Application of Radio Telemetry in Studies of Cranes

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Radio telemetry is a widely used tool in wildlife conservation which allows researchers to mark and study avian species from a distance. Researchers who use radio telemetry must weigh the relatively high costs for obtaining transmitters and tracking data compared with the benefits of repeatedly locating a few individuals, especially for fast-moving or wide-ranging migratory species. A larger sample of a population may be examined with surveys, or individuals species marked with less expensive techniques, such as leg bands or colored markers, but radio telemetry provides more detailed information on the individuals that are being studied.

So why are radio telemetry studies conducted? Many are undertaken when the information is otherwise unavailable. For example, recent studies with satellite telemetry have tracked migration of cranes across vast Arctic areas to reveal new breeding or wintering areas where other markers are rarely observed or recovered. In addition, much of the cost of band recovery or re-sighting studies of visual markers is in the costs of capture or field personnel. The fewer the number of birds that can be captured, the more important it is to maximize the information obtained from each. Researchers can obtain more detections from radio-marked individual species than from direct observations. Telemetry can improve on visual studies where birds may only be observed in limited portions of their range.

Studies of standard very-high-frequency (VHF) radio transmitters have been conducted since the 1960s. In the early 1970s, the development of satellite telemetry created a major technological advance in conservation studies by enabling researchers to track remote and trans-border species. The first platform transmitter terminal (PTT) used to track wildlife by satellite was deployed on a large mammal (Craighead et al. 1972). In the early 1980s, Strikwerda et al. (1986) developed the first bird-borne PTT. In the late 1980s, early generation PTTs for birds weighed more than 100 g and were deployed on large species such as cranes, swans, and eagles (Nagendran 1992; Higuchi et al. 1994a; Fuller et al. 1995; Higuchi et al. 1996). As the weight of PTTs decreased in the 1990s, studies were initiated on smaller species in groups such as waterfowl and seabirds. The first shorebird, the far eastern curlew (*Numenius madagascariensis*), was marked with a PTT (L. Bowden and P. Driscoll, unpublished data).

Radio Telemetry Studies on Cranes

VHF and PTT transmitters have made it possible to increase our knowledge of long-distance migratory birds such as cranes (Table 1). Cranes have been marked with VHF transmitters as early as 1975 (Nesbitt 1976) to examine local and regional migrations. Melvin and Temple (1983) reviewed early

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Table 1. Common and scientific names, radio type (VHF = very high frequency, PTT = satellite or platform transmitter terminal), sample size, study description, year, location, and references for radio telemetry studies of cranes.

Common name	Scientific name	Radio type	n	Study description	Year	Location	Reference
Sandhill	*G. canadensis*	VHF	3	wintering	1973	Florida	Nesbitt (1976)
Sandhill	*G. canadensis*	VHF	14	migration	1977	Minnesota, Wisconsin	Crete and Toepfer (1978)
Sandhill	*G. canadensis*	VHF	14	regional migration	1977	Minnesota, Wisconsin	Toepfer and Crete (1979)
Sandhill	*G. canadensis*	VHF	?	fall and spring migration	1978	East Coast	Anderson et al. (1980)
Whooping	*G. americana*	VHF	5	movement of juveniles	1978	Idaho	Drewien and Bizeau 1981)
Sandhill	*G. canadensis*	VHF	5	Captive release, local movements	1982	Idaho	Drewien et al. (1982)
Sandhill	*G. canadensis*	VHF	28	local movements, migration	1978	North Dakota	Melvin and Temple (1983)
Sandhill	*G. canadensis*		43	leg, backpack attachment	1978	Midwest USA	Melvin et al.
Whooping	*G. americana*	VHF	11	tests			(1983)
Sandhill	*G. canadensis*	VHF	20	habitat use of migrating cranes	1979	Nebraska	Krapu et al. (1984)
Sandhill	*G. canadensis*	VHF	22	habitat use if wintering	1979	Texas	Iverson et al. (1985)
Sandhill	*G. canadensis*	VHF	18	movement and home range	1985	Florida, Georgia	Bennett (1989)
Whooping	*G. americana*	VHF	9	migration, habitat use, survival	1981	Texas, Saskatchewan	Howe (1989)
Sandhill	*G. canadensis*	VHF	31	home range, habitat use	1981	Florida	Nesbitt and Williams (1990)
Sandhill	*G. canadensis*	VHF	4	implant transmitter test	1985	Florida	Klugman and Fuller (1990)
Sandhill	*G. canadensis*	VHF	6	habitat use	1985	Florida	Bishop (1991)
Siberian	*G. leucogeranus*	PTT	3	long distance migration	1989	Russia, China	Ellis and Markin (1991)
Eurasian	*G. grus*	PTT	3	breeding to wintering	1990	Siberia	Ellis et al. (1991)
Sandhill	*G. canadensis*	PTT	4	behavior of attachment	1989	Maryland	Olsen et al. (1992)

Table 1. Continued.

