First formal estimate of the world population of the Critically Endangered spoon-billed sandpiper *Calidris pygmaea*

NIGEL A. CLARK, GUY Q. A. ANDERSON, JING LI, EVGENY E. SYROECHKOVSKIY
PAVEL S. TOMKOVICH, CHRISTOPH ZÖCKLER, REBECCA LEE and RHYS E. GREEN

TABLE S1 Main assumptions of the method used to estimate the world population of spoon-billed sandpipers *Calidris pygmaea* in the age class after hatching year (AHY). The measures taken to avoid significant departure from each assumption are given, with an assessment of the likely effect of each assumption on the accuracy of the population estimate.

Assumption	Assessment & countermeasures
1. Migration movements were not affected directly by leg flags.	Leg flags were lightweight & lighter and smaller than the smallest leg-mounted geolocators, which have been assessed as having minor effects on shorebird demographic rates & no effect on movement patterns. See Discussion.
2. Migration movements were similar for birds in breeding areas where flags were & were not applied.	Potential to bias the estimated population size in either direction. Scale of possible bias cannot be evaluated accurately with available data. Flagging & scan surveying at more sites would resolve the issue. See Supplementary Material 1 & Discussion.
3. Flagged & unflagged birds present at Jiangsu were equally likely to be detected & recorded in scan surveys.	Scan surveys covered a substantial & representative part of the area of high-elevation flats used by the birds. The design of the scan surveys makes it unlikely that there was appreciable bias from this source. Strict adherence to the survey protocol is essential to avoid overestimation of the proportion with flags. See Methods.
4. Birds were aged accurately as hatching year (HY) & after hatching year (AHY) in Jiangsu scan surveys.	Ageing was carried out only on a subset of birds by expert observers with high-quality optics & good views. Unlikely to be bias from this source. See Methods.
5. Flag types & inscriptions were recorded correctly in Jiangsu scan surveys.	Only the flag type needed to be identified correctly for the estimate of the proportion of birds carrying engraved flags to be correct. Hence, it is unlikely that there was appreciable bias from this source. Accuracy of inscription reading was likely to be high for reasons given below.
6. Flag inscriptions were recorded correctly in the global resighting compilation.	Records were collected, compiled & checked carefully. There were often multiple sightings of the same individual by several observers. Observations were often supported by high-quality digital images. Hence, the frequency of errors was probably low.
7. Global resighting probabilities were	Heterogeneity of resighting probability would bias the estimated number of flagged AHY birds alive in autumn 2014

homogeneous across individual flagged AHY birds.	to be too low. This would bias the population estimate by the same proportion. It was unlikely to have a large effect because the geographical scale of the migration movements is such that flagged individuals pass through & are seen at several sites, which would smear out individual differences in resighting probability as a result of location, at least to a considerable extent.

SUPPLEMENTARY MATERIAL 1 Effect of the failure of key assumptions on the population estimate of the spoon-billed sandpiper *Calidris pygmaea*.

We assumed that the probability that a leg-flagged AHY spoon-billed sandpiper would visit the Jiangsu coast in autumn and be recorded there on the scan surveys was the same as for an AHY with no flag. This general assumption comprises Assumptions (1)–(3) in Table S1. We explored the consequences of failure of this group of assumptions using a simple model. Suppose that the expected mean number of scan records of a leg-flagged bird alive at the end of the breeding season on the Jiangsu coast in autumn is the product of the probability that it visits the Jiangsu coast in autumn V_f and the mean number of scan sightings per individual for birds that visit the Jiangsu coast is K_f. The equivalent values for AHY spoon-billed sandpipers without flags anywhere in the world are V_u and K_u. The proportion p of AHY spoon-billed sandpipers on the Jiangsu coast expected to be recorded as having leg flags is then given by

$$p = V_f \ K_f M/(V_f \ K_f M + V_u \ K_u (N-M)) \qquad (1)$$

where M is the number of leg-flagged adults/yearlings alive anywhere in the world at the end of the breeding season and N is the number of all adults/yearlings alive anywhere at that time. The proportion p is equivalent to what we estimated by A/B from the scan surveys and M is equivalent to the value we estimated using the Jolly–Seber method. Given the small size and light weight of the flags there was unlikely to be a difference between flagged and unflagged birds in the probability that a bird would move to the Jiangsu coast (Table S1, Assumption 1). The design of our scan surveys was such that we would expect the mean number of times a leg-flagged bird present on the Jiangsu coast was recorded on a scan survey to be the same as for a bird with no flag (Table S1, Assumption 3). In this case $K_f = K_u$, and equation (1) simplifies to

$$p = V_f M/(V_f M + V_u (N-M)) \qquad (2)$$

Rearranging equation (2) gives the world population N in terms of the other parameters:

