% ($n = 12$)	50.0% ($n = 12$)	52.9% ($n = 17$)	41.7% ($n = 12$)	41.7% ($n = 12$)	55.6% ($n = 9$)	57.1% ($n = 7$)	51.4% ($n = 105$)
Other locally breeding waders [39]	74.0% ($n = 46$)	64.0% ($n = 44$)	54.5% ($n = 55$)	65.4% ($n = 52$)	46.0% ($n = 50$)	68.6% ($n = 51$)	51.1% ($n = 47$)	49.1% ($n = 57$)	61.0% ($n = 59$)	68.6% ($n = 51$)	60.0% ($n = 512$)

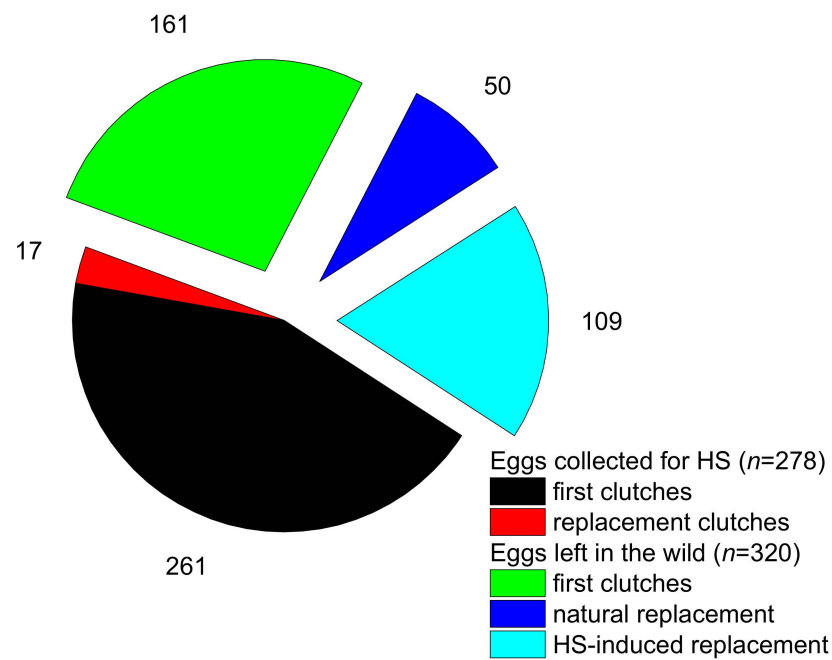


Figure 2. The fate of eggs found in the study area in the vicinity of Meinyipil'gyno in 2012–2022 ($n = 598$).

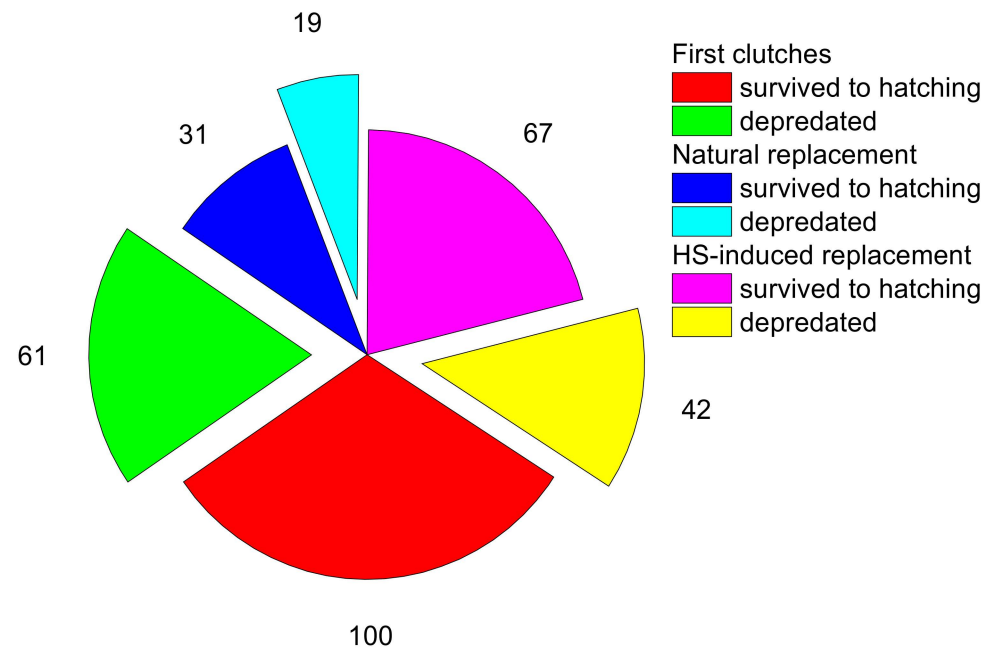


Figure 3. The fate of monitored eggs not collected for HS ($n = 320$). Predated eggs ($n = 122$) are shown in exploded wedges.

If a pair lost its clutch due to egg collection for HS, predation or flood within ca. 10 days of clutch completion (usually by 21 June), birds were capable of laying a replacement clutch. However, we have two documented cases when pairs produced replacement clutches having lost their first clutch after 21 June in 2015 and 2017. The time between first and replacement clutch hatching dates of a pair varied from 7.5 to 15.5 days (10.1 ± 2.5 , median 9, $n = 15$).

Of the 73 clutches collected for HS, 35 replacement clutches or broods were found. Where clutches were collected late in the season, or replacement clutches were taken, there was insufficient time for another clutch to be laid ($n = 24$). Minimum replacement probability after a clutch was taken was 71.4%. By contrast, among 22 depredated first clutches

not related to HS (regardless of predation date), only 8 (36.4%) were replaced, suggesting that HS-induced relaying probability is about twice as high as that experienced after natural loss of clutches. That could be explained by early collecting of the eggs when birds are still physiologically ready to produce more eggs.

Headstarting improves egg production per pair (number of eggs which survived to hatching) by 82%—from 2.84 to 5.16 for eggs taken for HS (see Methods). Thus, using mean clutch size, replacement probability and hatching rate (Table 2), 4.25 vs. 2.53 chicks are hatched per pair at headstarting. Of 278 eggs collected for HS, 6 appeared infertile, and 52 embryos died at different stages of incubation. The sample size for hatching rate estimations in nature is comparatively low, since it is harder to track without exposing birds to additional risk associated with frequent visits to nests. This could partially explain slightly higher artificial incubation success in some years.

Table 2. Percentage of SbS eggs hatched in 2011–2022 using artificial incubation and those incubated naturally.

Year	2011 *	2012 *	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total
HS	80.0% <i>n</i> = 25	75.7% <i>n</i> = 37	87.5% <i>n</i> = 24	87.1% <i>n</i> = 31	87.9% <i>n</i> = 33	86.1% <i>n</i> = 36	83.3% <i>n</i> = 36	71.4% <i>n</i> = 35	68.4% <i>n</i> = 38	90.0% <i>n</i> = 30	74.4% <i>n</i> = 39	0	80.5% <i>n</i> = 364
Wild	100% <i>n</i> = 4	100% <i>n</i> = 4	85.7% <i>n</i> = 7	85.7% <i>n</i> = 21	84.6% <i>n</i> = 13	92.9% <i>n</i> = 14	72.7% <i>n</i> = 11	91.7% <i>n</i> = 24	94.7% <i>n</i> = 19	94.4% <i>n</i> = 18	78.9% <i>n</i> = 19	86.7% <i>n</i> = 15	88.2% <i>n</i> = 169
Total	82.8% <i>n</i> = 29	78.0% <i>n</i> = 41	87.1% <i>n</i> = 31	86.5% <i>n</i> = 52	87.0% <i>n</i> = 46	88.0% <i>n</i> = 50	80.9% <i>n</i> = 47	79.7% <i>n</i> = 59	77.2% <i>n</i> = 57	91.7% <i>n</i> = 48	75.9% <i>n</i> = 57	86.7% <i>n</i> = 15	82.9% <i>n</i> = 533

* In 2011 data are for eggs collected for captive breeding; in 2012, results for captive breeding and HS were combined.

3.2. Fate of Chicks

In general, we do not know the sex of either embryo in the SbS eggs collected for HS or chicks subsequently hatched and released from those eggs. From 20 SbS eggs taken to the Wildfowl and Wetlands Trust, Slimbridge, UK in 2012 for captive breeding, 9 ♂ and 8 ♀ hatched; of those, 4 ♂ and 5 ♀ were still alive by the end of 2019.

