



Accelerating decline of an important wintering population of the critically endangered Spoon-billed Sandpiper *Calidris pygmaea* at Sonadia Island, Bangladesh

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Abstract

The critically endangered Spoon-billed Sandpiper *Calidris pygmaea* breeds in Russia and winters between Bangladesh and China. World population estimates during 2014–2019 suggested a decline at a mean rate of 8% per year. Several surveys of local populations also indicated declines. We report a rapid decline of another local population of the species based on a 9-year series of annual surveys during the boreal winter at Sonadia Island, Chattogram Division, Bangladesh. We made bounded-count estimates of local populations of the Spoon-billed Sandpiper and 25 other shorebird species based on monthly counts in each of nine winters (2012/2013 to 2020/2021). For three of these winters (2017/2018 to 2019/2020), we also made Lincoln–Petersen estimates of the local population of Spoon-billed Sandpipers using resightings and scan surveys of individually marked birds. Population and trend estimates for the two methods were similar during the 3-year period when results from both were available. Bounded-count estimates of Spoon-billed Sandpipers declined markedly over the 9-year period. Analysis of combined data from both methods indicated that an exponential decline at a mean rate of 9.5% per year during the period 2012/2013 to 2017/2018 was followed by a much more rapid decline at 49.1% per year during 2018/2019 to 2020/2021. Bounded-count estimates of the combined population of 25 other shorebird species in each winter showed no decline during the 9-year period, which suggests that the decline in the local population of the Spoon-billed Sandpiper was not part of a general decline in populations of wintering shorebirds due to local factors. Estimates of the mean trend of other Spoon-billed Sandpiper local populations and of the world population all indicate declines at broadly similar rates. We recommend immediate reassessment of threats faced by the Spoon-billed Sandpiper and improved conservation interventions.

Keywords Local population size · Population trend · Mark–resighting · Lincoln–Petersen · Leg-flags · Spoon-billed Sandpiper

Zusammenfassung

Beschleunigter Rückgang einer wichtigen Überwinterungspopulation des stark gefährdeten Löffelstrandläufers (*Calidris pygmaea*) auf der Insel Sonadia, Bangladesch. Der vom Aussterben bedrohte Löffelstrandläufer (*Calidris pygmaea*) brütet in Russland und überwintert im Gebiet zwischen Bangladesch und China. Schätzungen der gesamten Populationsgröße weltweit für den Zeitraum 2014–2019 deuten auf einen Rückgang von durchschnittlich 8% pro Jahr hin.

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Mehrere Erhebungen für lokale Populationen wiesen ebenfalls auf Rückgänge hin. Wir berichten hier über den raschen Rückgang einer anderen lokalen Population dieser Art, erfasst durch jährliche Erhebungen über neun Jahre während des nördlichen Winters auf der Insel Sonadia, Distrikt Chattogram, Bangladesch. Auf der Grundlage von monatlichen Zählungen in allen neun Wintern (2012/2013 bis 2020/2021) wurden Schätzungen der lokalen Populationsgrößen des Löffelstrandläufers und 25 weiterer Küstenvogelarten vorgenommen. Für drei dieser Winter (2017/2018 bis 2019/2020) nahmen wir außerdem anhand von Wiederfinden und Erhebungen bei einzeln markierten Vögeln Lincoln-Petersen-Schätzungen der lokalen Löffelstrandläufer-Population vor. Die Populations- und Trendschätzungen waren während des Dreijahreszeitraums, für den die Ergebnisse beider Methoden verfügbar waren, für beide ähnlich. Die Schätzungen auf der Basis der begrenzten Anzahl von Löffelstrandläufern sind im Verlauf der neun Jahre deutlich zurückgegangen. Die Analyse der kombinierten Daten aus beiden Methoden ergab, dass auf einen exponentiellen Rückgang mit einer durchschnittlichen Rate von 9,5% pro Jahr im Zeitraum 2012/2013 bis 2017/2018 im Zeitraum 2018/2019 bis 2020/2021 ein wesentlich schnellerer Rückgang von 49,1% pro Jahr folgte. Die Schätzungen der kombinierten Population von 25 anderen Küstenvogelarten in jedem Winter zeigten keinen Rückgang während des neunjährigen Zeitraums, was darauf schließen lässt, dass der Rückgang der lokalen Population des Löffelstrandläufers nicht Teil eines allgemeinen Rückgangs der Populationen überwinternder Küstenvögel aufgrund lokaler Faktoren war. Schätzungen des mittleren Trends für andere lokale Löffelstrandläuferpopulationen und für die Weltpopulation deuten alle auf einen Rückgang mit weitgehend ähnlicher Geschwindigkeit hin. Wir empfehlen eine sofortige Neubewertung der Gefährdungsfaktoren für den Löffelstrandläufer sowie verbesserte Schutzmaßnahmen.