Common name	Scientific name	Radio type	n	Study description	Year	Location	Reference
Sandhill	*G. canadensis*	VHF	10	distribution and movement	1983	California	Pogson and Lindstedt (1991)
White-naped Hooded	*G. vipio* *G. monacha*	PTT	26	migration routes, rest sites	1989	Korea	Chong et al. (1992)
Eurasian	*G. grus*	PTT	3	long distance migration	1990	Siberia	Ellis et al. (1992)
White-naped Hooded	*G. vipio* *G. monacha*	PTT	15	long distance migration	1991	East Asia	Higuchi et al. (1992)
Sandhill	*G. canadensis*	VHF	15	migration and wintering	1981	Central Canada, USA	Kuyt (1992)
Sandhill	*G. canadensis*	PTT	1	first satellite marked crane	1988	Texas	Nagendran (1992)
Sandhill	*G. canadensis*	VHF	7	reintroduction, regional movements	1988	Texas	Nagendran (1992)
Sandhill	*G. canadensis*	VHF	38	reintroduction, regional Movements	1988	Wisconsin, Michigan	Urbanek and Bookhout (1992)
Sandhill	*G. canadensis*	VHF	27	survival and movements	1982	Florida	Nesbitt and Carpenter (1993)
White-naped Hooded	*G. vipio* *G. monacha*	PTT	?	regional movements	1991	Korea	Chong et al. (1994)
Eurasian	*G. grus*	PTT	3	long distance migration	1994	India	Higuchi et al. (1994)
Eurasian	*G. grus*	VHF	14	foraging behavior, habitat use	1995	?	Alonso et al. (1995)
White-naped	*G. vipio*	PTT	15	long distance migration	1991	Korea	Higuchi et al. (1996)
Sandhill	*G. canadensis*	VHF	7	regional migration	1995	Idaho, New Mexico	Clegg et al. (1997)
Sandhill	*G. canadensis*	VHF	27	survival, habitat use of colts	1990	California	Desroberts (1997)
Sandhill	*G. canadensis*	VHF	38	home range, habitat use	1992	Michigan	Duan et al. (1997)
Sandhill	*G. canadensis*	VHF	14, 2	colt and local movements	1991	Oregon	Ivey and Scheuring (1997)

Table 1. Concluded.

Common name	Scientific name	Radio type	n	Study description	Year	Location	Reference
Whooping	*G. americana*	VHF	52	migration and release techniques	1993	Florida	Nesbitt et al. (1997)
Red-crowned	*G. japonensis*	PTT	12	long distance migration	1998–1999	Russia, China	Higuchi et al. (1999)
Sandhill	*G. canadensis*	VHF	134	Post release and survival	1989	Mississippi	Ellis et al. (1999)
Sandhill	*G. canadensis*	VHF	9	Seasonal movement	1984	Idaho	Drewien et al. (1999)
Eurasian	*G. grus*	PTT	8	migration and breeding areas	1998–2000	India	Higuchi et al. (2000)
Demoiselle	*A. virgo*		3				
White-naped	*G. vipio*	PTT	18	migratory stopover and wintering	2000	East China	Harris et al. (2000)
Hooded	*G. monacha*						

VHF telemetry methods and provided information on tracking procedures. Melvin et al. (1983) discussed VHF transmitters and attachment techniques on large birds such as cranes. Olsen et al. (1992) studied the effects of harnesses on the behavior of cranes, and Klugman and Fuller (1990) provided information on implant transmitters. Ellis et al. (1991) provided an update on progress on the development of satellite telemetry for cranes including transmitter design, tests, and trials.

VHF transmitters have been used to determine habitat use (Iverson et al. 1985; Bishop 1991; Krapu et al. 1994; Desroberts 1997; Duan et al. 1997), regional movement (Anderson 1980; Drewien and Bizeau 1981; Bennett 1989; Nesbitt and Carpenter 1993; Drewien et al. 1999); wintering distribution (Pogson and Lindstedt 1991); home range (Nesbitt and Williams 1990); and survival (Desroberts 1997; Ivey and Scheuring 1997; Ellis et al. 2000). Studies with VHF transmitters generally require a large amount of logistical support including truck-mounted telemetry systems, a network of roads, and aerial telemetry surveys (Gilmer et al. 1981; Kuyt 1992; Clegg et al. 1997).

Increased miniaturization of VHF and PTT transmitters and improved attachment techniques (Olsen et al. 1992; Nagendran et al 1994; Higuchi et al. 1994b) have allowed expansion of studies to include colt survival (Desroberts 1997; Ivey and Scheuring 1997) and reintroduction of pen- and hand-reared cranes to the wild (Nagendran 1992; Urbanek and Bookhout 1992; Nesbitt et al. 1997). Palearctic research on cranes has generally been limited to satellite telemetry because of the logistical difficulties in accessing remote areas in many of these countries. PTT transmitters have been successful for studying long distance migration (Chong et al. 1992; Ellis et al. 1992; Higuchi et al. 1992, 1996); locating resting areas (Chong et al. 1993; Higuchi et al. 1994); and wintering and breeding area (Higuchi et al 1996; Harris et al. 2000).

Designing Radio Telemetry Studies

Radio telemetry studies provide detailed location data for a species over a limited time period, generally several days to a few years. Radio telemetry has been used in studies of nesting and breeding, migration ecology, wintering ecology, habitat interactions, population dynamics, physiology, and behavior. The most common use of radio telemetry has been in migratory species. Several factors require consideration in designing telemetry studies.

Costs

In studies of marked individuals, different techniques had varying costs and benefits. The costs of capturing and marking individuals are incurred in all marking studies, but field personnel are needed for both observation of visual markers and location of standard radio transmitters. Personnel costs are typically much lower for satellite telemetry studies where the data are obtained remotely. Studies with visual markers typically require larger samples and produce fewer returns than telemetry projects. Leg bands or visual markers typically cost less than $5 USD per individual, and equipment for resighting animals usually require binoculars or a spotting scope ($100–$1,500 USD). A standard radio transmitter may be purchased for $100–$250 USD, and a single receiving system of a receiver ($1,000–2,500), handheld antenna ($100 USD), and accessories often cost over $2,000 USD. Satellite telemetry transmitters may cost $2,500 USD each, with data acquisition costs of $1,000 USD. Thus, the cost for supplies and equipment to conduct a study of 10 animals may be less than $1,000 USD for a marker study, $3,000 USD for a radio telemetry study, and $35,000 USD for a satellite telemetry study.

