Methods of band survival analysis: applied to studies of the Tundra Swan *Cygnus columbianus*

HUBERT A. ALLEN, JR., WILLIAM J.L. SLADEN, and D ROLAND J. LIMPERT

Data from a study of the Tundra Swan, were used to estimate the lifespan of one neck band design and compare it to the lifespan of the bird. Swans were originally marked with a U.S. Fish and Wildlife Service metal tarsus band, a plastic tarsus band, and a plastic neck band. A sample of 169 recaptured swans were used in order to estimate the median survival time of the neck band using three methods: a calibration of a weighted least squares fit of independent binomial estimates, the product-limit estimator and, survival analysis with interval censoring. Estimates of the median survival time of the plastic neck bands were 3.44, 3.05 and 2.90 years, respectively.

Estimates from the survival analysis techniques are expected to be more precise than those obtained by weighted least squares because they use resighting data to pinpoint when a band was lost. In fact, however, all methods yielded survival estimates within one year of each other and far below the longevity records of all swan species. In conclusion, estimates from three methods of band survival analysis suggest that neck band loss is a significant factor in this sample of Tundra Swan data, and most likely in the larger study of some 5,000 Tundra Swans. Therefore, estimates of annual and age-specific survival rates based on neck band resightings alone, without accounting for band loss, would be severely biased downward.

Waterfowl marked with highly visible plastic neck bands can be identified in the wild without being recaptured or shot. This technique has been used successfully for studies of migration and behaviour. When data from a neck banding study is used to estimate annual survivorship of a species, however, one must incorporate a band survival rate, as the assumption that neck bands survive the life of the bird may not be true.

One field technique which provides data on band survival involves placing two or more bands on a sample of individuals. Birds are then released back into the wild, where they may be resighted, recaptured, found dead or shot. At several of these points the bands become accessible again, and the presence and absence of one or the other may be noted.

Tundra Swans, *Cygnus columbianus columbianus,* marked under the Swan Research Program (SRP) were fitted with a uniquely coded plastic neck band, a plastic tarsus band having the same code as the neck band, and a metal tarsus band (Sladen, 1973). This protocol provides an ideal situation for testing the neck band survival assumption.

This paper presents three methods to estimate the median lifespan of a sample of neck bands. The method using binomial proportions is currently found in the literature as a special case of the more general multinomial model (Seber 1973). The other methods come from a branch of statistics called survival analysis and have only recently been used in the band survival problem (Allen 1985).

In order to use the three band survival methods it is assumed that the combination of tarsus bands endures with certainty for the life of the swan. When a swan is recaptured with the neck band missing, there is no precise information about the loss date. All that is known is that it was lost sometime during the interval between original banding and recapture. The three methods make different assumptions about when the band was lost in this interval. The major difference is that survival analysis can incorporate resighting data to shrink the interval in which the neck band was lost, while the binomial method cannot.

Each method has been used to estimate the median survival time of the plastic neck bands (the time at which 50% of the bands have been lost) in a sample of 169 recaptured Tundra Swans. A 95% confidence interval around the

Supplement No. 1 (1991): 340-347

median was calculated for each method. Finally, the estimated survival of the neck band is compared to the longevity record for a wild Tundra Swan.

Field Methods

The Tundra Swan is North America's most common native swan. It is a seasonal migrant between arctic breeding grounds and the temperate wintering areas, along the east and west coasts of the continental United States. The SRP began using neck bands in 1969 and has made more than 200 catches since then. The data described here involved recaptured swans from the eastern population.

Each catch is inspected for recaptures. For simplification in this paper the two tarsus bands will be treated as a single band. Therefore, at all catches after the first banding, four mutually exclusive categories of band status arise:

1. A swan may have both bands intact.
2. A swan may have only the neck band intact.
3. A swan may have only the tarsus band intact.
4. A swan may have neither band intact.

A recaptured swan wearing a neck band and either tarsus band is counted as having both bands intact. A swan having either tarsus band present but not a neck band is counted as having lost the neck band. A swan wearing a neck band only is counted as having lost the tarsus band. Banded swans which have lost all bands cannot be distinguished from birds that were never banded.

