



BIOLOGY AND CONSERVATION OF
**MARTENS, SABLES,
AND FISHERS**

A New Synthesis

EDITED BY

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The Use of Radiotelemetry in Research on *Martes* Species

Techniques and Technologies

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ABSTRACT

Radiotelemetry was first used on a *Martes* species in 1972, when 5 American martens (*Martes americana*) captured incidentally during a snowshoe hare (*Lepus americanus*) research project in Minnesota were radio-collared. Since then, at least 128 research projects have used radiotelemetry to investigate various aspects of the ecology of *Martes* species worldwide. The most common application of radiotelemetry to research on *Martes* species has been a ground-based study of American marten home range or habitat use in North America using VHF collars. Other telemetry-based projects have included studies involving all but 1 *Martes* species that were conducted in 20 additional countries, used Global Positioning System (GPS) or Argos telemetry, and addressed a broad spectrum of research questions such as survival, density, diet, community interactions, and responses to disturbance. To better understand the application of radiotelemetry to research on *Martes* species, we summarize the use of ground, aerial, and satellite-based telemetry techniques and outline the strengths and limitations of each. We also review the use of alternative attachment techniques such as break-away devices and intraperitoneal implant transmitters in research on *Martes* species, and provide recommendations for minimizing the risk of adverse effects while radio-tracking *Martes* species.

Introduction

Radiotelemetry was first used on a *Martes* species in 1972, when D. Mech and L. Rogers collared 5 American martens (*Martes americana*) that were captured incidentally during a snowshoe hare (*Lepus americanus*) research project in Minnesota in the United States (Mech and Rogers 1977; D. Mech,

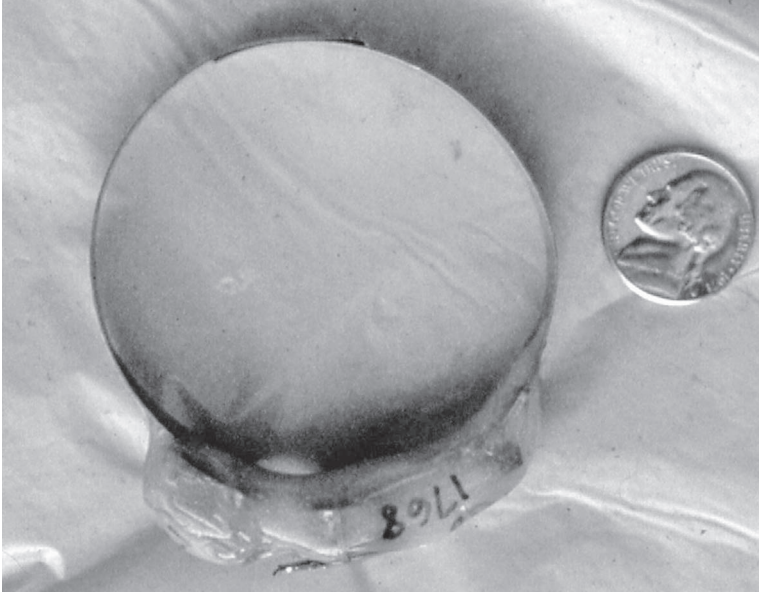


Figure 13.1. First-generation radio-collar used on American martens and fishers in 1972 (photo R. Powell).

U.S. Geological Survey, personal communication). Later that year, R. Powell began tracking 4 radio-collared fishers (*M. pennanti*) captured in the same area (R. Powell, North Carolina State University, personal communication). In 1973, researchers with the Ontario Ministry of Natural Resources in Canada began tracking 16 American martens in Algonquin Provincial Park to determine home range sizes and movement patterns (Taylor and Abrey 1982). The earliest collars, distributed by the AVM Instrument Co. (Champaign, Illinois, USA), consisted of a brass strip that doubled as the antenna and was either bolted or welded around the animal's neck (Figure 13.1). The transmitters, coated in dental acrylic, weighed 20–110 g, and had a lifespan of approximately 2 months and a range of 0.5–1.0 km (Buck 1982; D. Mech, personal communication; R. Powell, personal communication).