Capture

The difficulty in capturing live animals for research is often one of the most challenging aspects of the project. Researchers may benefit greatly by consulting biologists who have experience in capture and handling of similar species. Capture techniques for migratory birds include bait trapping, mist netting, rocket netting, drive trapping, and net gunning. Proper capture and handling techniques are essential to minimize stress and capture myopathy.

Cranes molt their flight feathers each summer during post-incubation, which provides an opportunity to capture flightless species. In the second half of the 19th century, molting cranes were captured by horseman throwing a whip with a lead weight at the end (Gunda 1968, 1969). More recently, airboats and helicopters have been used to locate cranes or crane colts for capture by hand or with a long-handled nets.

Corral traps have also been used to drive species into nets.

Rocket netting is a common technique for capturing cranes in other times of the year. Rockets consist of a blunt nose cone, a hollow tube body, a stabilizing fin (usually a long steel rod counterweight), and exhaust ports in the base. The rockets are propelled with an electrically-fired Class 1.3C explosive charge and are connected to a net with shock cords and ropes. Cranes are commonly captured in 10 x 20 m nets with three rockets per net or 13 x 20 m nets with four rockets per net. Only one to two nets are used per site, which results in the capturing of a few individuals, because cranes are very susceptible to capture stress and myopathy.

Alpha-chloralose is a sedative that can be mixed with bait at dosages ranging from 0.40 to 0.48 g per 284 cc (cup) of corn (Williams and Phillips 1973) and has been used to successfully capture sandhill cranes in Florida (Nesbitt 1975) and Eurasian cranes in India (M. Nagendran, personal communication). The bait site should not be placed near water because drinking water increases absorption and may cause overdose. Sedated birds may lose motor function and drown or die of exposure when confined (Nesbitt 1975).

Attachment

Perhaps the most overlooked issue in radio telemetry projects is the attachment of the transmitter. The best attachment for a species minimizes stress while providing the most data. Several factors need to be considered including: (1) the smallest possible transmitter (<3% of bird's body weight); (2) as streamlined and inconspicuous a package as possible; (3) preliminary trials on captive individuals; and (4) an acclimatization period of a few days to weeks for newly marked individuals.

The most common attachment method used on birds is a harness made of plastic-coated wire or Teflon ribbon. One of the oldest attachment methods for ducks is the Dwyer harness (Dwyer 1972), a continuous loop design with neck and body loops. A modification of this harness has been used for cranes (Nagendran et al. 1994). Incorporating transmitters on collars is commonly used on geese and swans. Soft collar necklaces have been used on grouse, pheasants, quail, and waterfowl. Gluing (Warnock and Warnock 1993), taping, suturing and subcutaneous anchors (Newman et al. 1999) have been used to attach transmitters to smaller birds (<1 kg). Transmitters may also be surgically implanted with internal or external antennas to eliminate problems from external harnesses.

Transmitters

Three types of radio transmitters are available for migratory bird studies: short-range VHF and long-range PTT and global positioning system (GPS) transmitters. Short-range VHF transmitters produce a unique frequency for each transmitter. Transmitters may be either one- or two-stage designs with an increase in range and size in the latter. Reception is typically limited to a few kilometers from the ground but up to 20 km from the air. The long-range transmitters use satellite technology and include PTT and global positioning system (GPS) transmitters. We provide a table of comparison of general features (Table 2) of the three types of transmitters (VHF, PTT, GPS).

The first PTTs were tracked from polar-orbiting satellites launched by the U.S. National Oceanographic and Atmospheric Administration to track currents in the ocean from buoys. The system works by examining the Doppler shift, or change in PTT frequency (401.65 MHz), detected by a passing satellite to produce a location varying in accuracy from 300 m to >10 km. Our experience is that almost all locations from small transmitters are not extremely accurate, usually within 10 km, but rarely less than that (Takekawa et al. 2000). Thus, satellite transmitters are excellent for determining migration routes, general distribution over large areas, or extensive movements, but they are not useful in examining local habitat use. More locations are

Table 2. Features and relative value of three types of radio transmitters (VHF = very high frequency, PTT = platform transmitter terminal, and GPS = global positioning system) from lower (*) to higher (***) value.

Category	VHF	PTT	GPS
Accuracy	**	*	***
Cost	*	**	***
Size	***	**	*
Logistics	***	*	**
Vendors	***	**	*

obtained in the upper latitudes because the satellites orbit the North Pole. The location data is downloaded to a radio receiving system developed by the French space agency subsidiary, Argos, Inc. PTTs were first used to track wildlife in a bear study in 1970, but since that time, transmitter size has decreased to 15–20 g, small enough for many waterbirds over 500 g. Now, more than 1,100 PTTs are used each year to track wildlife.

Recently developed GPS transmitters receive position data from a constellation of geosynchronous satellites and produce very accurate (<10 m) locations through triangulation. GPS transmitters are primarily data loggers. Obtaining the data from GPS transmitters often requires recovering the transmitter after the data is collected. A recent prototype was developed (Microwave Telemetry) that transmits the data through a satellite data link. We provide a general comparison of the utility of these three transmitters for different ecological study objectives (Table 3).

Sensors are available on many types of transmitters that record additional data besides location. These include temperature, pressure (depth or altitude), and heart rate.

Tracking Equipment, Methods, and Data Compilation

Equipment

A VHF receiver, headset, and antenna are the main pieces of equipment needed with short-range transmitter studies. A study with >10 transmitters will be easier to do with a scanning receiver that stores several frequencies. VHF receivers have a frequency selector, power source, signal-strength control (gain), a jack for headphones, and a jack for the antenna. Data loggers or combined receiver and data-logger systems may be used to automatically record information from a fixed location. Typically used in tower systems, data loggers are not as sensitive at separating signals from noise, but can provide good information on localized areas such as breeding sites.