The bands of recaptured swans are inspected. When any of the bands are in poor condition they are removed and replaced with a new set. Unmarked swans have the three bands placed accordingly. The age and sex are determined. Two age classes are recognized: juveniles or 'grey necks' are in their first year after hatching; adults are any all-white plumage birds. The bird is weighed, a set of measurements, a photo of the face and sometimes a blood sample is taken before release.

Field observations were made using 45 power spotting scopes. Observers searched out flocks along rivers, lakes, estuaries and in fields. Flocks numbered anywhere from a few individuals up to 15,000. Observers attempted to check each swan for a neck band and record its code. A few trained observers read the code on the plastic tarsus band in the absence of a neck band. In a large flock it can be quite difficult to read even the neck band because of crowding, movement and feeding behaviour.

The Binomial Estimator

The binomial model requires all recapture times be grouped into broad classes, typically one year intervals. A swan missing its neck band is treated as having lost it at exactly the year class of recapture; the upper bound of the interval. For example, a swan recaptured at 366 days is placed in the class of two year recaptures. If that swan has lost its neck band it is treated as though the band was lost at exactly two years after original banding, when in fact, such a band would have been lost much closer to the one year cutoff. The estimate of the cumulative band survival rate, at year i after the original banding is,

Eqn. 1 $\hat{p}_i = x_i/n_i$ where,

$i=1,...,5+$ years after original banding

x_i is the number of swans recaptured at time i retaining their neck band.

n_i is the total number of swans recaptured at time i.

Where $\hat{p}_i$ is the estimate of probability that the neck band survived to time i of the second sample. For example, the sample of recaptures at the second year gives an estimate of the cumulative survival rate to the second year.

The binomial model produce independent point estimates of cumulative survival rates at each year class after original banding. If we further assume that p is constant across swans, these estimates may be combined in a regression line. If there is enough data to stratify by sex and age the assumption of a constant p will be more tenable for the separated groups. If, however, the sample is small the only reasonable approach is to combine the data.

Weighted Least Squares

In practice, point estimates are based on different sample sizes and have unequal variances. Weighted least squares combines the point estimates using weights equal to the number of recaptures at each year class (Fjetland 1973). The dependent variable is the proportion surviving and the independent variable is the number of years after original banding. Weighted least squares produces estimates of the regression parameters, b_0 and b_1, that summarize a linear relationship between neck band survival and time.

Table 1: Band survival data on five swans (in days).

Swan	Time To Recapture	Neck Band Status	Type of Censoring	Band Loss LB	Band Loss UB	Interval MidPoint
C133	1088	Absent	Interval	777	1069	923
C002	903	Absent	Interval	0	903	452
F742	716	Absent	Interval	394	716	555
F639	1815	Absent	Interval	5	309	157
J193	712	Present	Right	712	2000	—

Calibration of the Median and 95% Confidence Interval

A graphical description of these procedures follows. First draw the fitted regression line, along with 95% confidence bands. Second, draw a horizontal line (H), parallel to the x-axis, through the point Y_M, the point on the regression line at which 50% of the bands are lost, and the confidence bands. The median neck band survival time is found by projecting down from Y_M to the corresponding point on the x-axis. Such a procedure is known as inverse regression or calibration.

Determination of a 95% confidence interval is more tedious. At the intersection of line H and the confidence bands, vertical lines are dropped to the x-axis. These lines define the 95% confidence intervals around the median survival time. It is best to draw the fitted line and confidence bands before making this calculation. For detailed formulae see Draper & Smith, (1981).

Survival Analysis

Survival analysis is a branch of statistics that deals with the time to an 'event,' for example the death of a cancer patient or loss of a neck band. A survivorship function is estimated, which is analogous to lifetables analysis. The survivorship function, S(t), is defined as the probability that a neck band survives longer than time t:

S(t) = P(a neck band survives longer than t)

A graphic representation of the survivorship function is called a survival curve. The survival curve shows a decreasing proportion of individuals surviving in a sample, over time. The median survival time is typically used to compare groups. The median is preferred to the mean survival time, because the latter can be influenced by a few long or short lived individuals while the former is not.