Fledging rate in HS birds is 92.9%, but we have insufficient data to evaluate this parameter in naturally raised chicks. Our optimistic expert evaluation is 62.5% based on both local broods' fate tracking and subsequent records of birds marked as chicks. This translates to 3.63 fledged chicks per pair involved in HS (including replacements) and 1.58 chicks per pair where HS was not involved. For HS 2012–2022, 12 chicks died during rearing due to unpreventable or untreatable issues (genetic defects, prolonged hatch, infection, etc.). For three chicks, the leg flags were removed before release (infected lesions at the heel joint or severe leg flicking), and three were known to have died before migration (infection or predation).

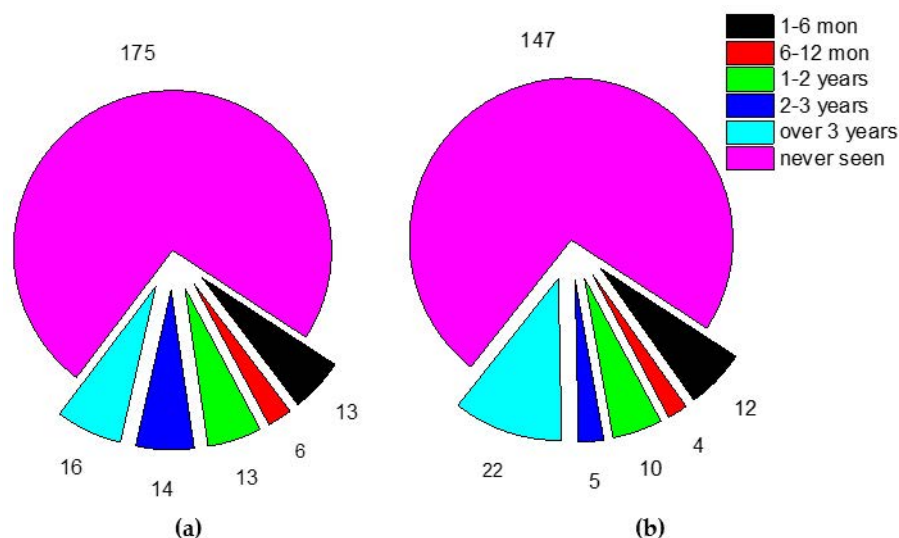
Almost all HS chicks come from the first clutches, while a significant proportion of chicks marked in the wild are from replacement clutches. Late hatching from replacement clutches of SbS at Belyaka Spit on the Arctic coast has been shown to influence survival of chicks and juveniles [32]. Of 50 SbS marked as wild chicks in 2013–2021 and observed after first departure from the natal area, 16 originated from replacement clutches. That gives a resighting probability of 32.7% for birds coming from the first clutches (*n* = 104) and 39.0% for those coming from replacements (*n* = 41). Thus, this difference in survival rates is opposite to that on the Arctic coast at least in some years. If HS and natural replacement clutches are considered separately, the resighting probabilities are similar: 38.5% (*n* = 13) and 42.9% (*n* = 28), respectively.

Numbers of HS and wild flagged chicks are presented in Table 3. Figure 4 shows the age at last observation of HS and wild chicks. It can be seen that only 23.2% of HS chicks have ever been observed either on the flyway or having returned to the natal area, which is a slightly lower rate than 26.2% of wild chicks. However, in comparison with HS birds, the wild cohort has a higher percentage of birds not seen after the age of 1 year—30.2% vs. 27.1% of relevant juveniles ever observed.

Table 3. Numbers of SbS chicks marked in 2012–2022 which returned to the natal area in subsequent year(s).

Year	Headstarting			Wild Chicks Marked	Birds Returned (HS/Wild)								
	Eggs Coll.	Chicks Hatched	Young Released		2014	2015	2016	2017	2018	2019	2020	2021	2022
2012	11	9	9	5	1/0	1/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
2013	24	21	18	3	0/0	3/1	2/1	0/1	0/1	0/0	0/1	0/1	0/1
2014	31	27	26	19	–	1/1	2/4	2/3	2/1	2/0	0/0	0/0	0/0
2015	33	29	28	12	–	–	1/0	4/3	1/3	1/1	0/1	1/1	0/1
2016	35	31	30	38	–	–	–	2/1	3/4	2/4	2/3	1/3	1/2
2017	38 *	30	30	16	–	–	–	–	0/0	1/0	1/0	2/0	2/0
2018	35	25	22	30	–	–	–	–	–	0/1	0/3	1/3	0/0
2019	38	26	23	26	–	–	–	–	–	–	0/0	5/4	2/4
2020	30	27	22	20	–	–	–	–	–	–	–	0/0	2/1
2021	39	29	28	18	–	–	–	–	–	–	–	–	0/0
2022	0	0	0	13	–	–	–	–	–	–	–	–	–
Total	314	254	236	200	1/0	5/2	5/5	8/8	6/9	6/6	3/8	10/12	7/9

* Two thin-shelled eggs were damaged.

**Figure 4.** Maximum ages at last observation of marked birds: (a) HS ($n = 237$) and (b) wild-reared ($n = 200$) chicks.

Observations, both in our study area and on the flyway, suggest that the expected recruitment of chicks from our study area to the global breeding population is higher for HS chicks (0.681) vs. naturally reared birds (0.42 birds) per pair per year. However, this is due to higher primary output of pairs involved in HS. For successful first breeders, their contribution to the local population was 0.416 and 0.3 birds per pair per year, respectively.

By the end of 2022, 29 HS (15 ♂, 11 ♀ and 3 birds of unknown sex) and 22 wild chicks (16 ♂, 5 ♀ and 1 bird of unknown sex) were known to have returned to the natal area (Figure 5). Return rates in these groups are almost equal at ca. 14%. For 7 out of 29 returned HS birds, no breeding or even successful mating was recorded. Of those birds, three were unsexed, two ♂ and two ♀, whose sex was assumed according to their behaviour and interaction with other birds, and six ♂ staying solitary during their first breeding season. So, of HS birds, there were 12 ♂ and 9 ♀ breeding. Among breeding birds marked as wild chicks, sex ratio was significantly different to HS: 12 ♂:4 ♀ overall and every year taken separate ($F_{1,17} = 8.66$, $p < 0.01$, power 0.79 for $\alpha = 0.05$). Noteworthy, among the breeding birds marked as wild chicks, three originated from HS-induced replacement clutches.

Among the HS birds that returned, four (15%) were first-years. Male “white OC” bred successfully with HS partner (also a first-time breeder), and had two clutches in one season:

the first one taken for HS, and the replacement resulted in two chicks (one fledged). We have no breeding observations for the remaining three HS birds (one ♀ and two unsexed birds) that returned in their first year. No other HS yearlings have ever been seen later again. Among wild chicks which returned to their natal area, three (15%) were first-year birds: two ♂ bred successfully for several years (one breeding from the very first summer, which is the very first documented case of such kind for SbS males). Such return rates of yearlings are unexpectedly high according to our previous knowledge from Northern Chukotka [33].

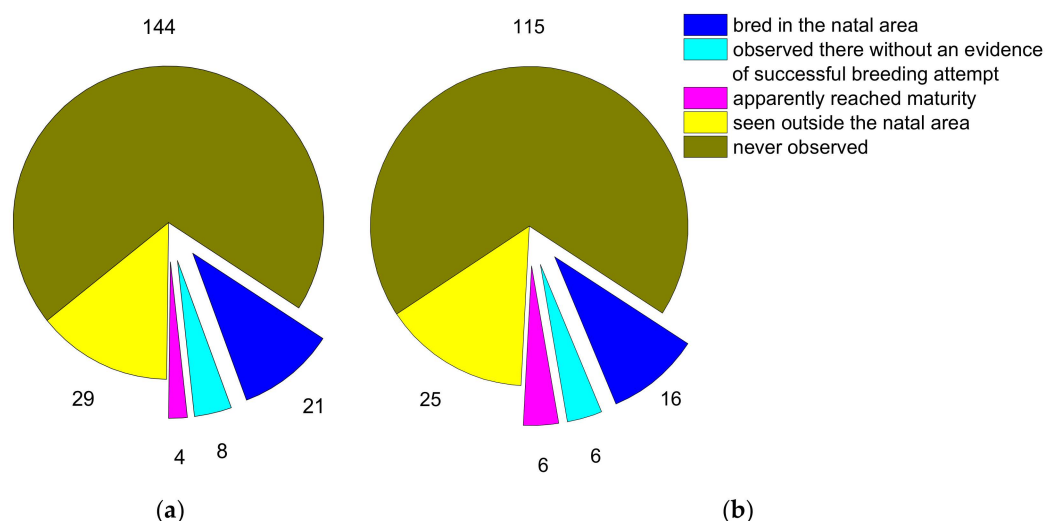


Figure 5. Fate of birds marked in 2012–2020 by the end of 2022 (a) HS ($n = 206$) and (b) wild-reared ($n = 168$) chicks based on known observations.