Several types of radio antennas are available for use in telemetry studies. Dipole (two-pole) antennas are the standard comparison for other antennas, suitable for presence and absence. Loop antennas are configured in a circle or diamond with a smaller size but less gain than directional antennas and are often used in fossorial or aquatic studies. Omni-directional (whip) antennas receive in all directions and are usually used to determine presence or absence. Yagi antennas are directional antennas with higher gain in front of the antenna, providing excellent directionality. Spacing of the 3 to 12 cross-elements depends on the frequency, but with decreasing portability. Adcock ("H") or 2-element antennas are more portable than Yagis but have lower gain than the 3-element Yagi. Many of these antennas are mounted on vehicles or aircraft for searching wide areas.

Table 3. The relative value of different types of three types of radio transmitters (VHF = very high frequency; PTT = satellite or platform transmitter terminal; and GPS = global positioning system) for different ecological study objectives, rated from lowest (*) to highest (***) value on the basis of the transmitter accuracy.

Ecological topics	VHF	PTT	GPS
Nesting and breeding	**	*	***
Migration	*	**	***
Wintering	***	**	***
Habitat interactions	***	*	**
Population dynamics	***	**	*
Physiology and behavior	***	*	***

Methods

Many studies simply use a transmitter to follow and approach marked individuals. Widespread availability of handheld GPS units makes it possible to more readily estimate locations of marked individuals once they are detected. This method is labor intensive and may cause disturbance to the marked individuals, if they are sensitive to human intrusion. Use of aircraft tracking is an effective and efficient method for locating large numbers of transmitters, searching rugged and remote areas, and for locating transmitters that can no longer be found with ground searches (Gilmer et al. 1981). Aerial tracking may be used to determine presence or absence in an area, or individuals may be located more accurately by flying in narrowing circles around the strongest signal. Accuracy of locations depends on altitude, air speed, visibility, and landmarks. The best altitude for a telemetry flight is usually 300–1,500 m.

More accurate locations are obtained with triangulation, where two or more directional bearings are obtained from known locations. Using a fixed tower or a roof-mounted directional antenna array (both affixed with compass rosettes and pointers), a bearing is obtained in the direction of the transmitter. Simultaneously, a bearing from true north is obtained for the observer's position. These bearing and azimuths are converted to angles (in radians), where the converging radians determine the location of the transmitter. There are several computer software programs available to calculate these locations once the bearing, azimuths, and Universal Transverse Mercator (UTM) or latitude and longitude of the two telemetry points are known. There is an error associated with each bearing to the transmitters (referred to as error polygon). The error is compounded by several factors: (1) accuracy of the antenna system, (2) accuracy of the observer, and (3) distance to transmitter. You have some control on all of these and care should be taken to minimize the error associated with each.

Data Compilation

Radio telemetry produces a large amount of information, both raw and processed. The easiest way to enter data is to use programs that provide triangulation calculations. Programs such as XYLOG (Dodge et al. 1986) written in BASIC provide users with a base to write individual code for programs. However, data compilation may be as simple as drawing points or the intersection of lines on a map and recording the final coordinates.

In satellite telemetry, location data is downloaded to a radio receiving system developed by the French space agency subsidiary, Argos, Inc. with offices in Toulouse, France and Landover, Maryland, USA. The easiest way to obtain the satellite data is by daily e-mail messages. However, the data is also available on CD or disk. Almost all waterbird transmitters are small, and the extra service known as animal processing will provide more locations, although their location class is generally less accurate. PTTs require a great deal of power to send their signal at a pulse rate of each 50–90 s during a period of 3–12 h set by the researcher. Different projects require different combinations of pulse rate and duty cycle. For example, a longer-term project might receive detections only every 3–5 days with a transmitter on for 6 hours so the PTT will last for a year. For birds where we are tracking migration, we usually use an on cycle of 4–8 hours, every second or third day.

The estimated location of the device is calculated and any other digital data from the transmitter is recorded. The 1998 cost is $14.93 USD per PTT per day of transmission. The animal location processing service includes the location calculated from fewer messages and is useful for animal transmitters with a cost of $2.88 per PTT per day. Finally, the multi-satellite service provides 50% more chances for locations than from the 2-satellite system and costs are $1.51 per PTT per day. Charges start from testing by the manufacturer until the study period ends. Data may be obtained from online services, telex, or e-mail, and costs for downloads are $0.08 per Kb transmitted. Costs for CD-ROMs are $271.19 each, while 1.44 MB disks are $128.81. A program is available from Argos to handle radio-tracking data to display it on the screen. Program ELSA is available with a world map for $2,542.37. However, many researchers either enter the data by hand or use geographic information systems such as ArcInfo or ArcView to display the data.

Analyzing Radio Telemetry Data

The analysis of radio telemetry and other marked animal data is rapidly advancing and many papers are written about different procedures each year. In this section, we present a general overview of major topics and refer the readers to general overviews, including Austin et al. (1997), Fancy et al. (1988), Harris et al. (1990), Kenward (1987), Samuel and Fuller (1994), and White and Garrott (1990).

Movements

Migratory birds are noted for their large-scale movements (i.e., migration and dispersal). Radio telemetry provides detailed information on these movements at finer levels of detail limited by the time and costs required to follow several individuals. Movement data must be collected at regular intervals for consistent results. For example, locations can be obtained daily or weekly, but waterbirds often move to different areas hourly. In our wintering studies, we usually estimate that 25 marked birds may be followed by an observer in a truck if the objective is daily or weekly observations. Analyses typically examine shifts in seasonal periods, weeks, or by time-of-day (Ely and Takekawa 1996; Warnock and Takekawa 1996). Analyses have also been produced to examine proximity or flocking (see Turchin 1998).