Introduction

The Spoon-billed Sandpiper *Calidris pygmaea* is listed as Critically Endangered on the IUCN Red List (BirdLife International 2021) because of its small global population and recent rapid rate of population decline. It breeds on coastal tundra in the Arctic and sub-Arctic zones of the Far East of the Russian Federation (BirdLife International 2021; Lappo et al. 2012). In the non-breeding season, it migrates to spend the boreal winter in coastal habitats, especially estuarine intertidal mudflats, in southeast Asia, between Bangladesh and south China (Zöckler et al. 2016).

Ten Lincoln–Petersen mark–resighting estimates of the global population size of the Spoon-billed Sandpiper during 2014–2019 indicated a mean population size at the end of the breeding season of 490 mature individuals and 773 individuals of all ages. Two of these estimates were based upon scan surveys at the site of the present study. These estimates also suggested a possible decline at a mean rate of 8% per year (Green et al. 2021), but the population trend was not estimated precisely and its 95% confidence interval overlapped zero (no change). Surveys at the Gulf of Mottama (Mon State, Myanmar), which is most important known site for the species during the boreal winter, also indicated a decline in the size of the local population, which declined at a mean rate of 9% per year during 2009–2016, but the rate was only estimated with low precision (Aung et al. 2020). A four-year series of Lincoln–Petersen estimates of local population size of adult Spoon-billed Sandpipers at Tiaozini (Jiangsu Province, China), which was used by approximately half of the world population of adults during their post-breeding moult in September–October in 2017, found a decline at a mean rate of 16% per year between 2017 and 2020 (Chang et al. 2021). A repeat survey using the same method found a further decline of 22% at this site between

2020 and 2021 (Leung and Chang 2021). The decline in numbers at this site may have been caused by rapid changes in the topography of the intertidal mudflats used for foraging (Chang et al. 2021). The decline at this important site was not compensated for by increased numbers at other monitored sites within 50 km of Tiaozini (Chang et al. 2021; Leung and Chang 2021).

Against this background of suggestive but incomplete evidence of declines in the world population of Spoon-billed Sandpipers, we report here a new analysis of a 9-year series of annual surveys of the species during the boreal winter at Sonadia Island (Chattogram Division, Bangladesh). Zöckler et al. (2016) reported counts at this site of between 12 and 27 birds during the boreal winters (November–March) of 2006–2013. Between zero and two birds, presumably immatures, were also recorded there during five boreal summers of 2011–2015 (Chowdhury and Foysal 2017). In this paper, we make bounded-count estimates for each of nine winters (2012/2013 to 2020/2021), based on 5 monthly (November–March) counts per winter. For three of these winters (2017/2018 to 2019/2020), we compare the bounded-count results with Lincoln–Petersen estimates of the local population, using mark–resighting and scan surveys of individually marked birds.

Methods

Study area

Sonadia Island (centre at 21.511° N 91.884° E) is in Maheshkhali subdistrict, Cox's Bazar district in Chattogram Division, on the coast of southeastern Bangladesh. It covers 49 km² and consists of a variety of coastal wetland habitats, including mudflats, sand dunes, mangroves, sandbars,

lagoons, salt pans and beaches (Fig. 1). Further details are provided by Chowdhury and Foysal (2017). The observations we report in this paper were made on part of the site in an area of intertidal mudflats at Kaladia (21.554° N 91.862° E), which is approximately 370 ha in extent at low tide during neap tides.

Rationale of the study

We wished to assess the trend in numbers of Spoon-billed Sandpipers using the Kaladia mudflat during a series of nine consecutive boreal winters. The mudflat was used consistently for foraging by Spoon-billed Sandpipers during some parts of the tidal cycle. However, they were not always present in large numbers when mud was exposed and we therefore recognise that counts at this site were unlikely to represent full censuses of the local wintering population because some of the individuals comprising the population probably spent some of their time on other unsurveyed parts of the coast (Chowdhury et al. 2017). We conclude that population estimation methods that allow for incomplete detection are required. We used two such methods: bounded-count estimation (Robson and Whitlock 1964) and Lincoln–Petersen estimation (Chang et al. 2019). In using these methods, we made the following assumptions: (1) that there was a local wintering population of the species on Sonadia Island, all individuals of which used the Kaladia mudflat on some, but not necessarily all, low-tide periods, (2) that the Sonadia Island population was closed during our study period between November and March, in

that individuals did not arrive or leave Sonadia permanently, though they moved between the Kaladia mudflat and other areas at Sonadia Island and (3) that mortality in the course of the winter was at a low enough level to be ignored. The first assumption seems reasonable, given that monthly counts of Spoon-billed Sandpipers at Kaladia fluctuated and marked individuals were recorded on some but not all survey visits throughout the winter (see “Results”). With regard to the second assumption, satellite-tracking studies have shown that Spoon-billed Sandpipers arrive on their wintering sites in early November and then remain at the site throughout the boreal winter up to March (Chang et al. 2020). Hence, we did not expect there to be migratory arrivals and departures to and from the study area to occur during the winter. There was likely to be some mortality during the course of the winter, but it has been shown for some other migratory shorebird species that mortality during winter is lower than in other phases of the annual cycle (Swift et al. 2020). In any case, we analysed monthly count data to check for any consistent decline in numbers counted across the five-month winter period, which would be expected in there was appreciable mortality (see “Results”).