Of 21 HS birds which bred in their natal area, only 8 bred more than once. One (“*L pink*”) attempted to breed during four successive years (2016–2019), but all the nests found were predated. Four HS males and two females were still breeding the age of 5 years. Of the birds marked as wild chicks, all that bred did so more than once. One male was still breeding when nine-years-old and one female when seven-years-old. It is noteworthy that, while all wild chicks started to breed by the time they were two-years-old, some HS birds started later—one ♂ and two ♀ started breeding when three-years-old and two ♂ when four [34].

There is a dramatic difference in the return rates of HS and wild chicks after their first arrival on the breeding grounds. While 95% ($n = 20$) of birds marked as wild chicks returned, only 48.1% ($n = 27$) of HS chicks returned a second time. In subsequent years, apparent survival of the wild chicks was similar to adult birds: 75% ($n = 20$) and 70% ($n = 10$), respectively.

Return rates of wild chicks are higher than those of HS chicks (Figure 6). It can also be seen that return rate was low for the cohorts marked in 2017 and 2018. In 2020, for the first time, we had no unmarked birds in the core monitoring area, indicating that there was no natal dispersal from other areas and no local chicks that had not been marked (not caught, missed broods, etc.), although the return rate for adults was still similar to the long-term mean. The main differences between the experiences of juveniles and adults away from the breeding grounds are: (1) earlier first southward migration and (2) remaining on the Yellow Sea coast during their first summer [40]. Recent habitat loss in the Yellow Sea [41,42] could be the key to this drop in juvenile return rates. Since the median age of the first observation of a colour-marked chick is 6 months, the percentage of chicks known to have reached maturity is similar to the adults’ return rate of 68.8% in our study area (see below). The similarity of this fraction in HS and “wild” cohorts and the slight advantage of wild-marked chicks in apparent maturity rate not normalised by fledging rate (0.625) indicate increased mortality of HS juveniles before the first observation. There also appear to be differences in

long-term return rate when considering the maximum age at which birds were observed on the breeding grounds (Figure 7). More than a half of HS returned chicks were recorded in only one breeding season.

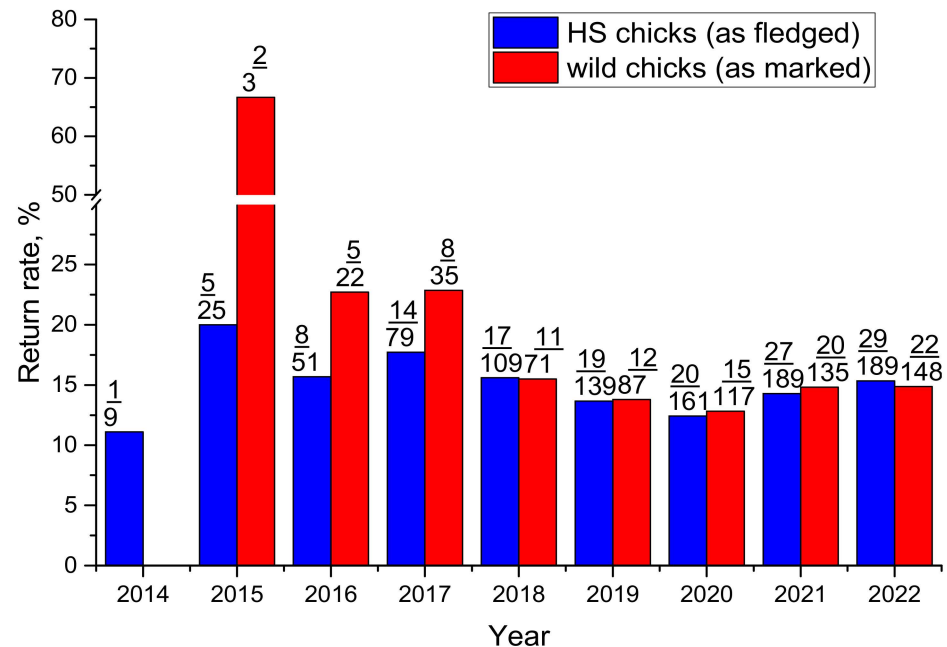


Figure 6. Return rates of HS and wild chicks (the upper number indicates the cumulative number of chicks returned by each year, while the lower value shows the number of second-year birds that could potentially return).

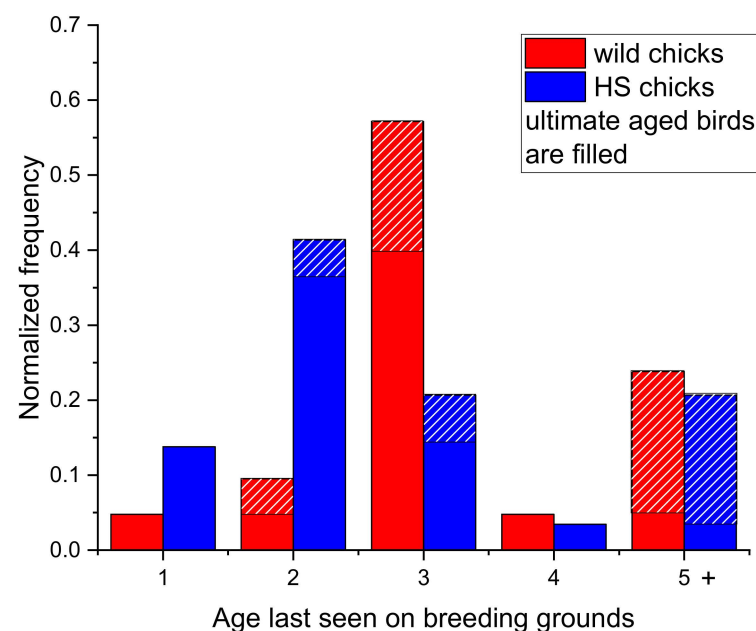


Figure 7. Maximum age at the last observation on breeding grounds of HS and wild SbS chicks. The hatched sections indicate birds that could not have exceeded the particular age at the time of analysis.

In addition to lower return rates for HS birds, it seems that they are less able to form a breeding pair (Figure 5). However, there have been three successful pairs consisting of both HS first-time breeders. The male of one pair was a yearling, and his father was also a HS bird. Low apparent survival of yearlings coming to the breeding grounds and

their lower pairing abilities suggest this phenomenon does not lead to the population productivity increase.

In total, seven HS and five wild birds that were marked as chicks were observed on the flyway at the age of at least 23 months, but were not recorded returning to the study site, suggesting possible juvenile dispersal rates of 20.5% (HS) and 20.0% (wild) and post-natal site fidelity (philopatry) of ca. 80% among young birds that reached maturity. A majority of chicks (HS 57.9%, $n = 57$ and wild 56.0%, $n = 50$) marked in 2012–2018 have been seen alive after leaving the breeding grounds. There are also very similar percentages for HS (16%) and wild chicks (16.7%) reaching “apparent maturity” (a breeding attempt or reaching 23 months of age).

Among HS birds, 68.5% ($n = 35$) were known to have paired successfully compared to 81.3% among those marked as wild chicks ($n = 32$); cases were calculated for (bird \times years) present in the study area. Egg safety was slightly higher for the pairs containing a HS partner compared to those with a partner marked as a wild chick: 46.8% ($n = 47$ eggs) vs. 40% ($n = 55$ eggs). Similar differences were found for hatch rates: 81.8% ($n = 6$ nests) vs. 75% ($n = 10$ nests), respectively. It was not possible to compare fledging rates due to paucity of data.

Data on post-natal dispersal are presented in Table 4. For HS chicks, the distance from the aviary is used. We suggest that median values are more appropriate for consideration in this case, since the distance distribution is different to normal. For both sexes, HS birds have nearly half lower post-natal dispersal than the wild ones. It is worth noting that the large Pekul’neyskoye Lake restricts the NE sector from the aviary, which means that less land is available for the birds within the same range compared to many other SbS territories.