$N = M\,((V_f/V_u)\,((1\text{-}p)/p)+1)$ (3)

If AHY birds with and without leg flags have the same probability of visiting the Jiangsu coast in the autumn then $V_f/V_u = 1$, and equation (3) simplifies to

$N = M/p$ (4)

which is the Lincoln–Petersen estimator of population size we used in our calculations in the main text. Dividing (3) by (4) gives the ratio R of the true world population size to the population size estimate obtained by our method.

$R = (V_f/V_u)\,(1\text{-}p)+p$ (5)

It can be seen from equation (5) that, if p is small, the ratio of the true population to the estimated population is approximately directly proportional to the ratio of the probability that a flagged bird visits the Jiangsu coast in autumn to the equivalent probability for a bird with no flag. Hence, our method will overestimate population size if $V_f < V_u$ and underestimate it if $V_f > V_u$. The most plausible reason why the probability of visiting the Jiangsu coast may differ between flagged and unflagged birds is if birds from different parts of the breeding range are more or less likely to migrate through the Jiangsu coast. Our method assumes that this probability is the same for flagged and unflagged AHY birds. This is Assumption (2) in Table S1. The principle of failure of this assumption as a potential source of bias is illustrated schematically in Fig. S1. Given that nearly all of the leg-flagging has been of birds breeding at one breeding site in arctic Russia, Meinypil'gyno, the probability of flagged birds migrating through the Jiangsu coast would differ from the mean if the probability for birds breeding in that region was different. This could cause our estimates to be too high or too low.

A constraint on the degree to which our method may underestimate the world population

Although, for obvious reasons, we cannot estimate directly V_u, the probability that an AHY bird without a leg flag will migrate to the Jiangsu coast in autumn, we can estimate a lower plausible bound for V_f, the equivalent probability for flagged birds. Given that V_u cannot be >1, this also gives a lower bound for the ratio V_f/V_u. We found that half (9/18) of the leg-flagged adults/yearlings known to be alive in September–October 2014 were recorded on the Jiangsu coast. The proportion of birds that visited the Jiangsu coast may have been greater than this because flagged birds may have been present and not recorded, so this is a minimum estimate for V_f. Given that V_u must be ≤1, and ignoring the uncertainty in our estimate of the proportion of flagged birds that visit the Jiangsu coast in autumn, the minimum value of V_f/V_u is 0.5. Using a value of $V_f/V_u = 0.5$ in equation (5) with the observed value of p (Table 1)

gives R = 0.521 (true population approximately half of the estimate). We can account for uncertainty in our estimate of the proportion of flagged birds that visit the Jiangsu coast in autumn by calculating, using the binomial theorem, the value of this proportion for which there would be a probability of 0.05 of observing 9 of 18 flagged individuals on the Jiangsu coast. This gives a minimum value of V_f / V_u of 0.291 and R = 0.321 (true population c. one-third of the estimate). Hence, it is unlikely that our estimate of the world population of spoon-billed sandpipers is an overestimate by more than a factor of two or three because of differential migration of birds with and without flags.