Following these early projects, the use of radiotelemetry to study American martens and fishers increased rapidly in the mid-1970s. In 1973, R. Powell began radio-tracking fishers in Michigan (USA) to investigate hunting patterns and ecological energetics (Powell 1977) and, in 1974, G. Kelly began following fishers in the White Mountains of New Hampshire (USA) to study movement patterns (Kelly 1977). In 1975, T. Campbell radio-tracked American martens in the Rocky Mountains of Wyoming (USA) to evaluate the impacts of timber harvesting (Campbell 1979), and M. Davis used telemetry to monitor the movements of American martens translocated into Wisconsin

(USA) (Davis 1983). From 1977 through 1979, additional telemetry studies were initiated on American martens in Maine and California in the United States, and the Yukon in Canada (Steventon 1979; Spencer et al. 1983; Archibald and Jessup 1984) and on fishers in California (Buck et al. 1979; Mullis 1985).

In Europe, radiotelemetry was first used on stone martens (*M. foina*) in 1980, when M. Herrmann began tracking 14 animals in Germany to study home range use and habitat preferences (Herrmann 1994), and on European pine martens (*M. martes*) in 1984, when P. Marchesi monitored the movements of 20 pine martens in Switzerland (Marchesi 1989). From 1986 to 1987, H. Kruger monitored the movements of both species near Gottingen, Germany, to determine the degree of ecological and spatial overlap (Kruger 1990). In Asia, M. Tatara began radio-tracking Japanese martens (*M. melampus*) in 1987 (Tatara 1994), and J. Ma and colleagues used telemetry in the 1990s to look at the seasonal activity patterns of sables (*M. zibellina*) in the Daxinganling Mountains of China (Ma et al. 1999).

To summarize the use of radiotelemetry in research on *Martes* species, we reviewed 178 published papers, book chapters, dissertations, theses, and unpublished reports, ultimately identifying 129 distinct research projects that used radiotelemetry to investigate various aspects of *Martes* ecology (Figure 13.2). We considered all work done in 1 study area over the same time span to be 1 research project, because the number of publications or reports varied greatly by project. Most studies focused on a single species, but 5 studies involved 2 species. We contacted *Martes* researchers worldwide and requested copies of unpublished reports, regional articles, and contact information for other relevant researchers. Where possible, we included preliminary results (e.g., posters, symposium abstracts) not published elsewhere. Regrettably, we undoubtedly missed some unpublished reports, theses and dissertations, or articles published in non-English journals that were not readily available. These 129 projects were conducted on 7 of the 8 recognized *Martes* species (no radiotelemetry research has been conducted on the Nilgiri marten [*M. gwatkinsii*]) and represented 22 countries (Figure 13.3). There was a clear bias toward North American species, with 58 research projects focused on American martens, 42 on fishers, 14 on European pine martens, 12 on stone martens, 4 on sables, 2 on Japanese martens, and only 1 on yellow-throated martens (*M. flavigula*). Although this bias is certainly inflated by our resources and search techniques, it was corroborated by numerous *Martes* researchers worldwide. Habitat use is the most widely reported ecological characteristic investigated (54% of studies), followed by home range (49%), movement patterns (21%), activity patterns (16%), and spatial organization (15%). Least reported are community interactions (2%), responses to disturbance (10%), density (10%), and survival (11%; Table 13.1). A list of the documents we reviewed is available from the authors on request.