Table 4. Distances from origin to the first own nest (post-natal dispersal) in m.

	Wild *			HS from Aviary		
	♂	♀	♂ + ♀	♂	♀	♂ + ♀
<i>n</i>	11	4	15	10	9	19
mean	9251	5720	8309	5191	8833	6916
s.d.	10,866	4671	9572	7960	10,646	9249
median	4370	6002	4370	1781	3180	2502
min	42	146	42	650	763	650
max	30,594	10,730	30,594	26,216	26,846	26,846

* One male and one female marked as chicks in 2010 are added.

3.3. Population Level Impact

There is no evidence of long-term HS affecting the productivity or breeding behaviour of SbS. Clutches have been taken (or predated) from both males and females, but they continue to fledge chicks from replacement clutches and remain in the same territories for more than five years. The birds that do not return have also not been seen again anywhere in the flyway and are likely dead (the maximum age at first resighting was 40 months, median—5 months). Figure 8 shows that birds marked locally as chicks from 2012 onwards were present in over half of the pairs in the local population by 2020. A slight increase in the number of breeding pairs was observed initially, but this has become a decline in recent years, with a return to numbers seen in 2013 when there was no apparent impact of HS on the population. The number of wild adults is continuing to decrease, and the lower return rate of juveniles and their rather short life expectancy (Figure 7) no longer compensate for this decline. To keep the population sustainable with the current survival rate of birds, increased productivity is needed (Table 5). There are no natural mechanisms for that, and only artificial efforts, such as HS, could help at least to decelerate the species extinction unless conservation activities outside of the breeding grounds will not improve the survival of birds.

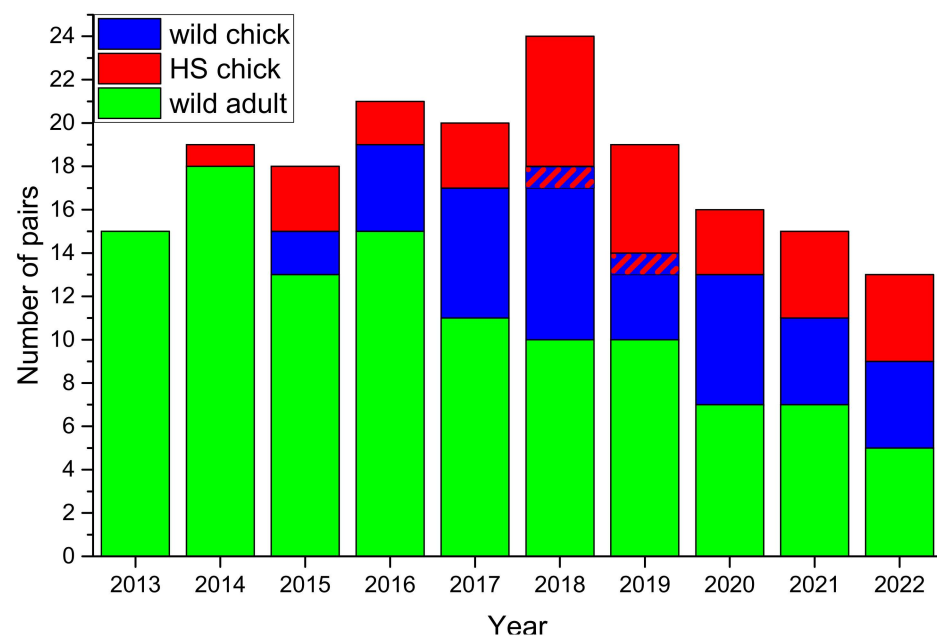


Figure 8. Number of pairs recorded in the Meinypil'gyno area 2013–2022. Different colours show the numbers of pairs consisting of birds marked as wild chicks, those marked as HS chicks, with two-colour hatching showing pairs consisting of partners marked as wild and HS chicks. Wild adults were marked as adults or remained unmarked.

Table 5. Evaluation of HS gain at different stages per a pair in the study population.

	Eggs Produced	Chicks Hatched	Chicks Fledged	Mature Birds	Recruits in Natal Area	Successful First-Breeders	Successful Second-Breeders
HS	5.15	4.29	3.67	0.681	0.496	0.416	0.299
Nature	3.08	2.73	1.71	0.42	0.32	0.3	0.282
Gain	1.68	1.57	2.14	1.62	1.55	1.39	1.06

The condition for the local population being self-sustaining is $B/(1 - q) = 1$ (sum of the infinite geometric series), where B is the successful first-breeder output per breeding partner and q is the annual adults' return rate. It can be simplified to $B + q = 1$. In our study area, q mean values were different ($p < 0.001$) for adult males (0.728, $n = 57$) and females (0.751, $n = 56$), or 0.739 on average. For sustainability (zero balance in a population), it would need to be 0.792 with full HS recruitment into the population (all available pairs involved), or 0.85 without intervention at the current natural productivity. If we assume that immigration from other populations is equal to the emigration rate we evaluated for our birds (B should be divided by post-natal fidelity equal to 80%), then the target return rates would change to 0.723 (and can be further improved if better HS pairing success is shown) and 0.8 in natural conditions. Even full HS recruitment does not make the local population sustainable. In addition, if other local populations are stressed, interchange flows may not be balanced.

If all HS birds join the local breeding population, it would be possible to decelerate annual decline to -4.4% against -14.0% without HS birds. Based on the age of recruitment ($G/2$ taken instead of B) and adult survival rates, an optimistic projection of the population trend would be $+8.2\%$ per annum for HS and -8.6% per annum without it. Therefore, HS could potentially lead to a viable local population, but there is definitely no chance of the population becoming sustainable without HS. Our local population comprises ca. 10% of the global population [21], and currently only about a half of it is involved in HS. This cannot affect the global population decline of -8.1% evaluated in [21] using different

calculation methods, and our evaluation of mature birds trend (same as the reference work) matches it perfectly.

Noteworthy, breeding sites of only ca. 40–50 pairs are known worldwide currently, which comprises about a quarter of the current breeding population estimate [21]. So in addition to all logistic issues in such remote and unpopulated areas, expansion of HS activities is limited by lack of sites where at least 10 breeding pairs could be found within a reasonable distance from each other and from facilities required for HS activities.

4. Discussion

It seems likely that chicks raised in captivity by humans have reduced abilities for independent living in nature. This might be a particular issue for long distance migrants experiencing variable environmental conditions in different parts of their range during the annual cycle. Our study provides the first opportunity to compare return rate, productivity, and several natural history characteristics for chicks of a long distance migrant wader species, the SbS, raised in semi-natural conditions in comparison with chicks raised by their parents in the wild.

4.1. Survival of Chicks

There is a high probability that SbS will lay replacement clutches early in a breeding season, suggesting that egg collection for HS has limited impact on the local SbS population. In addition, in our study site eggs are taken from only about half of the population, especially if we take into consideration the likelihood that not all replacement clutches were found before their loss due to predation. Overall return rates and maturity ages were similar for HS and wild chicks. Despite this finding, we cannot be sure that there is no difference in HS and wild chick survival, because the return rate of HS chicks is considered for fledglings. Wild chicks were marked mainly during the first days of their lives, and not more than 62.5% of those would fledge. Therefore, to get equal return rates for the two groups of chicks, the mortality of wild chicks would need to be compensated by higher survival rate after fledging.

4.2. Sex Issues in Chicks

We found the sex ratio in returned birds differed between those marked as HS and wild chicks. Annual sex ratios in the local breeding population of SbS never differed significantly from equality, although territorial solitary males were always present in small numbers. If females tend to disperse further than males, then it is likely that the same effect should be seen among HS birds. It is also possible that HS birds return to the vicinity of the aviary, which is situated in the centre of the monitoring team activities and, thus, it may be that a higher percentage of returning birds would be recorded. However, we consider this to be unlikely. Among chicks hatched and marked in the wild, only four females were later recorded breeding in the study area, two of which hatched in 2015, and other two in 2018. This might suggest that some unknown conditions in some seasons are influencing chicks' survival and thus the subsequent sex bias.

Since HS birds have lower post-natal dispersal in comparison with those marked as wild chicks, we would suggest that this finding evidences a good choice of the aviary site. This also suggests a potentially increased risk of inbreeding. However, in the only case when HS male and female siblings returned to the natal area, they settled 27 km apart.