The notion of 'censoring' is fundamental to methods of survival analysis. Two types of censoring are relevant to band survival. The first type, called 'right censoring,' means that the event of interest has not occurred by the end of the study. This occurs when a swan still wears its neck band at recapture.

The second type, called 'interval censoring', usually occurs when a swan has lost its neck band. Since band loss is rarely, if ever, observed exactly, the investigator only knows that the band was lost in an interval. The loss of the band is then said to be interval censored.

The two nonparametric methods of survival analysis deal with censored data differently. A hand-worked example of the PLE is provided using data on the five swans in Table 1. References for the theory and a hand-worked example of the interval censored method is provided.

The Product-limit (or Kaplin-Meier) Estimator (PLE)

The theory of the PLE may be found in Kaplin & Meier (1958). The PLE handles exact and right censored observations. In band survival analysis, the PLE requires an assumption to transform interval censored data into exact loss times. The assumption used here is that bands

Table 2: Calculation of the PL survivorship function.

(1) t	(2) i	(3) r	(4) (n-r)/(n-r+1)		(5) S(t)
157	1	1	4/5	4/5=	0.80
452	2	2	3/4	4/5 x 3/4=	0.60
555	3	3	2/3	4/5 x 3/4 x 2/3=	0.40
712+	4				
923	5	5	0		0.00

were lost at the midpoint of the interval. The worked example below shows how estimates can be made using a five column table.

Column 1: All n neck band survival times, censored and exact, are ordered from smallest to largest. '+' shows which cases are right censored.

Column 2: The rank order of times, i, is shown.

Column 3: For uncensored observations, r=i, denoting those at risk.

Column 4: A computation for every uncensored observation gives the proportion of bands surviving up to and then through $t_{(i)}$.

Column 5: The product of all values of (n-r)/(n-r+1) up to and including t, is the PL estimate of the survivorship function.

In summary, the five survival times are ordered in the first column and their ascending rank is noted in the second column. The third column distinguishes the observed versus censored times for the calculation in the fourth column. The survivorship function is only calculated when a band is lost, as the product of the preceding estimate and the value in the fourth column.

Details of rules for tied cases and the calculation of variance, can be found in Lee (1980). The survival curve decreases only when an event is observed exactly. The risk set decreases when either an exact or a censored observation is made. A nonparametric asymptotic confidence interval for the median survival time of the neck band is calculated using the method of Brookmeyer & Crowley (1982).

Interval Censoring

Theory and development of the equations for estimation of the survivorship function of interval censored data may be found in Turnbull (1976). A method for estimation of the survivorship function using interval censored data was outlined by Peto (1973). A worked example of how to calculate the survivorship function of interval censored data, and a 95% confidence interval, can be found in Allen (1985).

Use of Resighting Data for Survival Analysis Methods

The two survival analysis methods can incorporate resighting data to shrink the band loss interval. To do this the detailed resighting histories of all swans that lost bands are collected. The intervals in which bands were lost is then determined using the dates of original banding, resightings and recapture.

Results

Between 1969 and 1984, the SRP triple banded 3,513 Tundra Swans, and made 169 recaptures (rate=4.8%). Recaptured swans were selected for this study because observations of all three bands could reliably be made. Recapture times ranged from 1 to 3,650 days after original banding. The median recapture time was 365 days.

Thirteen swans were originally banded on the breeding grounds in summer. Of 156 swans originally banded on the wintering grounds, 36% were banded in Maryland, and 64% in North Carolina. Most swans, 93.5%, were recaptured in the same state as their original banding.

The age distribution at original banding was similar between recaptures, 79% adult, and all other banded swans, 82% adult (χ^2 = 0.52, P<0.47). However, recaptures consisted of a larger proportion of males, 63%, than did the original bandings, 51% (χ^2= 8.70, P<0.05).

One hundred twenty three swans, 72.8%, retained their neck bands to recapture. There were 46 swans, 27.2%, that lost their neck band by the time they were recaptured. The plastic tarsus band was lost by 19 swans,

Table 3: Band status of Tundra Swans at recapture, by number of years after original banding.