Home Range

Home range models depict the areas where animals spend most of their time. Radio telemetry is an excellent means of collecting these data because the animal may be located repeatedly during a study period. Convex polygons are a simple methods of mapping the distribution of telemetry data by drawing an outline around the use area. More complex polygons have also been developed to remove empty areas within the polygons (Kenward 2000). More data points (>25) are required to examine harmonic mean or elliptical home ranges (Samuel and Garton 1985; Warnock and Takekawa 1995). Probabilities are calculated from grid systems super-imposed on an animal's use area, and indicate major concentration areas. Even more data intensive, kernel-methods (Worton 1989; Seaman et al. 1999) use non-parametric approaches to estimate home range from 50–100 locations for an individual. Although these home ranges are considered the best from a statistical model standpoint, the sample sizes are rarely obtainable for a large sample of individuals.

Habitat Use

Habitat provides the food, cover, and other factors necessary for the survival of a wildlife population. Knowledge of the habitat requirements for a wildlife species is a critical component in its management. Analysis of wildlife habitat use patterns, including availability, use, preference, and criticalness, has been one of the principal applications of radio telemetry. Typically the observed frequency of locations (see Otis and White 1999) within a given habitat type are compared to an expected frequency (Neu et al. 1974). Thus, the analyses are based on proportions, where the proportion of area of each habitat is considered its availability or expected value, and the proportion of locations in each habitat is considered the use. When use of a particular habitat exceeds its availability, the animal is thought to have a preference for that habitat. If availability exceeds use, then the area may have been avoided.

Determining habitat availability may be a subjective process. One way to reduce researcher influence is to use home ranges to determine availability (Johnson 1980) where the proportion of habitats within the home range are used to estimate the available habitats. Second-order selection compares habitat use in individual home ranges with habitat availability in the overall study area. In contrast, third-order selection compares habitat use determined from radio locations with habitat availability in home ranges. Generally, these reflect a difference in the scale of the problem of interest at a local or regional level (Johnson 1980; Thomas and Taylor 1990; Warnock and Takekawa 1995).

A basic analysis (Neu et al. 1974) compares the differences in proportions among availability and use. More recent methods (Aebischer 1993) have used statistical methods for determining compositions to examine preference while accounting for dependency among habitats (i.e., proportions sum to 1.0). Composition analysis is based on the logarithm of the proportions, rather than on the proportions directly. In addition, it standardizes the proportions to one habitat type, usually the most abundant. Composition analysis accounts allows for testing of habitat differences by classes such as age, sex, or season (Warnock and Takekawa 1995).

Population Size

Population estimation is central to many wildlife management decisions. For example, harvest limits, pest management, recovery population levels, and determination of threatened or endangered species status, are all based on population size. Population size is the currency by which the success of many management programs is judged. Radio telemetry can be used to assist in the estimation of population size and can be useful in validating the assumptions or developing correction factors for other population estimation procedures.

One of the most critical assumptions in capture-recapture population estimates is that the number of marked animals in the population is known (i.e., no loss of marks or death of marked animals). With radio-marked animals, the number of marked animals in the population can be verified prior to a recapture period. Similarly, radio-marked individuals may help verify the proportion of animals not counted in aerial surveys or observer avoidance by animals in line transect estimates (Buckland et al. 1993). Analyses are available for population estimation specific to radio telemetry data. White (1996) and Lancia et al. (1994) provide an extensive review of general population estimation methods.

Survival

Radio telemetry studies can be very important in identifying mortality factors, survival rates, and factors that influence survival. Transmitters may be used to locate animals soon after death to identify the cause of death and also allow estimation of period-specific survival rates for populations. In its simplest form, survival data is recorded by producing a matrix of 1 and 0 for alive and dead animals for each study interval (days, weeks). Radio telemetry data can also include fate of the individual and covariate analyses such as body weight or age. Simple comparisons of the number of animals that die during an interval may be estimated from telemetry data. More sophisticated methods are available for comparing actual survival curves or to test for the effects of time-specific covariates on survival. It is important to recognize the assumptions for survival estimation regardless of which method is chosen for the analysis (see Bunck 1987).

There are basically two general types of statistical methods to estimate survival rates. The first method involves estimating the rate for a specific time interval and assumes that mortalities occur at a constant rate during the study period; the exact times of mortality are not the primary concern. The second method estimates a continuous survival curve and can be applied when animals are radio-tagged over an extended time period, when censoring occurs, when mortality rates are not constant, or when factors influencing survival are evaluated (Pollock et al. 1989). For example, we can estimate the survival of a population of cranes during the winter if they are located regularly (daily, weekly). Rather than simply using the proportion of radio-marked individuals that die during the period as the rate of mortality, these estimates depend on the number of days of exposure when the animal is detectable by the researcher. This provides a more conservative estimate of survival. It may also be possible to examine covariates such as weight at capture to determine if relationships exist between survival and body mass. In addition, cause-specific mortality estimates are possible if the cause can be determined before the animal is scavenged. Many of the statistical analyses for these types of estimates with marked populations have been included in generalized models (Lebreton et al. 1992; White et al. 1999).

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References

Aebischer, N. J., P. A. Robertson, and R. E. Kenward. 1993. Compositional analysis of habitat use from animal radio-tracking data. Ecology 74:1313–1325.

Alonso, J. C., J. A. Alonso, L. M. Bautista, and R. Munoz-Pulido. 1995. Patch use in cranes: A field test of optimal foraging predictions. Animal Behavior 49:1367–1379.

Anderson, R. K., J. P. Velga, and T. Cogger 1980. Fall and spring migration route and behavior of eastern Greater Sandhill Cranes: 1978–1979. Unpublished report. U.S. Fish and Wildlife Service, St. Paul, Minn. 21 pp.