In addition to estimating the trend over time in the local population of Spoon-billed Sandpipers, we also assessed changes in the numbers in the same study area of all other shorebird species combined, using the bounded-count method. Our objective was to check whether changes in Spoon-billed Sandpiper numbers were likely to have been caused by changes in habitat, the abundance of invertebrate food or disturbance from human activities, which

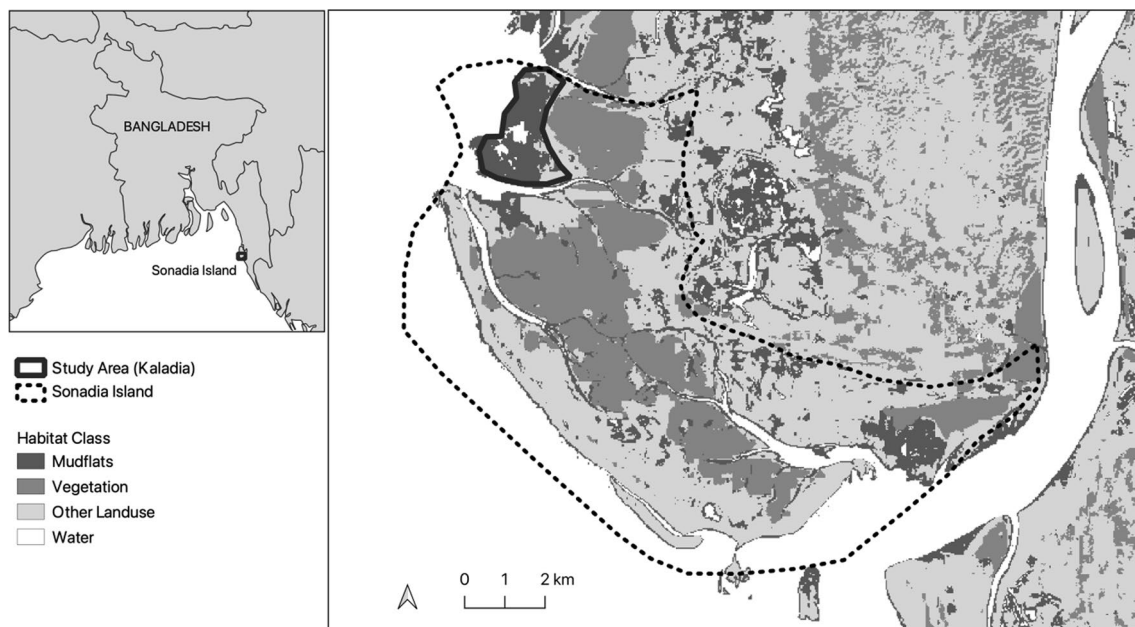


Fig. 1 Map of the Kaladia mudflats at Sonadia Island, Cox's Bazar, Bangladesh

might be expected to affect the aggregated total of other shorebird species (Zhang et al. 2019).

Monthly shorebird counts

We used standard methods for counting non-breeding shorebirds outlined by Bibby et al. (2000), Li et al. (2009), and Chowdhury and Foysal (2017). Between two and four observers, all with at least ten years of shorebird survey experience, conducted the counts on each occasion. One of us (MF) participated in all of the counts. The boundaries of the surveyed site were the same for each count (Fig. 1). Observations were made using 10×42 binoculars and 25–50× spotting scopes. We counted all shorebird species present. Each flock was counted twice, with the second count being immediately after the first. We recorded the larger of the two counts for each species. We scanned each flock for Spoon-billed Sandpipers, which were usually foraging singly within flocks of other shorebird species and were much less numerous. The time spent surveying on each occasion varied depending upon the number of shorebirds present, but was typically 3–8 h. We undertook all counts during neap tides and covered both the falling and rising tides.

Individually marked Spoon-billed Sandpipers

We recorded the presence or absence and identity of individual marks on the Spoon-billed Sandpipers in our study area. We did not capture any Spoon-billed Sandpipers for marking within our study area: all of the marked birds recorded had been marked elsewhere. Marks were coloured uPVC leg-flags applied to the right or left tibia and engraved with two black alphanumeric characters (Clark et al. 2005; Lee et al. 2016). We refer to individuals by the two-character inscription on the flag, prefixed by the flag colour (L = lime green, Y = yellow, W = white). Hence, the bird with yellow flag EU is referred to as YEU. We recorded seven flagged individuals in the boreal winters 2017/2018, 2018/2019 and 2019/2020 when scan surveys were conducted. Five of these (L09, L31, W3C, W3M, WMC) had been marked as adults or chicks on the breeding grounds in the Russian Federation at Meinypil'gyno, Chukotka, Russia (62.533° N 177.050° E), one (YVE) was marked as a juvenile at Ustyevoe (54.183° N 155.817° E) at an autumn migration stopover site on the west coast of the Kamchatka Peninsula, Russia, and one adult (YEU) was marked during its post-breeding moult at Tiaozini, Jiangsu Province, China (32.761° N 120.970° E).