	Years after original banding					
	1	2	3	4	5+	Total
Both bands intact (x)	79	22	13	6	3	123 (73%)
Tarsus band only intact	6	1	11	7	21	46 (27%)
Neck band only intact	0	0	0	0	0	0 (0%)
Total recaptures (n)	85	23	24	13	24	169 (100%)
x/n	79/85	22/23	13/24	6/13	3/24	
Percent surviving	0.929	0.956	0.541	0.461	0.125	

11.2%. In contrast, only two swans, 1.2%, lost their metal band. No swan was found with a neck band only.

The Binomial Method

A summary of band status at recapture by the number of years after original banding is found in Table 3. This table forms the raw data used by the binomial method. The row marked 'Both bands intact' divided by 'Total recaptures' at that year forms the binomial point estimate, the bottom row of the table.

These binomial proportions are combined using weighted least squares after arcsine transformation. The coefficients of the resulting equation (Eqn. 2) were highly significant (P<0.01). Neck band survival decreased over time, as indicated by the negative slope for time.

Eqn. 2 $$\hat{p}_i = 1.5764 - 0.2299(t_i)$$

Calibration of a median survival time was straightforward. However, determination of the 95% confidence interval was problematic. In fact, Draper & Smith (1981) warn there can be difficulties in solving the equations that determine the confidence interval. Here the equation led to an imaginary number. Therefore, the lower limit was fitted by eye as the point projected from the intersection of the lower confidence limit of the regression line and the line drawn at the arcsine of 0.50, onto the time axis (See Fig. 1). No upper limit was determined because at year 5+ the upper confidence limit of the regression did not intersect the line at the arcsine of 0.50. Figure 1 shows the regression line, the 95% confidence limits of the regression and calibration of the median survival time.

Survival Analysis Methods

Of 46 swans that lost neck bands, 74% had a resighting history. Twenty-three swans were seen at least once with a neck band present. For a swan seen more than once with a neck band on, the latest resighting date was used. Each of these resightings moved the lower limit away from the date of original banding, closer to the time at which the band was actually lost. These intervals shrink from the left.

Nine swans were resighted with the neck band present and later with their neck band missing. The code on the plastic tarsus band was read in the absence of the neck band. The interval in which these bands were lost shrinks

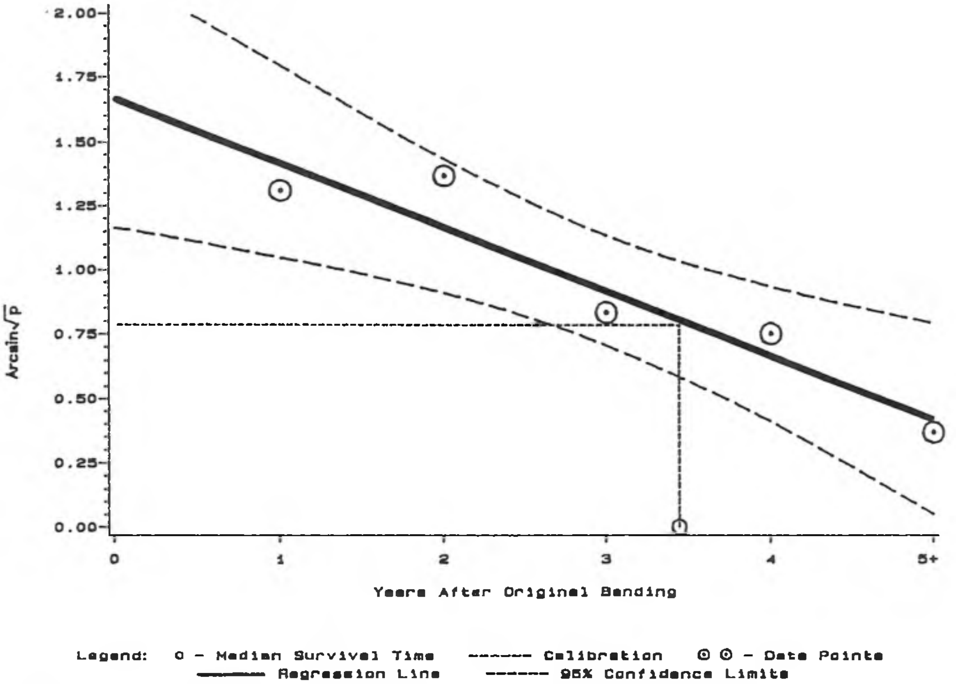

Figure 1. Weighted least squares fit of independent binomial estimates and calibration of median neck band survival time.