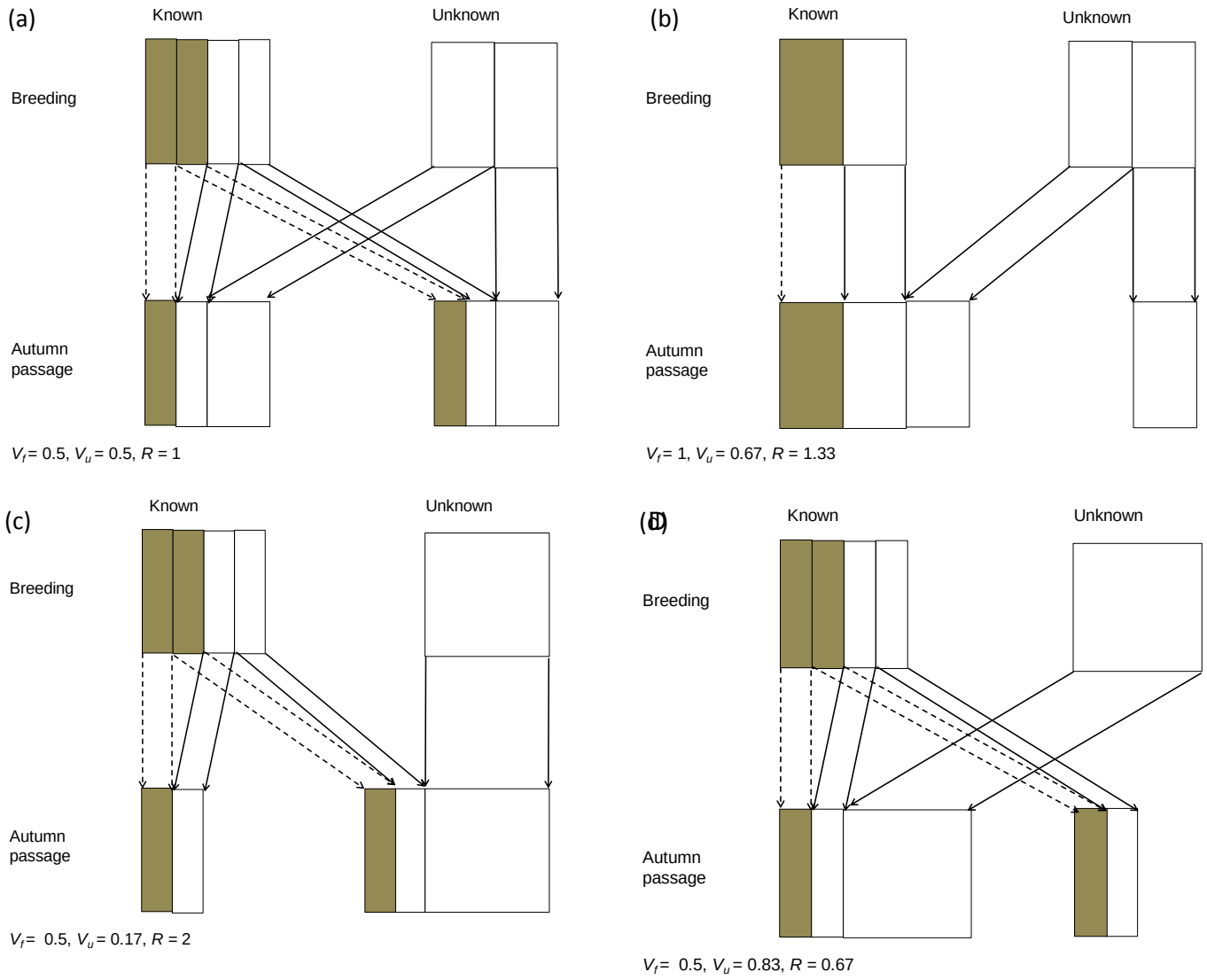

FIG. S1 Illustration of how differences in the proportion of birds travelling from known and unknown breeding areas to a known autumn passage site could bias population estimates, if birds are leg-flagged only at known breeding sites. In the schematic maps of known (left) and unknown (right) breeding (top) and autumn passage (lower) sites the area of each box is proportional to the population size, with shading denoting the part of the population that is leg-flagged. Autumn movements of flagged (dashed) and unflagged (solid) population components are indicated by arrows. Proportions of flagged and unflagged birds that move to the known passage site are indicated by V_f and V_u, respectively. The ratio R of the true population size to that calculated from scan surveys at the known passage site using the Lincoln–Petersen estimator indicates that the true population size is underestimated ($R > 1$) if $V_f > V_u$ (b and c) and overestimated ($R < 1$) if $V_f < V_u$ (d).