Adult SbS males have shown 2.3% lower return rate than females (even though females are less site faithful and more cryptic so could be more easily missed in surveys). However, as with other local populations of monogamous waders, males in our study area outnumber females. As there is an equal sex ratio among embryos, it suggests there is higher mortality of females prior to breeding: among embryos, chicks, juveniles, and sub-adults. However, this could also be the result of some females dispersing outside the study area.

The sex ratio among wader embryos is generally close to parity (e.g., Ref. [43]), and our data on SbS embryos confirm this. Since for HS females survival from fledging to

arrival to natal area appears similar to HS males, it may suggest that wild females are lost prior to fledging. We were unable to find direct evidence for this, but there are examples in the literature. Liker et al. [44] found that species with male-biased care usually have a male-biased adult sex ratio. The ratio may also be biased at hatching as in the mountain plover (*Charadrius montanus*) (Ref. [45], but just within 10% of sex ratio difference. Heg et al. [43] did not find a sex bias in the survival of chicks during the hatch-to-fledge period in Eurasian oystercatchers (*Haematopus ostralegus*). Some higher hatch-to-fledge survival was shown for males of mountain plover chicks: 54.8% vs. 47.2% in females [45]. However, Saunders and Cuthbert [46] found significant male-biased survival during pre-fledging in piping plover. Eberhart-Phillips et al. [47,48] state that the survival rate of juveniles (fledging to first breeding) mainly defines sex ratio in breeding populations of the polygamous snowy plover, being also male-biased. For *L. limosa*, male-biased chicks' survival was explained by larger females failure to grow fast enough in poor habitats [49]. Hallgrímsson et al. [50] also found female juveniles were in a poorer condition than male in *C. maritima*. Significant difference in sex-related survival of chicks was found in the Kentish plover (*Ch. alexandrinus*) (Ref. [51]; although it appears to be too strong.

HS female chicks in this study had a slower growth rate than males, but they survive as well as males during captive rearing. However, a slower growth rate in the wild may lead to higher mortality [52]. In addition, many of the chicks marked in the wild are from replacement clutches, which may also affect the survival of slower growing female chicks. Slower growth rate of females after nearly equal initial size of chicks seems to be the most likely reason for the differences in sex ratio.

There is little information on sex ratio in juvenile calidrids captured during their first migration. For the great knot (*C. tenuirostris*), at a migration stopover in Kamchatka, Russia, average sex ratio (identified genetically) was male-biased (2:1, $n = 300$) (A. Ivanov, pers. comm.). Hallgrímsson et al. [50] found no significant deviation of sex rate from parity in purple sandpiper (*C. maritima*) chicks, but it was male-biased in juveniles (1.56:1), while for the dunlin (*C. alpina*) in Poland, it was female-biased (1:1.33, $n = 56$) [53]. However, in the latter study, sex was identified by dissection of birds that died accidentally at banding sites, which might affect the sample composition and reflect that females are more likely to die in this way. Other studies with sex ratio evaluations in waders mainly use data from the wintering grounds where bias could be caused by sex-specific spatial distribution over habitats. However, Summers et al. (2013) still found an apparent male bias among first-year purple sandpiper and bar-tailed godwit and suggested increased juvenile mortality among females to be responsible for the bias in breeding population.

4.3. Comparison to the Northern SbS Population

For the SbS population on Belyaka Spit on the Arctic coast of Chukotka [32], 36.4–66.7% (mean 50%) of nests survived annually to hatching (mean 46.9% success from 311 eggs found), and hatchability of eggs was slightly higher than in our study area: 91.5–95.2% annually (mean 93.6%, $n = 173$ eggs survived to hatching). Hatch-to-fledge rate was evaluated as at least 55%. However, the loss of a whole brood was not a rare event there. Despite rather high replacement probabilities (59% for clutches lost early, which is rather similar to our HS induced value, and 24% on average), the input of re-laying into productivity was rather low. On average, 0.57 chicks per pair were fledged from first clutches compared to 0.08 for replacements. This could be explained by higher predator activity later in the season on both sites and harsh weather conditions on the Arctic coast. In our study area in Southern Chukotka, we are likely to have found the pairs with less secret behaviour and collected their eggs to HS. This could also affect the reduced success of their replacement clutches.

Thus, for northern populations, HS gain could be significantly improved if first clutches are taken for artificial incubation, and then substituted with re-laid eggs. Thus, egg production is increased, and birds can rear first clutch chicks returned to them in more

favourable conditions, while aviculturists provide extra-care to replacement ones when it is especially needed later in the season.

The northern SbS population produced 0.31–0.95 (mean 0.58) fledged chicks per pair annually [32]. Almost the same figures were obtained for the population in southern Chukotka in 2003–2007: 0.61 ± 0.14 SE, range 0.32–0.93 [18]. Similarly, low breeding success continued to happen in our study area in some years. Three two-year-old males returned to the Arctic natal area (5.76%, $n = 52$), and one unmarked breeding first-year female was also caught. This result is half the average in our study area, but is similar to recent years, which might indicate the start of similar fast decline. Therefore, despite the much smaller sample size for the northern population, among first-breeders, both the fraction of returning first-years and sex ratio matched our findings in the southern population. Given the low productivity and an adult return rate of just 0.657 reported for Belyaka Spit in 1986–1988, it appears that this population was declining faster than our southern population. In addition, the northern population was estimated to be twice as high in 1974 [20,54]. However, to some extent, this difference could come from methods of counting birds there. Similar return rates of adults in both areas 30 years ago and currently also suggests that the population will continue to decline without HS.

4.4. Comparison to Other Headstarted Species

Data comparison between projects is not easy because of differences in methods and situations between HS activities and the species' natural histories. Thus, not a complete clutch like in case of SbS, but only one egg of two was collected for the takahē project [8]. For the piping plover [13] and snowy plover [14], abandoned eggs and, for the latter species, also chicks were taken. To improve the safety of clutches of American oystercatchers, anchoring of artificial eggs was used (mainly against flood), which increased probability of nest survival to hatching from 7–30% in a reference group and to 71–74% in the incubator [10]. For mangrove finches, only 27.7% of nests in nature were successful; therefore, egg collection considerably improved egg survival with help of HS [9].

The artificial hatch rate is usually similar to the natural hatch rate. Only maleo could be an exception with 41–78% success of parentless natural incubation, but 91% in Bronx Zoo [7]. For SbS, the artificial incubation success was ca. 10% less on average, although it reached the same levels as nests in the wild in some years. For piping plovers [13], hatch rates were 85% vs. 59% in nature, resulting in ca. 30% advantage of HS. Artificial hatching success for American oystercatchers was 62% and 84% in two subsequent years [10], but there are no data available on success in nature for comparison. For mangrove finches, the artificial hatching rate was 88.2% and unlikely to be improved considerably [9]. Black-tailed godwits artificial hatching rate was 79.3%, comprising 90.7% of eggs viable at collection [11].

The highest possible fledging rate is one of the main goals for HS projects, since captive rearing is usually the most demanding stage for resources. In the case of SbS, HS gain was ca. 1.6-fold compared to natural fledging and could hardly be improved over 92.9%. For piping plovers [13], the gain was similar, with 77% HS fledging rate compared to natural 50%, but this could still be improved. For the maleo, the protocol target was 40% in terms of reaching 30 days age [7]. For the takahē, 90% survival up to the age of 1 year has been reported with one- to fourfold improvement of the natural rate in different years [8]. All artificially hatched mangrove finches were fledged, a 2.9 higher rate than in nature [9]. For black-tailed godwits, the fledging rate was 91.3% [11]. For American oystercatchers that were not raised in captivity, hatching eggs were returned to the nest and mean fledged chicks output was lower for HS compared to natural—0.27 vs. 0.35 chicks per pair despite higher safety of clutches [10]. This suggests that without captive rearing and the opportunity for parents to re-nest, HS is far less effective and may not increase fledging rates at all.

For released takahē, 14% were resighted 4–9 years after release with no obvious difference in post-release mortality in comparison with birds raised naturally; eight females and two males (sex parity at release) are known to have bred [8]. No significant difference

was found in captive and wild-reared snowy plovers [14]: apparent survival to the age of 1 year (ca. 36%) and of 2+ years (ca. 69%). In both cohorts of snowy plovers, ca. 36% of birds were recruited to the local breeding population the next year after release. Captive-reared snowy plovers had slightly lower hatching and fledging rates than in naturally raised chicks, and HS males fledged fewer offspring in the subsequent breeding seasons. For piping plovers, threefold lower resighting rates (8–9%) for captive-reared birds were reported compared to wild-reared ones; however, there could be ecological reasons for that, not just a lower survival rate [14]. In black-tailed godwits, 26.6% of first-year-birds came back to the release site the next year [11], and 30.7% of the returnees attempted to breed. Results achieved for SbS show no significant difference in return rates of the HS and wild cohorts of chicks (in terms of marked birds, but different considering the age at marking), and suggested lower HS birds pairing capabilities. As SbS is a small, long distance migrant, it is not surprising that their fledging and return rates are lower than for other species. In addition, the majority of young SbS do not return to their natal areas until they are two years old.