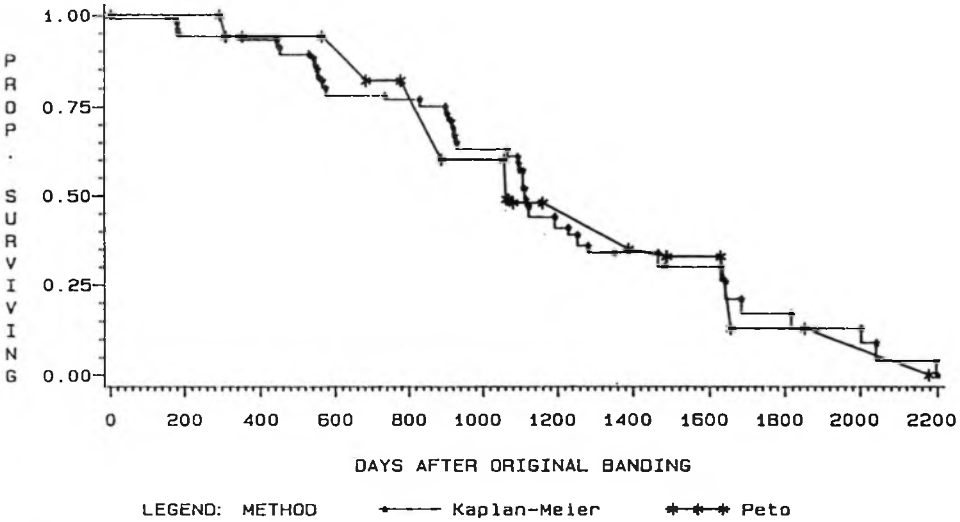

Figure 2. Neck band survival curves.

from the left and right limits.

Two swans were observed once wearing only tarsus bands. The code on the plastic tarsus band was read. For these swans the band loss interval shrinks from the right.

For the remaining 12 swans no resightings were made. The interval between original banding and recapture cannot be reduced. For swans retaining their neck bands at recapture the details of resightings are irrelevant to the study of band survival.

Since these intervals could not be used directly by the product-limit method, the midpoint of the interval was used as the exact time at which the band was lost. Product-limit estimates were made using a computer package named Survpak (Huster *et al.* 1983). The median survival time was estimated and a 95% Brookmeyer-Crowley Confidence Interval was obtained.

Survival analysis with interval censoring was implemented using a Fortran program named Peto (Self & Grossman, 1984). A bootstrap confidence interval was obtained by drawing 200 samples of 169 survival times, estimating the median survival time using the Peto program, and finding the 2.5% intervals at either tail. Fig. 2 compares the survival curves for these two methods.

Estimates of the median survival time of the plastic neck band for three methods are presented in Table 4 with 95% confidence intervals. The range of these estimates is 0.54 years.

When the interval censored analysis was repeated by sex the median survival time of the plastic neck band for males was 2.95 years and the median for females was 4.50 years. For the plastic tarsus band it was 4.04 and 4.46 years respectively. Finally, the metal band, of which only two were lost, gave median survival times of 9.45 years for males, and 17.17 years for females.

Discussion

Three methods of estimating the median survival time of the plastic neck band have been reviewed. The first point to note is that the range of estimates is only 0.54 years. Having three estimates, all within one year, shows a high degree of consistency in the results of these methods. Therefore, under the circumstances of this sample, each method provides a reasonable estimate of neck band survival.

Secondly, compared to the longevity record for a metal banded Tundra Swan, of 19.5 years

Table 4: Estimated median survival times of the plastic neck band by method.