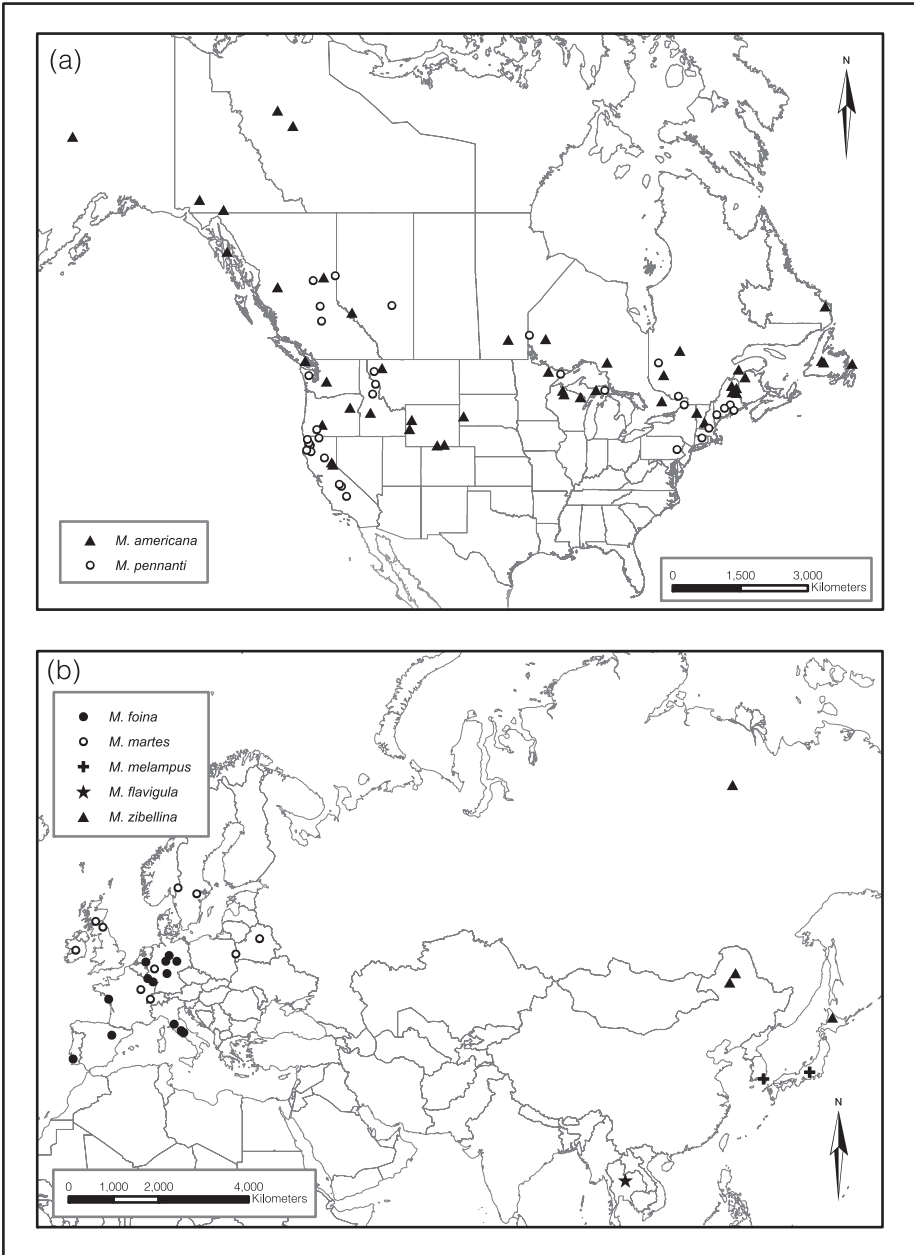


Figure 13.2. Distribution of telemetry-based *Martes* research projects in (a) North America and (b) Europe and Asia.



Figure 13.3. Radio-transmitter attachments on *Martes* species. *Top*: radio-collared yellow-throated marten (photo P. Grassman); *center left*: VHF collar on a Japanese marten (photo T. Nakamura); *center right*: ARGOS collar on a female fisher (photo J. Sauder); *lower left*: GPS collar on a male American marten (photo K. Moriarty); *lower right*: insertion of an implant transmitter into the body cavity of a fisher (photo R. Weir).

We collected methodological information from 119 research projects to evaluate data-acquisition rates, location accuracy, and efficiency. To estimate the relative cost per location for different telemetry techniques, we also interviewed many current *Martes* researchers. We summarized the results of these comparisons in Table 13.2.

Table 13.1. Summary of telemetry-based research on *Martes* species

Species	Total number of studies	Home range	Move-ment	Repro-duction	Density	Spatial organi-zation	Habitat use	Survival	Activity patterns	Diet	Distur-bance	Reintro-duction	Com-munity
<i>M. americana</i>	58	31	12	4	7	4	39	9	7	3	10	2	—
<i>M. flavigula</i>	1	1	1	—	—	—	—	—	1	—	—	—	1
<i>M. foina</i>	12	10	1	2	—	5	5	—	5	3	1	1	2
<i>M. guatkinsii</i>	0	—	—	—	—	—	—	—	—	—	—	—	—
<i>M. martes</i>	15	8	2	1	1	7	7	—	2	3	1	—	1
<i>M. melampus</i>	2	2	—	—	—	1	2	—	—	1	—	—	—
<i>M. pennanti</i>	42	16	11	9	4	5	25	5	5	4	2	4	—
<i>M. zibellina</i>	4	1	1	1	1	—	2	1	1	1	—	—	—