Scan surveys and flag reading

We conducted scan surveys in November–March of the boreal winters 2017/2018, 2018/2019 and 2019/2020. We located Spoon-billed Sandpipers foraging on the mudflats at Kaladia using binoculars or spotting scopes when the tide level was between 0.5 and 2.5 m relative to the local datum. We aimed to estimate the proportion of Spoon-billed Sandpipers in the local population that had an individually identifiable leg-flag. To do this, we watched each Spoon-billed Sandpiper that we detected to establish whether or not it had a leg-flag. To be eligible for inclusion in the scan survey analysis, each bird had to be observed well enough and at close enough range for the observer to be confident that both tibiae were checked for marks. It was often necessary to watch a bird for several minutes to do this. Resting birds were excluded from the scan sample if they remained sitting and their tibiae could not be seen. Birds that were too distant to be checked or that flew away before a good enough view could be obtained were also excluded. The presence or absence of flags was assessed whenever the observer found an individual which might not have been checked before during that fieldwork session. Birds were not disregarded if the observer realised, by reading the flag, that they had previously recorded the same marked individual recently nearby. Unmarked birds were also recorded when located, despite being suspected to be the same ones as had been recorded previously (Chang et al. 2019; Green et al. 2021). We recorded the colour of the flag (light green, white or yellow) and its position (left or right tibia), even if the flag inscription could not be read. We read flag inscriptions using 25–50× spotting scopes and also collected images of marked Spoon-billed Sandpipers using a DSLR camera with a 300 mm lens. We were not always able to read the inscription on a flag directly, but it was sometimes possible to decipher it afterwards using the images. The date, time and GPS co-ordinates were recorded for all scan surveys and flag reading observations.

Bounded-count analysis

We analysed the monthly count data in two stages. In the first stage, we wished to establish whether the number of birds recorded on the monthly counts showed any consistent tendency to decline during the course of the winter. This was a necessary first step because the bounded-count method assumes that the population is closed within the study period and is only affected by mortality, immigration and emigration to a negligible extent (Robson and Whitlock 1964; Johnson et al. 2007). Although we did not expect many arrivals and departures to and from the study area to occur during the winter, there was likely to be some mortality affecting population size during the course of the winter, which might be

apparent as a consistent decline in numbers counted across the 5-month winter period.

We performed an ordinary least squares regression and analysis of covariance with \log_e -transformed monthly count as the dependent variable. We treated the month of the count (coded 1–5 for November to March) as a continuous covariate and analysed the effect on count of different winters by including it in the model as an eight-level categorical variable. Our objective was to estimate the within-winter trend in $\log_e(\text{count})$ in relation to survey month and to test whether the regression slopes of $\log_e(\text{count})$ on survey month varied significantly among winters.

The second stage of the analysis was to estimate the size of the local population of Spoon-billed Sandpipers in each winter from the five monthly counts using the bounded-count method of Robson and Whitlock (1964). We used the notation and methods of Johnson et al. (2007). We ranked the five counts for each winter and identified the largest count $X_{(k)}$ and the second-largest count $X_{(k-1)}$. The bounded-count estimate was $2X_{(k)} - X_{(k-1)}$ and its 95% confidence interval was: lower bound = $X_{(k)}$, upper bound = $X_{(k)} + (X_{(k)} - X_{(k-1)}) \cdot 0.95/0.05$. We also used the monthly counts of other shorebird species, pooled across all species, to calculate bounded-count estimates of their numbers in each winter by the same method.

Lincoln–Petersen estimate of the total number of Spoon-billed Sandpipers

We calculated the local population size by dividing a closed-population mark–resighting estimate of the total number of marked individuals present in each winter N by a scan survey estimate of the proportion of birds that were marked F . Hence, the Lincoln–Petersen estimate was N/F . We performed this analysis in two stages. First, we estimated the numbers of individually marked Spoon-billed Sandpipers present in each winter N . We used a closed-population mark–resighting method which was previously used by Chang et al. (2019, 2021) to estimate a local population of Spoon-billed Sandpipers at a post-breeding moult site in Jiangsu Province, China.