Austin, J. E., P. J. Pietz, J. L. Godbey, D. W. Howerter, K. P. Kenow, and W. Norling. 1997. Forum on wildlife telemetry: Innovations, evaluations, and research needs. Unpublished program and abstracts. Snowmass, Colo. 40 pp.

Bennett, A. J. 1989. Movements and home ranges of Florida sandhill cranes. Journal of Wildlife Management 53:830–836.

Bishop, M. A. 1991. Habitat use by Florida Sandhill Cranes on the Kissimmee Prairie in central Florida. Proceedings of the North American Crane Workshop 6:175.

Buckland, S. T., D. R. Anderson, K. P. Burnham, and J. L. Laake. 1993. Distance sampling: Estimating abundance of biological populations. Chapman and Hall, London. 446 pp.

Chong, J. R., H. Higuchi, and U. Pak. 1992. The migration routes and important rest areas of cranes in the Korean Peninsula from the results of satellite tracking. Strix 11:21–34.

Chong, J. R., H. Higuchi, and U. Pak. 1993. The migration routes and important rest-sites of cranes on the Korean Peninsula. Pages 41–50 *in* H. Higuchi, J. Minton, and R. Kurosawa, editors. Proceedings of the International Symposium. The Future of Cranes and Wetlands. Tokyo.

Clegg, K. R., J. C. Lewis, and D. H. Ellis. 1997. Use of ultralight aircraft for introducing migratory populations. Proceedings of the North American Crane Workshop 7:105–113.

Craighead, F. C., Jr., J. J. Craighead, C. E. Cote, and H. K. Buechner. 1972. Satellite and ground radio tracking of elk. *In* S. R. Galler, K. Schmidt-Koenig, G. J. Jacobs, and R. E. Belleville, editors. Animal Orientation and Navigation, NASA SP-262, Washington D.C.

Crete, R. A., and J. E. Toepfer. 1978. Migration of radio-tagged eastern greater sandhill cranes. Unpublished report, U.S. Fish and Wildlife Service, St. Paul, Minn. 42 pp.

Desroberts, K. J. 1997. Survival and habitat use of greater sandhill crane colts on Modoc National Wildlife Refuge, California. Proceedings of the North American Crane Workshop 7:18–23.

Dodge, W. E., D. S. Wilke, and A. J. Steiner. 1986. XYLOG: A computer program for the field processing locations of radio-tagged wildlife. Technical Report No. 4. U.S. Fish and Wildlife Service, Washington, DC.

Drewien, R. C., S. C. Derrickson, and E. G. Bizeau. 1981. Experimental release of captive parent-reared Greater Sandhill Cranes at Grays Lake Refuge, Idaho. Pages 99–111 *in* J. C. Lewis, editor. Proceedings of the 1981 Crane Workshop, Grand Teton National Park, Wyoming. National Audubon Society, Tavernier, Fla.

Drewien, R. C., and E. L. Bizeau. 1981. Use of radio telemetry to study movements of juvenile Whooping Cranes. Pages 130–134 *in* J. C. Lewis and H. Masatomi, editors. Crane research around the world. Proceedings of the International Crane Symposium, Sapporo, Japan. International Crane Foundation, Baraboo, Wisc.

Drewien, R. C., W. M. Brown, J. D. Varley, and D. C. Lockman. 1999. Seasonal movements of sandhill cranes radio-marked in Yellowstone National Park and Jackson Hole, Wyoming. Journal of Wildlife Management 63:126–136.

Duan, W., T. A. Bookhout, and R. Urbanek. 1997. Home range and habitat use by isolation-reared Sandhill cranes. Proceedings of the North American Crane Workshop 7:72–78.

Dwyer, T. J. 1972. An adjustable radio package for ducks. Bird Banding 43:282–284.

Ellis, D. H., and Y. Markin. 1991. Satellite monitors cranes migrating from Siberia. International Crane Foundation Bugle 17:1–5.

Ellis, D. H., Y. M. Markin, C. H. Vermillion, C. M. Hoisington, A. G. Sorokin, and G. W. Pendleton. 1991. Satellite telemetry reveals winter home of Eurasian crane from northwestern Siberia. Proceedings of the North American Crane Workshop 6:172.

Ellis, D. H., D. G. Smith, G. H. Olsen, M. R. Fuller, S. E. Landfried, H. Higuchi, and C. H. Vermillion. 1992. Progress in satellite tracking cranes. Proceedings of the North American Crane Workshop 6:57–61.

Ellis, D. H., G. F. Gee, S. G. Hereford, G. H. Olsen, T. D. Chisolm, J. N. Nicolich, K. A. Sullivan, N. J. Thomas, M. Nagendran, and J. S. Hatfield. 2000. Post-release survival of hand-reared and parent-reared Mississippi sandhill cranes. Condor 102:104–112.

Ely, C. R., and J. Y. Takekawa. 1996. Geographic variation in migratory behavior of greater white-fronted geese (*Anser albifrons*). Auk 113:889–901.

Fancy, S. G., L. F. Pank, D. C. Douglas, C. H. Curby, G. W. Garner, S. C. Amstrup, and W. L. Regelin. 1988. Satellite telemetry: a new tool for wildlife research and management. U.S. Department of the Interior, Fish and Wildlife Service, Resource Publication 172. Washington, D.C.

Fuller, M., W. S. Seegar, and P. W. Howey. 1995. The use of satellite systems for the study of bird migration. Israel Journal of Zoology 41:243–252.

Gilmer, D. S., L. M. Cowardin, R. L. Duval, L. M. Mechlin, C. W. Shaiffer, and V. B. Kuechle. 1981. Procedures for the use of aircraft in wildlife biotelemetry studies. Resource Report No. 140. U.S. Fish and Wildlife Service, Jamestown, ND. 19 pp.