4.5. Suggestions for Headstarting Improvement

Although headstarting has a positive effect on the population trend in SbS and provides the only chance to reduce its decline, the gain seems to be reduced over the life of the birds. The most critical periods are survival to the first and second arrivals to the breeding grounds. The findings of [38] should be implemented and further investigated for the earliest age at release, since that could double the apparent survival of captive-reared birds to first breeding. Reduced survival rates after first arrival on the breeding grounds could be caused by numerous threats, to which wild-reared birds are more resistant.

Lower survival of HS birds could be caused by their increased tameness to the presence of humans, which has been reported by observers on the wintering grounds. This could lead to increased mortality from active hunting or impact from other human activities like leaving fishnets open. This negative effect may be partially reduced by human and predator avoidance training at rearing and just after release of HS birds. Furthermore, nets used as the rearing pen walls could be made less net-like for the birds did not experience of safe net impacts. The latter issue could explain the finding of [38] that the highest post-release survival rate is reached for the age when the birds are just fledged and flying into the pen wall.

Another reason for lower survival may be that less viable chicks are still reared to fledging, but later congenital diseases and other health issues (including in-house infections and reproductive hormone-activated issues) affect their long-term survival. Effect of HS on genetic diversity in the population needs a special investigation [55,56]. Pairs (or long-term partners) whose nests are easier to find mainly due to proximity to the avicultural station have a competitive advantage, as there are more of their offspring fraction in the population. Ideally, such partners should be checked for unfavourable allele presence to reduce their spread in the population.

We have not found any negative effect of first clutches being collected from the same pairs (or females) in multiple years. However, we have seen a yearly effect (cold, strong wind and poor foraging abilities) on egg laying and shell thickness.

The positive effect of HS on the population of SbS could be increased if the sex ratio is changed in favour of females among released birds, but there is no simple way to implement that. However, sexing embryos [57,58] would allow females to be taken for HS, and males redistributed between nests. Some impact on females to stimulate them to produce more female embryos appears even less realistic. At the moment, the most realistic way is to select females among chicks just hatched in incubators to be raised in captivity, reducing their mortality to fledging. Males hatched from artificially incubated eggs could be returned to nature, while wild female chicks could be taken for captive rearing. This would require extra work in finding suitably aged broods and rapid sexing of chicks hatched in captivity.

Headstarting applied to the Arctic coast populations of SbS, where survival from replacement clutches is very low due to harsh weather conditions, could be more beneficial than for the southern ones where it was performed.

5. Conclusions

Implementation of HS for 10 years has shown that it helps to sustain or even slightly increase the local population of the critically endangered spoon-billed sandpiper. This was provided by a significant increase in egg production per pair due to stimulation of replacement clutches and high hatch-to-fledge survival rate ensured by careful captive rearing, which more than doubled the number of fledged chicks. The negative results were in reduced survival from fledging to recruiting in the natal area and pairing capabilities in the HS birds, still adding 1.4 more successful first-time breeders to the population. However, the 1.9-fold lower survival of HS first-breeders eliminates this initial advantage, which needs to be investigated. The additional unexpected positive result was an equal sex ratio among returned birds compared to an over threefold male bias among wild chicks marked during the same period. Calculated for breeding female recruiting, it is still not outweighed by the combination of all negative effects.

Based on the recruitment rate of marked chicks into the local breeding population as well as on annual return of recruits, we have shown that the local population can potentially be sustained using HS. Any future growth depends mainly on the return rate of juveniles that has dropped strongly in recent years. Without HS, there will be further, rapid decline. Headstarting gain can be improved by these data driven changes of protocols. Assuming that the local SbS population in Meinypil'gyno area comprises ca. 10% of the global population [21], HS is able to reverse the negative global trend only if there is no long-term gain reduction. Therefore, further improvement of SbS survival on the flyway is still the key to prevent SbS extinction. Meanwhile, HS scaling up (number of eggs collected) is able to provide extra time for other activities to increase survival of SbS on the flyway.

HS work has significantly improved understanding of SbS ecology, and ensured species safety at least in the study area. HS also has a significant social effect due to the involvement of an increasing number of people both in the local communities in Chukotka and from many countries on the flyway searching for marked SbS and learning about waders. This raises awareness of ecological problems on the EAAF, thus making the need for conservation actions on the flyway (not for SbS only) cleared and more acceptable.

Author Contributions: Conceptualisation, E.Y.L. and E.E.S.; methodology, E.Y.L., R.A.D., N.N.Y., I.A.S., J.P.C., P.S.T., N.S.J. and E.E.S.; validation, N.A.C. and R.E.G.; formal analysis, E.Y.L., P.S.T., N.A.C. and R.E.G.; investigation, E.Y.L., R.A.D., N.N.Y., I.A.S., J.P.C., P.S.T., N.S.J., N.A.C. and R.E.G.; resources, E.Y.L., N.S.J., N.A.C., E.G.L. and E.E.S.; data curation, E.Y.L., J.P.C., P.S.T. and N.A.C.; writing—original draft preparation, E.Y.L., J.P.C. and P.S.T.; writing—review and editing, E.Y.L., R.A.D., J.P.C., P.S.T., N.A.C., R.E.G. and E.E.S.; visualisation, E.Y.L. and P.S.T.; supervision, E.E.S.; project administration, N.S.J., N.N.Y. and E.G.L.; funding acquisition, N.S.J., N.A.C., E.G.L. and E.E.S. All authors have read and agreed to the published version of the manuscript.

Funding: The work has been funded from multiple sources over the years. The Wildfowl and Wetlands Trust (WWT), Royal Society for the Protection of Birds (RSPB) and Mangrove Conservation Fund (MCF) were the major sponsors. The work of E.G.L. was supported by the Russian Science Foundation (grant No. 22-17-00168). P.S.T. was supported by research project funding by the Lomonosov Moscow State University (No. 121032300105-0).

Data Availability Statement: Not applicable.

Acknowledgments: The authors are grateful to the non-authoring aviculturists and their assistants: Yuriy Bragin, Elizabeth Brown, Elizabeth Mackley, Richard Hesketh, Richard Smith, Nicola Hiscock, Anastasia Yukusheva, Yuriy Lobachev, Fyodor Kondrashov, Dmitriy Moseykin. Baz Hughes, Rebecca Lee, Christoph Zöckler and the Spoon-billed Sandpiper Task Force have provided invaluable organisational support. Numerous reporters of colour-marked SbS observations all over the flyway made these evaluations possible in principle. We also thank over a dozen field assistants who helped to locate SbS and find nests in our research area, of whom Tong Mu was the most long-standing. The data was stored and treated at research facility “Beam-M” (Bauman Moscow State Technical University). We thank the Animal Welfare and Ethics Committee of the Wildfowl and Wetlands Trust for scrutiny of the headstarting procedures. We are grateful to Jacquie Clark for English editing and anonymous reviewers for significant improvement of the manuscript.