We divided the scan survey results for each winter by date into three time periods such that each period had a similar number of scan survey records and had at least ten records. We then used the information on whether each marked individual was recorded or not in each of the three periods to estimate the mean probability of detection u per period. To do this, we assumed that the probability of detection was the same in each of the three periods and fitted a closed-population mark–resighting model using the maximum-likelihood methods described by Lukacs (2018) and the Huggins conditional likelihood formulation (Huggins 1989). The estimated number of individuals present N was then obtained

by dividing the number of marked individuals detected during the whole winter by the probability of detection for the whole winter $1 - (1 - u)^3$. We used the asymptotic standard error of u and the delta method (Cooch and White 2021) to calculate the 95% confidence interval of the estimate of N .

In the second phase of the analysis, we estimated the proportion of Spoon-billed Sandpipers in the local population that were individually marked F in each winter by dividing the number of observations of marked birds on scan surveys M by the total number of scan survey records of all birds S . We calculated Clopper–Pearson exact binomial 95% confidence intervals for each value of F (Clopper and Pearson 1934) and also a 95% confidence interval based upon the asymptotic large-sample standard error of F which is $\sqrt{[F(1 - F)/S]}$.

Finally, we calculated the Lincoln–Petersen estimate of local population size by dividing the total number of marked individuals detected in each winter N by the scan survey estimate of the proportion of birds that were marked F . We obtained the 95% confidence interval for N/F by the delta method (Cooch and White 2021), using the asymptotic standard errors of u and F .

Regression analysis of bounded-count and Lincoln–Petersen estimates of Spoon-billed Sandpiper populations

We used ordinary least squares regression to analyse the nine bounded-count estimates and three Lincoln–Petersen estimates. We \log_e -transformed these values and treated them as the dependent variable in our analyses. We performed the analysis in two stages. We first wished to determine whether the values and trend in relation to year of $\log_e(\text{population})$ were similar for the bounded-count and Lincoln–Petersen estimates during the 3-year period in which we had both types of estimate. We calculated the difference in $\log_e(\text{population})$ between the results from the two methods in each winter and obtained the mean and standard error of these differences. We also compared trends estimated by the two methods by regression modelling of $\log_e(\text{population})$ in relation to year as a continuous covariate, with estimation method coded as a binary variable (bounded-count = 0; Lincoln–Petersen = 1). We used an F test of the significance of the interaction term between year and estimation method. In the second stage of the analysis, we modelled all 12 $\log_e(\text{population})$ values (nine from the bounded-count method and three from Lincoln–Petersen) together in relation to year as a continuous covariate using piece-wise regression, assuming one breakpoint. We determined the breakpoint value (year) iteratively by finding the value at which the residual sums of squares of the fitted model was minimised.

Results

Within-winter trend in Spoon-billed Sandpiper counts

We found no consistent tendency for monthly counts to increase or decrease with time during the course of a winter (Table 1). Five of the nine regression coefficients of $\log_e(\text{count})$ on month were negative, the other four being positive. Analysis of covariance indicated that the interaction term between winter (as a factor) and the linear effect of month was non-significant ($F_{7,27} = 1.855$, $P = 0.110$). We conclude that the slope of the within-winter relationship between $\log_e(\text{count})$ and month did not vary significantly among winters. For the model with effects of winter as a factor and with the slope of the within-winter relationship between $\log_e(\text{count})$ and month assumed constant across winters, there was no indication of a marked within-winter trend. The slope of the fitted regression was not significantly different from zero (slope = -0.0236 , $t_{35} = 0.744$, $P = 0.462$). The modelled change in count between the beginning of November and the end of March, calculated from the regression coefficient, was a decrease

in count of 11%, with its 95% confidence interval being a decrease of 33% and an increase of 23%. Based on these results, we consider it acceptable to treat systematic trends within-winter in counts of Spoon-billed Sandpipers as being negligible for the purposes of the bounded-count analysis.

Bounded-count and Lincoln–Petersen estimates of the local population of Spoon-billed Sandpipers

Bounded-count estimates of the local population of Spoon-billed Sandpipers varied among winters between 4 and 32 individuals (Table 1). Lincoln–Petersen estimates varied between 4.9 and 22.7 individuals (Table 2). Bounded-count and Lincoln–Petersen local population estimates were both available for three winters. The mean difference in $\log_e(\text{population})$ between results from the two methods for the same winter was -0.191 (1 SE = 0.212), indicating that the mean Lincoln–Petersen estimate was 17% lower than the mean bounded-count estimate. However, one of the three Lincoln–Petersen estimates (that for 2017/2018) was 26% higher than the bounded-count estimate and the mean difference was therefore not statistically significantly

Table 1 Monthly counts of Spoon-billed Sandpipers and all other shorebird species combined at Kaladia mudflat, Sonadia Island (Cox's Bazar, Bangladesh) in nine boreal winters between 2012/2013 and 2020/2021