Gunda, B. 1968/69. Die Jagd und Domestikation des Kranichs bei den Ungarn. Anthropos 63/64:473–496.

Harris, R. B., S. G. Fancy, D. C. Douglas, G. W. Garner, S. C. Amstrup, T. R. McCabe, and L. F. Pank. 1990. Tracking wildlife by satellite: Current systems and performance. U.S. Fish and Wildlife Service, Fish and Wildlife Technical Report 30. Washington, D.C.

Harris, J., L. Su, H. Higuchi, M. Ueta, Z. Zhang, Y. Zhang, and X. Ni. 2000. Migratory stopover and wintering locations in eastern China used by White-naped Cranes, *Grus vipio*, and Hooded Cranes, *G. monacha*, as determined by satellite tracking. Forktail 16:93–99.

Higuchi, H. K., S. Javed, and M. Nagendran. 1999. Satellite tracking of large wetland birds in Kutch, Gujarat. Unpublished Progress Report. Tokyo University and Aligarh Muslim University, Tokyo and Aligarh, India.

Higuchi, H. K., M. Nagendran, A. G. Sorokin, and M. Ueta. 1994a. Satellite Tracking of common cranes, *Grus grus*, migrating north from Keoladeo National Park, India. Pages 26–31 *in* H. Higuchi and J. Minton, editors. Proceedings of the International Symposium "The Future of Cranes and Wetlands." Tokyo, Japan.

Higuchi, H., G. Ozaki, J. Fujita, M. Minton, M. Ueta, M. Soma, and N. Mita. 1996. Satellite tracking of white-naped crane migration and importance of Korean Demilitarized Zone. Conservation Biology 10:806–812.

Higuchi, H., K. Ozaki, G. Fujita, M. Soma, N. Kanmuri, and M. Ueta. 1992. Satellite tracking of the migration routes of cranes from Southern Japan. Strix 11:1–20.

Higuchi, H., K. Ozaki, K. Golovuskin, O. Goroshko, V. Krever, J. Minton, M. Ueta, V. Andronov, S. Smirenski, V. Ilyashenko, N. Kanmuri, and G. Archibald. 1994b. The migration routes and important rest-sites of cranes satellite tracked from south-central Russia. Pages 15–25 *in* H. Higuchi and J. Minton, editors. Proceedings of the International Symposium "The Future of Cranes and Wetlands." Tokyo.

Howe, M. A. 1989. Migration of radio-marked whooping cranes from the Aransas-Wood Buffalo population: Pattern of habitat use, behavior, and survival. U.S. Fish and Wildlife Service Technical Report No. 21, 33 pp.

Iverson, G. C., P. A. Vohs, and T. C. Tacha. 1985. Habitat use by sandhill cranes wintering in western Texas. Journal of Wildlife Management 49:1074–1083.

Ivey, D. L., and E. J. Scheuring. 1997. Mortality of radio-equipped sandhill crane colts at Malheur National Wildlife Refuge. Proceedings of the North American Crane Workshop 7:14–17.

Kenward, R. 1987. Wildlife radio tagging. Academic Press, London. 222 pp.

Krapu, G. L., D. E. Facey, E. K. Fritzell, and D. H. Johnson. 1984. Habitat use by migrant sandhill cranes in Nebraska. Journal of Wildlife Management 48: 407–417.

Kuyt, E. 1992. Aerial radio-tracking of Whooping cranes migrating between Wood Buffalo National Park and Aransas National Wildlife Refuge, 1981–84. Canadian Wildlife Service Occasional Papers No. 74. 50 pp.

Klugman, S. S., and M. R. Fuller. 1990. Effects of implanted transmitters in captive Florida sandhill cranes. Wildlife Society Bulletin 18:394–399.

Lancia, R. A., J. D. Nichols, and K. H. Pollock. 1996. Estimating the number of animals in wildlife populations. Pages 215–253 *in* T. A. Bookhout, editor. Research and management techniques for wildlife and habitats. Fifth edition. The Wildlife Society, Bethesda, Md.

Lebreton, J. D., K. P. Burnham, J. Clobert, and D. R. Anderson. 1992. Modeling survival and testing biological hypotheses using marked animals: A unified approach with case studies. Ecological Monographs 62:67–118.

Melvin, S. M., and S. A. Temple. 1983. Fall migration and mortality of Interlake, Manitoba Sandhill Cranes in North Dakota. Journal of Wildlife Management 47:805–817.

Melvin, S. M., R. C. Drewien, S. A. Temple, and E. G. Bizeau. 1983. Leg-band attachment for radio transmitters for large birds. Wildlife Society Bulletin 11:282–285.

Melvin, S. M., and S. A. Temple. 1987. Radio telemetry techniques for international crane studies. Pages 481–492 *in* G. W. Archibald, and R. F. Pasquier, editors. Proceedings of the 1983 International Crane Workshop. Bharatpur, India. International Crane Foundation, Baraboo, Wisc.

Nagendran, M. 1992. Satellite tracking of a greater sandhill crane. Proceedings of the North American Crane Workshop 6:173.

Nagendran, M. 1992. Winter release of isolation-reared Greater Sandhill Cranes in south Texas. Proceedings of the North American Crane Workshop 6:131–136.

Nagendran, M., H. Higuchi, and A. G. Sorokin. 1994. A harnessing technique to deploy transmitter on Cranes. Pages 57–60 *in* H. Higuchi, and J. Minton, editors. The future of cranes and wetlands. Proceedings of the International Symposium. Tokyo.

Nesbitt, S. A. 1975. Capturing sandhill cranes with oral tranquilizers. Pages 296–298, *in* J. C. Lewis, editor. Proceedings of the International Crane Workshop. Oklahoma State University Publisher, Stillwater.