Method	Median Survival Time	95% Confidence Interval
Binomial	3.44 years	(2.66, ++++)
Product-limit	3.05	(2.99, 3.69)
Interval censoring	2.90	(2.37, 4.06)

(R. Limpert, pers. obs.), the neck band survival time of three years is very short. It is possible, however, that the sample drawn for this analysis is biased compared to the experience of the entire banded sample at large. The explanation for this could lie in the sex bias of the sample. For example, Scott (1981) found aggressive encounters to be slightly more common for adult males than for any other age, sex combination of the Eurasian Bewick's Swan, *Cygnus columbianus bewickii*.

If this were true of Tundra Swans, then the increased aggression of males could lead to more rapid neck band losses as observed. Tundra Swan aggression, may involve one swan lunging for the neck of another and directing blows of the wing to the base of the neck. A neck band may receive additional stresses in this way.

Comparison of Methods

The weighted least squares estimate was the largest of the three. This might be expected because the point estimates were made after data were lumped into one year classes, causing a loss of information. Perhaps more important than lumping data was the inability to incorporate resighting data into the analysis. It is critical that resighting data, if available, be incorporated into an analysis of band survival. The capability of utilizing resighting data is a valuable asset common to the survival analysis techniques. The simple probability models cannot incorporate such data.

When the exact observations used by the product-limit method were analyzed by the interval censoring method the estimated median survival time was identical to that obtained through the product-limit estimator. This is a mathematical necessity because the PLE is a special case of survival analysis with interval censoring.

Therefore, an interpretation of the median values obtained by these two methods can be made. The product-limit estimate of the median survival time is based on the explicit assumption that bands were lost at exactly the midpoint of the interval. The lower interval censoring estimate implies that, on the average, bands were lost before the midpoint of the interval.

If intervals are long, compared to the average times bands were lost, the product-limit method will over estimate the median survival time of the bands.

Conclusions

It is essential for any banding program to examine the survivorship of the bands in use. A comprehensive protocol will include the study of band loss by double-banding at least a proportion of birds. For swan researchers it is quite typical to double band all birds.

A sample of subsequently encountered swans, or better still several samples, must be identified for appropriate analysis of band survival. While recaptures were discussed here the option remains to use recoveries or even field observations of a closely watched population.

With the ubiquity of computers today it is recommended that investigators use both the binomial and Product-limit methods. These are available on many standard statistical packages. The objective to keep in mind is to produce reasonable estimates of band survival not figures cast in stone. The neck bands used by the SRP, by all estimates, survive a much shorted period of time than the swans themselves.

References

Allen, H. 1985. Methods of Band Survival Analysis: Applied to Studies of the Tundra Swan, *Cygnus columbianus columbianus*. Johns Hopkins School of Hygiene and Public Health.

Draper, N.R. & Smith, H. 1981. *Applied Regression Analysis*. 2nd Edition. John Wiley and Sons, Inc. New York. pp. 47-51.

Fjetland, C.A. 1973. Long-term retention of plastic collars on Canada Geese. *J. Wildl. Manage.* 37(2):176-178.

Huster, W., Brookmeyer, R. & Self, S. 1983. Survpak.

Kaplin, E.L. & Meier, P. 1958. Nonparametric Estimation from Incomplete Observations. *J. Am. Stat. Assn.* 53:457-481.

Peto, R. 1973. Experimental Survival Curves for Interval-censored Data. *Appl. Stats.* 22:86-91.

Scott, D.A. 1981 Social behaviour of wintering *Cygnus columbianus bewickii*. In G.V.T. Matthews and M. Smart (eds.) *Proc. 2nd Int. Swan Symp.*, Sapporo, 1980 IWRB, Slimbridge.

Self, S. & Grossman E. 1984. A computer Implementation of methods described by Peto (1973). Unpublished. (Available from the authors).

Sladen, W.J.L. 1973. A continental study of whistling swans using neck collars. *Wildfowl* 24:8-14.

Turnbull, B.W. 1976. The empirical distribution function with arbitrarily grouped, censored and truncated data. *J. Royal Stats. Soc.* Series B, 38:290-295.

Hubert Allen, Jn., 2901 Elliot Street, Baltimore, Maryland, 21224, USA.
William J. L. Sladen, Airlie Centre, Airlie, Virginia, 22186, USA.
Roland J. Limpert, Chesapeake Wildlife Heritage, PO Box 1745, Easton, Maryland, 21638, USA.