Boreal winter	Monthly count totals X					Largest count $X_{(k)}$	Second largest count $X_{(k-1)}$	Bounded-count estimate	95% CI of estimate
	November	December	January	February	March				
<i>Spoon-billed Sandpiper</i>									
2012/2013	23	16	15	13	11	23	16	30	23–156
2013/2014	20	12	18	19	26	26	20	32	26–140
2014/2015	17	16	23	19	9	23	19	27	23–99
2015/2016	14	17	19	18	21	21	19	23	21–59
2016/2017	17	18	14	15	11	18	17	19	18–37
2017/2018	16	5	16	18	18	18	18	18	18–18
2018/2019	9	10	14	10	10	14	10	18	14–90
2019/2020	5	7	7	6	4	7	7	7	7–7
2020/2021	4	4	3	2	3	4	4	4	4–4
<i>Other shorebird species</i>									
2012/2013	379	594	807	1406	1161	1406	1161	1651	1406–6061
2013/2014	3685	2626	1224	2000	941	3685	2626	4744	3685–23,806
2014/2015	884	3823	1708	1585	1454	3823	1708	5938	3823–44,008
2015/2016	1006	5529	977	3867	1608	5529	3867	7191	5529–37,107
2016/2017	1371	4908	3444	2199	1320	4908	3444	6372	4908–32,724
2017/2018	3361	1403	2680	2400	2404	3361	2680	4042	3361–16,300
2018/2019	3598	7597	3088	979	1638	7597	3598	11,596	7597–83,578
2019/2020	1348	2869	3801	2848	509	3801	2869	4733	3801–21,509
2020/2021	1528	3907	1683	1508	1205	3907	1683	6131	3907–46,163

Bounded-count estimates of population size for each winter and 95% confidence intervals (CI) were calculated from the largest and second largest counts

Table 2 Lincoln–Petersen estimates of the size of the local population of Spoon-billed Sandpipers at Kaladia mudflat, Sonadia Island (Cox’s Bazar, Bangladesh) in three boreal winters between 2017/2018 and 2019/2020

Parameter	Value for this boreal winter		
	2017/2018	2018/2019	2019/2020
Number of scan survey dates	8	6	7
Number of marked individuals recorded for winter	5	2	3
Estimated number of marked individuals present N	5.5	2.1	3.0
95% CI of N	5.0–8.4	2.0–4.0	3.0–3.4
Number of scan survey records S	127	49	41
Number of scan survey records of marked birds M	31	9	25
Proportion marked $F = M/S$	0.244	0.184	0.610
Clopper–Pearson 95% CI of F	0.172–0.328	0.088–0.320	0.445–0.758
Asymptotic 95% CI of F	0.169–0.319	0.075–0.292	0.460–0.759
Local population estimate N/F	22.7	11.5	4.9
95% CI of local population estimate	16.3–38.8	6.5–27.7	4.0–6.8

different from zero ($t_2 = 0.900$, $P = 0.463$). Confidence intervals for the two types of estimates overlapped substantially in the 2017/2018 and 2018/2019 winters, but in the 2019/2020 winter, the Lincoln–Petersen estimate was lower than the bounded-count estimate and the two 95% confidence intervals did not overlap (Tables 1, 2). The trends in $\log_e(\text{population})$ in relation to year for the two methods during the 3-year period were broadly similar and both were strongly negative (regression slopes; bounded-count -0.472 [1 SE = 0.273]; Lincoln–Petersen -0.763 [1 SE = 0.047]). Analysis of covariance indicated a non-significant interaction term between year and estimation method ($F_{2,2} = 0.891$, $P = 0.529$). We, therefore, conclude that it is reasonable to use the estimates from the bounded-count and Lincoln–Petersen methods together in further analyses of trends in population size over time.

Trends in Spoon-billed Sandpiper local winter population size over time

Considering initially only the bounded-count local population estimates, we found a highly significant tendency for the population to have declined over the 9-year period (Spearman rank correlation $r_s = -0.967$, $P < 0.0001$). Examination of a graph of population estimates in relation to year (Fig. 2) suggested that a period of exponential decline at a constant rate (i.e. linear decline when population is plotted on a logarithmic scale) was followed by a period of much more rapid decline. We tested this conjecture by fitting a piece-wise regression model, which gave a significantly better fit than a model with a constant rate of decline of $\log_e(\text{population})$ ($F_{2,8} = 14.400$, $P = 0.002$). The breakpoint of the regression model occurred between the 2017/2018 and 2018/2019 winters (Fig. 2). The rate of geometric population growth, obtained from the regression model, was -0.1000 (1 SE = 0.03294) before the breakpoint and

-0.6754 (1 SE = 0.0792) after the breakpoint. These rates are equivalent to mean annual rates of decline of 9.5% per year and 49.1% per year respectively.