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

References

1. Payevsky, V.A. *Demography of Birds*; Nauka: Leningrad, Russia, 1985.
2. Lack, D. *The Natural Regulation of Animal Numbers*; Clarendon Press: Oxford, UK, 1954; p. 343.
3. Studds, C.E.; Kendall, B.E.; Murray, N.J.; Wilson, H.B.; Rogers, D.I.; Clemens, R.S.; Gosbell, K.; Hassell, C.J.; Jessop, R.; Melville, D.S.; et al. Rapid population decline in migratory shorebirds relying on Yellow Sea tidal mudflats as stopover sites. *Nat. Commun.* **2017**, *8*, 14895. [[CrossRef](#)] [[PubMed](#)]
4. Piersma, T.; Lok, T.; Chen, Y.; Hassell, C.J.; Yang, H.-Y.; Boyle, A.; Slaymaker, M.; Chan, Y.-C.; Melville, D.S.; Zhang, Z.-W.; et al. Simultaneous declines in summer survival of three shorebird species signals a flyway at risk. *J. Appl. Ecol.* **2016**, *53*, 479–490. [[CrossRef](#)]
5. Murray, N.J.; Marra, P.P.; Fuller, R.A.; Clemens, R.S.; Dhanjal-Adams, K.; Gosbell, K.B.; Hassell, C.J.; Iwamura, T.; Melville, D.; Minton, C.D.T.; et al. The large-scale drivers of population declines in a long-distance migratory shorebird. *Ecography* **2018**, *41*, 867–876. [[CrossRef](#)]
6. Melville, D.S.; Chen, Y.; Ma, Z. Shorebirds along the Yellow Sea coast of China face an uncertain future—A review of threats. *Emu-Austral Ornithol.* **2016**, *116*, 100–110. [[CrossRef](#)]
7. Thomas, P.; Boyer, D.M.; Oehler, D.A.; Silver, S.; Perrotti, L. Headstarting as a Conservation Strategy for Threatened and Endangered Species. In *Scientific Foundations of Zoos and Aquariums: Their Role in Conservation and Research*; Kaufman, A.B., Bashaw, M.J., Maple, T.L., Eds.; Cambridge University Press: Cambridge, UK, 2019; pp. 91–111. [[CrossRef](#)]
8. Maxwell, J.M.; Jamieson, I.G. Survival and Recruitment of Captive-Reared and Wild-Reared Takahe in Fiordland, New Zealand. *Conserv. Biol.* **1997**, *11*, 683–691. [[CrossRef](#)]
9. Cunningham, F.; Switzer, R.; Parks, B.; Young, G.; Carrion, A.; Medranda, P.; Sevilla, C. Conserving the Critically Endangered Mangrove Finch: Head-Starting to Increase Population Size. In *Galapagos Report 2013–2014*; GNPD; GCREG; CDF; GC: Puerto Ayora, Ecuador, 2015.
10. Collins, S.A.; Sanders, F.J.; Jodice, P.G.R. Assessing conservation tools for an at-risk shorebird: Feasibility of headstarting for American Oystercatchers *Haematopus palliatus*. *Bird Conserv. Int.* **2016**, *26*, 451–465. [[CrossRef](#)]
11. Hiscock, N.; Brand, E.; Calvo-Carrasco, D.; Donaldson, L. *Headstarting the Black-Tailed Godwit Limosa Limosa at Key Breeding Sites for the UK Population: 2018 Annual Report*; Wildfowl & Wetlands Trust: Slimbridge, UK, 2018.
12. van Heezik, Y.; Maloney, R.F.; Seddon, P.J. Movements of translocated captive-bred and released Critically Endangered kaki (black stilts) *Himantopus novaezelandiae* and the value of long-term post-release monitoring. *Oryx* **2009**, *43*, 639–647. [[CrossRef](#)]
13. Powell, A.N.; Cuthbert, F.J.; Wemmer, L.C.; Doolittle, A.W.; Feirer, S.T. Captive-rearing piping plovers: Developing techniques to augment wild populations. *Zoo Biol.* **1997**, *16*, 461–477. [[CrossRef](#)]
14. Neuman, K.K.; Stenzel, L.E.; Warriner, J.C.; Page, G.W.; Erbes, J.L.; Eyster, C.R.; Miller, E.; Henkel, L.A. Success of captive-rearing for a threatened shorebird. *Endanger. Species Res.* **2013**, *22*, 85–94. [[CrossRef](#)]
15. Boyd, H.; Piersma, T. Changing balance between survival and recruitment explains population trends in Red Knots *Calidris canutus islandica* wintering in Britain, 1969–1995. *Ardea* **2001**, *89*, 301–317.
16. Lappo, E.G.; Tomkovich, P.S.; Syroechkovskiy, E.E. *Atlas of Breeding Waders in the Russian Arctic*; Publishing House “UF Ofsetnaya Pechat”: Moscow, Russia, 2012; p. 448.
17. Zöckler, C.; Beresford, A.E.; Bunting, G.; Chowdhury, S.U.; Clark, N.A.; Fu, V.W.K.; Htin Hla, T.; Morozov, V.V.; Syroechkovskiy, E.E.; Kashiwagi, M.; et al. The winter distribution of the Spoon-billed Sandpiper *Calidris pygmaeus*. *Bird Conserv. Int.* **2016**, *26*, 476–489. [[CrossRef](#)]
18. Zöckler, C.; Syroechkovskiy, E.E.; Atkinson, P.W. Rapid and continued population decline in the Spoon-billed Sandpiper *Eurynorhynchus pygmaeus* indicates imminent extinction unless conservation action is taken. *Bird Conserv. Int.* **2010**, *20*, 95–111. [[CrossRef](#)]
19. Tomkovich, P.S.; Syroechkovski, J.E.E.; Lappo, E.G.; Zöckler, C. First indications of a sharp population decline in the globally threatened Spoon-billed Sandpiper *Eurynorhynchus pygmaeus*. *Bird Conserv. Int.* **2002**, *12*, 1–18. [[CrossRef](#)]