Nesbitt, S. A. 1976. Use of radio telemetry techniques on Florida sandhill cranes. Pages 299–303 *in* J. C. Lewis, editor. Proceedings of the International Crane Workshop, Oklahoma State University Publisher, Stillwater.

Nesbitt, S. A., and J. W. Carpenter. 1993. Survival and movements of Greater Sandhill Cranes experimentally released in Florida. Journal of Wildlife Management 57:673–679.

Nesbitt, S. A., and K. S. Williams. 1990. Home range and habitat use of Florida sandhill cranes. Journal of Wildlife Management 54:92–96.

Nesbitt, S. A., M. J. Folk, M. G. Spalding, J. A. Schmidt, S. T. Schwikert, J. M. Nicolich, M. Wellington, J. C. Lewis, and T. H. Logan. 1997. An experimental release of Whooping Cranes in Florida – the first three years. Proceedings of the North American Crane Workshop 7:79–85.

Neu, C. W., C. R. Byers, and J. M. Peek. 1974. A technique for analysis of utilization-availability data. Journal of Wildlife Management 38:541–545.

Newman, S. H., J. Y. Takekawa, D. L. Whitworth, and E. E. Burkett. 1999. Subcutaneous anchor attachment increases retention of radio transmitters on Xantus' and Marbled murrelets. Journal of Field Ornithology 70:520–534.

Olsen, G. H., D. H. Ellis, S. E. Landfried, L. J. Miller, S. S. Klugman, M. R. Fuller, and C. H. Vermillion. 1992. Behavior of Sandhill Cranes harnessed with different satellite transmitters. Proceedings of the North American Crane Workshop 6:50–56.

Otis, D. L., and G. C. White. 1999. Autocorrelation of location estimates and the analysis of radio tracking data. Journal of Wildlife Management 63:1039–1044.

Pogson, T. H., and S. M. Lindstedt. 1991. Distribution and abundance of large Sandhill Cranes, *Grus canadensis*, wintering in California's Central Valley. Condor 93: 266–278.

Pollock, K. H., S. R. Winterstein, C. M. Bunck, and P. D. Curtis. 1989. Survival analysis in telemetry studies: the staggered entry design. Journal of Wildlife Management 53:7–15.

Samuel, M. D., and M. R. Fuller. 1994. Wildlife radiotelemetry. Pages 370–418 *in* T. A. Bookhout, editor. Research and management techniques for wildlife and habitats. Fifth edition. The Wildlife Society. Bethesda, Md.

Samuel, M. D., and E. O. Garton. 1985. Home range: A weighted normal estimate and tests of underlying assumptions. Journal of Wildlife Management 49:513–519.

Seaman, D. E., J. J. Millspaugh, B. J. Kernohan, G. C. Brundige, K. J. Raedeke, and R. A. Gitzen. 1999. Effects of sample size on kernel home range estimates. Journal of Wildlife Management 63:739–747.

Strikwerda, T. E., M. R. Fuller, W. S. Seegar, P. W. Howey, and H. D. Black. 1986. Bird-borne satellite transmitter and location program. Johns Hopkins APL Technical Digest 7:203–208.

Takekawa, J. Y., R. I. Leyva-Espinosa, and E. E. Klaas. 2000. Comparing radio and satellite telemetry to assess movements and habitat use of Arctic nesting geese in northern Mexico. Pages 109–122 *in* F. A. Comin, J. A. Herrera, and J. Ramirez, editors. Limnology and aquatic birds. Monitoring, modeling, and management. Universidad Autonoma de Yucatan, Merida, Mexico.

Thomas, D. L., and E. J. Taylor. 1990. Study designs and tests for comparing resource use and availability. Journal of Wildlife Management 54:322–330.

Toepfer, J. E., and R. A. Crete. 1979. Migration of radio-tagged Greater Sandhill Cranes from Minnesota and Wisconsin. Pages 159–174 *in* J. C. Lewis, editor. Proceedings of the 1978 Crane

Workshop. State University Print Service, Fort Collins, Colo. 595 pp.

Turchin, P. 1998. Quantitative analysis of movement: Measuring and modeling population redistribution in animals and plants. Sinauer Associates, New York. 360 pp.

Urbanek, R. P., and T. A. Bookhout. 1992. Development of an isolation-rearing/gentle release procedure for reintroducing migratory cranes. Proceedings of the North American Crane Workshop 6:120–130.

Warnock, S. E., and J. Y. Takekawa. 1995. Habitat preferences of wintering shorebirds in a temporally changing environment: Western Sandpipers in the San Francisco Bay estuary. Auk 112:920–930.

Warnock, S. E., and J. Y. Takekawa. 1996. Wintering site fidelity and movement patterns of western sandpipers *Calidris mauri* in the San Francisco Bay estuary. Ibis 138:160–167.

Warnock, N., and S. Warnock. 1993. Attachment of radio-transmitters to sandpipers: review and methods. Wader Study Group Bulletin 70:28–30.

White, G. C. 1996. NOREMARK: Population estimation from mark-resighting surveys. Wildlife Society Bulletin 24:50–52.

White, G. C., and K. P. Burnham. 1999. Program MARK: Survival estimation from populations of marked animals. Bird Study 46(Supplement):120–138.

White, G. C., and R. A. Garrott. 1990. Analysis of radio-tracking data. Academic Press, San Diego. 383 pp.

Williams, L. E., Jr., and R. W. Phillips. 1973. Capturing Sandhill Crane with alpha-chloralose. Journal of Wildlife Management 37:94–97.

Worton, B. J. 1989. Kernel methods for estimating the utilization distribution in home-range studies. Ecology 70:164–168.