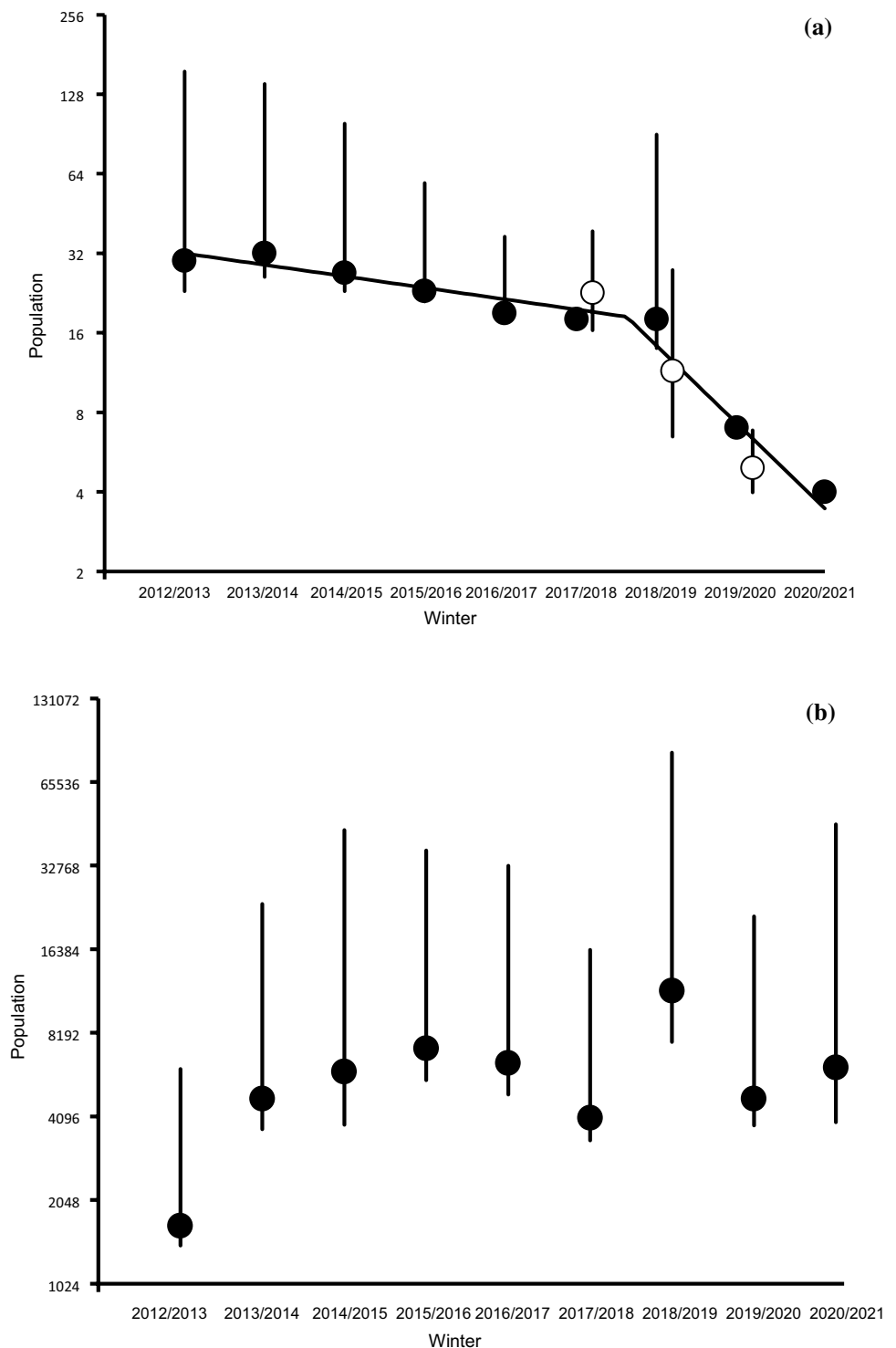
Changes in numbers of other shorebird species

During the whole study period we obtained monthly counts of all 25 of the shorebird species (Supplementary information) other than Spoon-billed Sandpiper observed during the study. The bounded-count estimates of the total population of these species combined for each winter showed no clear trend over the nine-year period (Spearman rank correlation $r_s = 0.317$, $P = 0.445$; Table 1; Fig. 2). We conclude that the decline in the local population of the Spoon-billed Sandpiper has not been accompanied by a general decline in populations of other wintering shorebird species due to local factors.

Discussion

Our study provides clear evidence of a rapid and accelerating decline in the local population of the critically endangered Spoon-billed Sandpiper during the boreal winters of a nine-year period. It also offers further evidence that Lincoln–Petersen analysis of resightings of individually marked birds is a useful tool to determine local population trends. At the beginning of our study, Sonadia Island was an internationally important wintering area for the species. At that time, it held about 4% of the world population, using the estimate of 773 individuals of all ages for the period 2014–2019 proposed by Green et al. (2021). Between the boreal winters of 2012/2013 and 2017/2018 the Sonadia population declined at an average rate of 9.5% per year. This rate of decline is similar to those reported for the world population between 2014 and 2019 (7.8% per year; Green et al. 2021) and for the formerly large wintering population at the Upper Gulf of Mottama, Myanmar, between 2009 and 2016