20. Syroechkovski, E.E.; Tomkovich, P.S.; Kashiwagi, M.; Taldenkov, I.A.; Buzin, V.A.; Lappo, E.G.; Zöckler, C. Population decline in the spoon-billed sandpiper (*Eurynorhynchus pygmeus*) in northern Chukotka based on monitoring on breeding grounds. *Biol. Bull.* **2010**, *37*, 941–951. [\[CrossRef\]](#)
21. Green, R.E.; Syriechkovsliy, E.E.; Anderson, G.Q.A.; Chang, Q.; Chowdhury, S.U.; Clark, J.A.; Foysal, M.; Gerasimov, Y.; Hughes, B.; Kelly, C.; et al. New estimated of the size and trend of the world population of the Spoon-billed Sandpiper using three independent statistical models. *Wader Study* **2021**, *128*, 22–35. [\[CrossRef\]](#)
22. Clark, N.A.; Anderson, G.Q.A.; Li, J.; Syroechkovskiy, E.E.; Tomkovich, P.S.; Zöckler, C.; Lee, R.; Green, R.E. First formal estimate of the world population of the Critically Endangered spoon-billed sandpiper *Calidris pygmaea*. *Oryx* **2018**, *52*, 137–146. [\[CrossRef\]](#)
23. Peng, H.-B.; Anderson, G.Q.A.; Chang, Q.; Choi, C.-Y.; Chowdhury, S.U.; Clark, N.A.; Gan, X.; Hearn, R.D.; Li, J.; Lappo, E.G.; et al. The intertidal wetlands of southern Jiangsu Province, China—Globally important for Spoon-billed Sandpipers and other threatened waterbirds, but facing multiple serious threats. *Bird Conserv. Int.* **2017**, *27*, 305–322. [\[CrossRef\]](#)
24. Menxiu, T.; Lin, Z.; Li, J.; Zöckler, C.; Clark, N.A. The critical importance of the Rudong mudflats, Jiangsu Province, China in the annual cycle of the Spoon-billed Sandpiper *Calidris pygmeus*. *Wader Study Group Bull.* **2012**, *119*, 208–211.
25. Clark, N.A.; Pain, D.; Green, R.E. Saving the Spoon-billed Sandpiper: An update on the conservation programme. *Br. Birds* **2014**, *107*, 467–475.
26. Chang, Q.; Anderson, G.Q.A.; Brides, K.; Clark, J.A.; Clark, N.A.; Hearn, R.; Leung, K.; Melville, D.S.; Weston, E.; Weston, J.; et al. A high proportion of the world population of the Spoon-billed Sandpiper occurs at Tiaozini, China, during the post-breeding moult. *Wader Study* **2019**, *126*, 35–42. [\[CrossRef\]](#)
27. Zöckler, C.; Chowdhury, S.U.; Sun, L.; Qing, C.; Aung, P.P.; Clements, J.; Klovov, K.; Lappo, E.G.; Syroechkovskiy, E. The Spoon-billed Sandpiper *Calidris pygmaea* conservation project in 2019 and 2020: Population trends continue to be negative. *BirdingASIA* **2020**, *33*, 51–56.
28. Chowdhury, S.U.; Foysal, M.; Green, R.E. Accelerating decline of an important wintering population of the critically endangered Spoon-billed Sandpiper *Calidris pygmaea* at Sonadia Island, Bangladesh. *J. Ornithol.* **2022**, *163*, 891–901. [\[CrossRef\]](#)
29. Syroechkovskiy, E.E.; Lappo, E.G. Information from regions: Chukotka. *Inf. Mater. Work. Group Waders* **2002**, *15*, 17–18. (In Russian)
30. Tomkovich, P.; Syroechkovskiy, E.; Yakushev, N.; Loktionov, E.; Digby, R.; Shepelev, I. Spoon-billed Sandpipers in Meinypilgyno: Update of the 2016 breeding season. *Spoon-Bill. Sandpipers Task Force News Bull.* **2016**, *16*, 13–15.
31. Tomkovich, P.S. Maximum life longevity of some waders in Chukotka. *Inf. Mater. Work. Group Waders* **2003**, *16*, 55–56.
32. Tomkovich, P.S. Breeding biology and breeding success of the Spoon-billed Sandpiper *Eurynorhynchus pygmeus*. *Russ. J. Ornithol.* **1995**, *4*, 77–91.
33. Tomkovich, P.S. Spatial structure of the Spoon-billed Sandpiper (*Eurynorhynchus pygmeus*) population at the breeding grounds. In *Modern Ornithology*; Kurochkin, E.N., Ed.; Nauka: Moscow, Russia, 1994; pp. 130–148.
34. Tomkovich, P.S.; Loktionov, E.Y. Age of first breeding of Spoon-billed Sandpipers *Calidris pygmaea*. *Wader Study* **2021**, *128*, 96–98. [\[CrossRef\]](#)
35. Tomkovich, P.S. Migration of the Spoon-billed Sandpiper *Eurynorhynchus pygmeus* in the Far East of the Russian Federation. *Stilt* **1992**, *21*, 29–33.
36. Tomkovich, P.S. External morphology of the Spoon-billed Sandpiper (*Eurynorhynchus pygmeus*) at Chukotski Peninsula. *Ornithologia* **1991**, *25*, 135–144. (In Russian)
37. Cook, M.I.; Beissinger, S.R.; Toranzos, G.A.; Arendt, W.J. Incubation reduces microbial growth on eggshells and the opportunity for trans-shell infection. *Ecol. Lett.* **2005**, *8*, 532–537. [\[CrossRef\]](#)
38. Clements, J.; Loktionov, E.Y.; Yakushev, N.; Clark, N.A.; Digby, R.; Jarrett, N.; Shepelev, I.; Tomkovich, P.S.; Green, R.E. Effect of age at release on the post-release survival of head-started Spoon-billed Sandpipers. *Wader Study* **2022**, *129*, 100–104. [\[CrossRef\]](#)
39. Tomkovich, P.S.; Loktionov, E.Y.; Syroechkovskiy, E.E. Predators of wader nests in Southern Chukotka, Russia, as leant with camera traps. In *Actual Issues of Wader Studies in Northern Eurasia, Proceedings of the XI International Scientific and Practical Conference, Minsk, Belarus, 29 January–2 February 2019*; pp. 5–11. (In Russian).
40. Li, J.; Lin, Z. Spoon-billed Sandpiper in Jiangsu Province, China and Korea in spring and summer. *Spoon-Bill. Sandpiper Task Force News Bull.* **2016**, *16*, 22–23.
41. Moores, N.; Rogers, D.I.; Rogers, K.; Hansbro, P.M. Reclamation of tidal flats and shorebird declines in Saemangeum and elsewhere in the Republic of Korea. *Emu* **2016**, *116*, 136–146. [\[CrossRef\]](#)
42. Ma, Z.; Melville, D.S.; Liu, J.; Chen, Y.; Yang, H.; Ren, W.; Zhang, Z.; Piersma, T.; Li, B. Rethinking China's new great wall. *Science* **2014**, *346*, 912–914. [\[CrossRef\]](#)
43. Heg, D.; Dingemanse, N.J.; Lessells, C.M.; Mateman, A.C. Parental Correlates of Offspring Sex Ratio in Eurasian Oystercatchers. *Auk* **2000**, *117*, 980–986. [\[CrossRef\]](#)
44. Liker, A.; Freckleton, R.P.; Székely, T. The evolution of sex roles in birds is related to adult sex ratio. *Nat. Commun.* **2013**, *4*, 1587. [\[CrossRef\]](#)
45. Riordan, M.M.; Lukacs, P.M.; Huyvaert, K.P.; Dreitz, V.J. Sex ratios of Mountain Plovers from egg production to fledging. *Avian Conserv. Ecol.* **2015**, *10*, 3. [\[CrossRef\]](#)
46. Saunders, S.P.; Cuthbert, F.J. Chick mortality leads to male-biased sex ratios in endangered Great Lakes Piping Plovers. *J. Field Ornithol.* **2015**, *86*, 103–114. [\[CrossRef\]](#)

47. Eberhart-Phillips, L.J.; Küpper, C.; Carmona-Isunza, M.C.; Vincze, O.; Zefania, S.; Cruz-López, M.; Kosztolányi, A.; Miller, T.E.X.; Barta, Z.; Cuthill, I.C.; et al. Demographic causes of adult sex ratio variation and their consequences for parental cooperation. *Nat. Commun.* **2018**, *9*, 1651. [[CrossRef](#)]
48. Eberhart-Phillips, L.J.; Küpper, C.; Miller, T.E.X.; Cruz-López, M.; Maher, K.H.; dos Remedios, N.; Stoffel, M.A.; Hoffman, J.I.; Krüger, O.; Székely, T. Sex-specific early survival drives adult sex ratio bias in snowy plovers and impacts mating system and population growth. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, E5474–E5481. [[CrossRef](#)]
49. Loonstra, A.H.J.; Verhoeven, M.A.; Senner, N.R.; Hooijmeijer, J.C.E.W.; Piersma, T.; Kentie, R. Natal habitat and sex-specific survival rates result in a male-biased adult sex ratio. *Behav. Ecol.* **2019**, *30*, 843–851. [[CrossRef](#)] [[PubMed](#)]
50. Hallgrimsson, G.T.; Palsson, S.; Summers, R.W.; Benediktsson, G.Ö. Sex ratio and sexual size dimorphism in Purple Sandpiper *Calidris maritima* chicks. *Bird Study* **2011**, *58*, 44–49. [[CrossRef](#)]
51. Székely, T.; Cuthill, I.C.; Yezerinac, S.; Griffiths, R.; Kis, J. Brood sex ratio in the Kentish plover. *Behav. Ecol.* **2004**, *15*, 58–62. [[CrossRef](#)]
52. Clark, J.A. Selective mortality of waders during severe weather. *Bird Study* **2009**, *56*, 96–102. [[CrossRef](#)]
53. Meissner, W. Sex determination of juvenile Dunlins migrating through the Polish Baltic region. *J. Field Ornithol.* **2005**, *76*, 368–372. [[CrossRef](#)]
54. Tomkovich, P.S.; Soloviev, M.Y. Numbers of the Spoon-billed Sandpiper *Eurynorhynchus pygmeus* at the north of Kolyuchinskaya Gulf, Chukotka, and count methods for the species on breeding grounds. *Russ. J. Ornithol.* **2000**, *8*, 3–10.
55. Rönkä, N.; Pakanen, V.-M.; Pauliny, A.; Thomson, R.L.; Nuotio, K.; Pehlak, H.; Thorup, O.; Lehtikoinen, P.; Rönkä, A.; Blomqvist, D.; et al. Genetic differentiation in an endangered and strongly philopatric, migrant shorebird. *BMC Ecol. Evol.* **2021**, *21*, 125. [[CrossRef](#)]
56. Valdebenito, J.O.; Maher, K.H.; Zachár, G.; Huang, Q.; Zhang, Z.; Young, L.J.; Székely, T.; Que, P.; Liu, Y.; Urrutia, A.O. Sex differences in immune gene expression in the brain of a small shorebird. *Immunogenetics* **2022**, *74*, 487–496. [[CrossRef](#)]
57. Galli, R.; Preusse, G.; Schnabel, C.; Bartels, T.; Cramer, K.; Krautwald-Junghanns, M.-E.; Koch, E.; Steiner, G. Sexing of chicken eggs by fluorescence and Raman spectroscopy through the shell membrane. *PLoS ONE* **2018**, *132*, e0192554. [[CrossRef](#)]
58. Dutton, C.J.; Tieber, A. A Modified Protocol for Sex Identification of in Ovo Avian Embryos and Its Application as a Management TOOL for Endangered Species Conservation Programs. *J. Zoo Wildl. Med.* **2001**, *32*, 176–180. [[CrossRef](#)]

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