Note: Spatial organization refers primarily to inter- or intraspecific territoriality

Table 13.2. Comparison of telemetry techniques used to study *Martes* species

Parameter	Ground	Aerial	Ground and aerial	Argos	GPS
Number of studies	78	14	23	1	3
Mean number of study animals	18 ± 19 (<i>n</i> = 67)	39 ± 52 (<i>n</i> = 7) ^a	24 ± 15 (<i>n</i> = 15)	~20	ongoing
Mean number of locations	1990 ± 2897 (<i>n</i> = 14)	1961 ± 2707 (<i>n</i> = 3)	447 ± 236 (<i>n</i> = 3)	~3000	ongoing
Efficiency (locations per animal)	132 ± 185 ^b (<i>n</i> = 15)	25 ± 8 ^a (<i>n</i> = 3)	31 ± 13 (<i>n</i> = 3)	~50	~123
Cost per location ^c	\$8.26–\$43.90 ^d	\$26.50	— ^e	\$16.75	\$21.06
Estimated average location error	102.6 m (<i>n</i> = 8)	212.4 m (<i>n</i> = 13)	— ^e	68% class 3 (<250 m)	12.4 m
Transmitter mass ^f	20–40 g	20–40 g	20–40 g	75–120 g	45–75 g
Estimated battery life ^f	2–3 yr	2–3 yr	2–3 yr	1–2 yr	3–5 months

Note: Mean values are followed by standard deviations when appropriate

^a Three large research efforts using aerial telemetry are currently ongoing in Washington, California, and New York (USA); summary statistics from these studies are not yet available

^b One research project was excluded from this summary because of the large number of locations collected on a small number of animals: Posillico et al. (1995) collected >7500 locations on 3 stone martens in rural Italy; inclusion of this study results in an average of 291 ± 641 locations per study animal for ground-based telemetry projects

^c Cost per location was roughly estimated by several researchers based on equipment, contractor services, and labor costs as well as sample size

^d Cost per ground telemetry location varies widely depending on terrain and access

^e Data on the distribution of aerial vs. ground locations were not presented; values will reflect some combination of ground and aerial cost and accuracy

^f In all cases, mass and life span depend on battery size and reflect programmable factors such as pulse rate, range, fix interval, etc.; values reflect those typically selected by current *Martes* researchers

Primary Telemetry Techniques

Ground-based VHF Telemetry

Background

Of the 129 discrete research projects we reviewed, 86 used ground-based telemetry as the primary tracking technique. These 86 studies included 7 *Martes* species: American marten (38), fisher (28), European pine marten (10), stone marten (7), sable (4), Japanese marten (2), and yellow-throated marten (1); 4 studies included both American marten and fisher (Raine 1981;

Gilbert et al. 1997; Zielinski et al. 1997a; Belant 2007). Seventeen of these projects were supplemented by aerial telemetry.

A wide variety of questions have been addressed via radio-tracking using ground-based techniques, but the majority (81%) examined habitat use. Many of these habitat-oriented studies compared animal locations or home ranges with random locations, but others specifically addressed resting (40% of studies examining habitat), denning (18%), and traveling habitat (6%). Traveling habitat was generally addressed using snow tracking of radio-collared individuals. Resting-site studies examined the effects of season, sex, weather, and site availability on resting-site selection. Denning-site studies have examined the timing and duration of denning, as well as the characteristics of cavities and surrounding habitat conditions.

More than half the studies (58%) estimated home-range size and examined variation in home ranges due to sex, season, reproductive status, and habitat. Studies addressing questions related to the spatial organization of local populations were also common (27%), as well as studies that estimated density (19%). Other research objectives that have been addressed with ground-based telemetry include rates of movements or dispersals (30%) and the timing of seasonal or daily activities (20%). Thirteen percent of studies examined some aspect of the effects of disturbance, including logging, road construction, fire, sensitivity to fragmentation, and trapping. Studies done in areas with fur-trapping assessed harvest rates, responses to trapping pressure, and the sustainability of harvest practices. Seven studies evaluated reintroductions, addressing questions related to optimal release dates, release methods, post-release movements, and the fates of translocated animals.

Tracking Techniques

Three primary techniques were used to locate radio-marked animals: omnidirectional antennas, directional antennas, and homing. Omnidirectional antennas mounted on vehicles were often used to obtain approximate locations before obtaining more-precise locations with directional antennas.