Fig. 2 Bounded-count (filled circles) and Lincoln–Petersen (open circles) estimates of the size of **a** the local population of Spoon-billed Sandpipers at Sonadia Island in nine boreal winters. Vertical lines show 95% confidence intervals of the estimates. The line is the piece-wise ordinary least squares regression model fitted to \log_e -transformed values from both methods combined. **b** The equivalent graph for bounded-count estimates of the population of all other shorebird species combined. The vertical axes are logarithmic, but the values shown on them are not transformed



(8.7% per year; Aung et al. 2020), which held 31% of the estimated world population in 2009. These three estimates of decline at broadly similar mean rates, including from ten Lincoln–Petersen estimates of the world population based upon data from four widely separated monitoring sites, suggest that population changes are occurring, rather than redistribution of birds within the geographical range.

From 2017/2018 to 2020/2021, the rate of decline of the Spoon-billed Sandpiper population at Sonadia Island has accelerated and it seems unlikely that it will persist at the site for much longer. Other wintering sites for the species are known in Bangladesh (Bird et al. 2010; Chowdhury et al. 2017, 2020), but none are reported to have substantially increased populations in recent years, so it seems

unlikely that birds that formerly wintered at Sonadia Island have moved to other places in Bangladesh. The lack of any evidence of decline in the combined numbers of shorebirds of species at Sonadia Island suggests that changes in habitat, food supply or disturbance are not likely to have caused the rapid decline of Spoon-billed Sandpiper numbers there. Furthermore, the site is better protected with regular guarding by local community members. Shorebird hunting was not reported in the area since 2011 (Chowdhury and Chowdhury 2018).

Mortality caused by loss of intertidal foraging habitat to land claim has been identified previously as a probable environmental driver of the decline of the global Spoon-billed Sandpiper population (Zöckler et al. 2010a). Recent land claim causing loss and degradation of intertidal mudflats important as foraging habitat for Spoon-billed Sandpipers and other shorebird species has proceeded at especially high rates around the Yellow Sea (Murray et al. 2014). Studds et al. (2017) found that variation among different species and populations of shorebirds on the East-Asian Australasian Flyway in their recent rate of population decline was closely correlated with the degree to which each species relies upon the Yellow Sea wetlands during its annual migration cycle. The analysis by Studds et al. (2017) did not include any data on Spoon-billed Sandpipers, but the species is highly dependent on the Yellow Sea region during both the autumn and spring migrations (Chang et al. 2020). The rate at which the world population of the species was declining up to 2019 is similar to that expected from the cross-species regression analysis of data from other species by Studds et al. (2017), so this provides some quantitative support for the hypothesis that land claim of intertidal wetlands has contributed to causing the decline.

Mortality of Spoon-billed Sandpipers during the non-breeding season caused by hunting has been documented in Myanmar (Zöckler et al. 2010b) and China (Martinez 2014). Conservation efforts co-ordinated by the Spoon-billed Sandpiper Task Force of the East Asian–Australasian Flyway Partnership have probably reduced this mortality at some sites (e.g. Aung et al. 2018; Chowdhury 2010; Chowdhury and Foysal 2014; Htin Hla et al. 2011). However, results from tracking onward migration of satellite-tagged individuals from their autumn stopover sites indicate that less than half of them spent the boreal winter at sites covered by counting surveys (Green et al. 2021), so there may well be other wintering locations where hunting has important effects which have not yet been rigorously documented. In recent years, hunting has also been reported along the Gulf of Tonkin coastline in Vietnam (Nguyen et al. 2021; Yong et al. 2022) as well as in Kamchatka (Gerasimov et al. 2018) and Sakhalin (Aleksandr et al. 2021) in the Russian Far East. Other factors such as coastal pollution (Tang et al. 2015), the loss of open mudflats caused by the spread of Smooth

Cordgrass *Spartina alterniflora* (Kirby 2010; MacKinnon et al. 2012; Zuo et al. 2012), lack of suitable high tide roosts (Jackson et al. 2021) and the establishment of new mangrove plantations on mudflats (Choi et al. 2022) may also be contributing to the decline of the Spoon-billed Sandpiper population.

Conclusions

The rate of decline of the Spoon-billed Sandpiper, based upon repeat surveys at other non-breeding season sites using methods that allow for incomplete detection and Lincoln–Petersen estimates of the world population based upon data from four widely separated monitoring sites (Green et al. 2021), suggest that the global population is declining. No increases in local populations have been detected so far using these methods, so no clear evidence exists at present that redistribution of birds within the geographical range during boreal winter can explain these observations. Totals from annual coordinated January counts throughout the winter range during 2015–2020 also indicate a decline (Zöckler et al. 2020), although it should be borne in mind that the methods used do not allow for incomplete detection, the extent of which may vary among survey years. We therefore recommend immediate reassessment of the threats faced by the Spoon-billed Sandpiper and urgent enhancement of conservation interventions.

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