Most studies used hand-held directional H, or 2-, 3-, or 4-element hand-held Yagi antennas. Locations were triangulated from points on the ground, usually taking advantage of road systems, and considering topography, accessibility, and known home ranges of animals. Most studies that used triangulation techniques specified the following: (1) a minimum number of bearings (2–7), (2) a maximum time period (usually 10–30 min) to help ensure the animal had not moved far during the interval, and (3) a minimum angle (generally 30°) between azimuths; these guidelines help to reduce errors associated with animals moving too far, while maximizing the accuracy of locations. To further increase accuracy, some studies attempted to be within a given distance of the animal (≤ 50 m to ≤ 1 km, depending on the study objectives). Directional antennas can be mounted on vehicles (Powell 1977; Gilbert et al.

1997; Pereboom et al. 2008) or used by observers on snowmobiles, skis, snowshoes, mountain bikes, or foot (Hauptman 1979; Simon 1980). Directional antennas can also be mounted on towers to increase detection range. Powell (1977) used directional antennas on two 14-m towers permanently mounted in the study area, and Taylor and Abrey (1982) used 3 permanent towers situated at high points approximately 1.5 km apart. Each of the latter towers was fitted with an omnidirectional antenna, an 8-element Yagi antenna, and a communications antenna to maintain continuous contact among observers. Observers at all 3 towers located animals simultaneously, removing any error associated with the focal animal's movement.

Typically, researchers used homing techniques when animals were inactive to locate resting and denning sites and to locate animals with mortality signals. Variations in signal strength and pulse rate are often used to determine activity, though activity sensors have recently been incorporated into some collars. Hand-held directional telemetry antennas and receivers were used to follow the radio signal to the point of origin, following the increasing strength of the signal. When close to an inactive animal, the external antenna of the receiver was often disconnected to assess proximity, based on whether a signal could be detected with only the internal antenna of the receiver (the "box signal"). When sufficiently close, observers generally reduced the gain and used the external antenna to identify the exact location. In a few cases, automated telemetry receivers were used near resting and denning sites to monitor attendance (Buskirk et al. 1989; Ruggiero et al. 1998), or near noninvasive monitoring stations (e.g., track plates, hair snares) to evaluate research effectiveness (Ivan 2000).

The interval between locations of individual animals has varied greatly among studies, depending on their objectives. Intervals between successive locations ranged from 3 min for studies examining activity cycles and movement patterns, to >1 week in others. A few studies focused on movement patterns and space use plotted sequential locations using a grid system (Taylor and Abrey 1982; Balharry 1993; Herrmann 1994). The size of the grid was determined on the basis of the accuracy of telemetry-based locations (Balharry 1993). Most studies focused on diurnal locations, but species that are strictly nocturnal (stone marten) or primarily nocturnal (European pine marten) were located at night unless daytime resting locations were of interest (Schröpfer et al. 1997; Herr 2008; Pereboom et al. 2008). A few studies noted the proportion of locations taken at night, and several studies obtained locations over time periods as long as 24–48 h to monitor activity (Fuller and Harrison 2005; Santos and Santos-Reis 2010; E. Manzo, Ethoikos, Convento dell' Osservanza, unpublished data).

Accuracy

The accuracy of locations acquired via ground-based triangulation is highly variable and depends on the terrain, observer experience, animal move-

ment, proximity to the animal, number of bearings taken, and the angle of intersection between subsequent bearings (White and Garrott 1990). Acceptable error depends on the objectives of the study and the precision of locations needed to address those objectives. Homing to locate resting and denning sites generally results in accurate locations because errors are limited to Global Positioning System (GPS) or mapping errors. Excluding studies where homing was used to locate structures and those that relied solely on visual sightings, approximately 45% of the studies reviewed described methods for assessing accuracy or estimates of accuracy. However, given the use of rugged terrain and cavities by *Martes* species, as well as their capacity for rapid movements, some consideration of triangulation accuracy and data screening is necessary, depending on project objectives.

Location error reported in 12 studies of *Martes* species ranged from ≤ 5 m in a study of Japanese martens (Tatara 1994) to 848 m for fishers (Tully 2006). Mean bearing error varied from 2° for fishers (Johnson 1984) to 12.6° for American martens (Dumyahn et al. 2007). Roy (1991) reported a 95% error arc of 16° for his study of fishers in Montana (USA). Few studies reported the mean size of error polygons. Self and Kerns (2001) calculated error polygons of approximately 2.5 ha, but they also noted that actual locations of their collared fishers were often outside the polygon. Payer and Harrison (2003) estimated a mean error-polygon size of 3.7 ha. More often, authors discarded observations when the associated error polygon exceeded some predetermined size. Weir and Corbould (2008) assigned precision classifications based on the size of the error polygon and then used various subsets of the data, depending on the precision needed for analyses at various spatial scales. Poole et al. (2004) calculated a mean error ellipse of 9.8 ha and used the 90th percentile ellipse (75 ha) as the upper limit for locations used in data analyses. Koen (2005) calculated a 95% confidence ellipse of 99 ha. Dumyahn et al. (2007) used only locations with an error ellipse ≤ 20 ha. Caryl (2008) calculated both error ellipses and mean location error, then used the larger estimate.

Koen (2005) provided an extensive evaluation and review of telemetry accuracy and triangulation error for fishers. Location and angular errors were estimated using a combination of blind tests and known positions of dead fishers. The author evaluated the effect of animal movements on location precision by having volunteers carry a transmitter while walking along forest trails in occupied fisher habitat at an average speed of 0.6 m/sec. Average angle error was $6.4 \pm 14.5^\circ$, and average location error was 268.6 ± 270.9 m, with an average distance of 1014 m between the observer and transmitter. Error did not vary significantly based on the statistical approach used (geometric mean vs. maximum likelihood, $P = 0.068$), but was significantly correlated with the distance between observer and transmitter ($P < 0.001$). Location error was 49% greater for mobile compared with stationary locations. See Koen (2005) for a detailed explanation of analytical techniques, discussion of error, and guidance on screening bearings.

Efficiency

Ground-based telemetry is labor- and time-intensive, particularly with highly mobile animals in rugged terrain. Although some study animals may be relatively easy to locate, others may require days of effort to obtain a single location. Of the 84 studies reviewed that used ground-based telemetry, 25 included sufficient information to calculate data-production rates. Studies that relied exclusively on ground telemetry collected an average of 132 locations per study animal (range: 20–425) over the life of the project, monitoring an average 18 animals per study (range: 1–126); however, terrain and animal behavior heavily influenced these numbers. In Italy, Genovesi and Boitani (1997a) generated 5782 independent locations for 16 stone martens over 53 months because of the animals' relatively small territories, predictable behavior, and use of agricultural landscapes. In contrast, Jones (1991) generated 264 locations over 36 months for 16 fishers in the Rocky Mountains of northern Idaho (USA).

Current and Future Applications

Ground-based telemetry is well suited to investigate questions related to habitat use at all spatial scales, but it is particularly applicable to fine-scale habitat selection, because it produces relatively precise location estimates and enables researchers to identify individual rest and den structures (Jones and Garton 1994). Selection and avoidance of particular structures, forest or cover types, developments, or disturbances can be studied by comparing used with either unused or available habitat. Home ranges and core-use areas can be delineated and home range size can be estimated and compared across study areas, habitats, and years, and intra- and intersexual overlap can be examined. Survival and mortality rates can also be studied with ground telemetry, and causes of mortality can often be determined via necropsy or forensic evidence, or both, if carcasses are recovered quickly (McCann et al. 2010). Homing can also lead to tracks that, when backtracked in the snow, can provide unbiased data on movements and fine-scale habitat use (Raine 1981; Jones 1991; Drew 1995), prey encounter and kill rates (Powell 1977; Thompson and Colgan 1994), and diet (from scats collected along snowtracks; Hauptman 1979; Arthur et al. 1989; Genovesi et al. 1996).

The primary limitation of ground-based telemetry is the difficulty of obtaining accurate directional signals in all types of terrain and equally across a study area (Baker 1992; Balharry 1993). Locating animals in mountainous and rugged terrain or during inclement weather can be difficult; consequently, inaccessible areas are often underrepresented. Elevational gradients may prevent signal reception or cause signal reflection or bounce. The study animal's position and microsite influences signal quality, as well; for example, if an animal is curled up or in a cavity, the signal can be blocked. Urban environments also present challenges; while tracking stone martens, Herr

(2008) found that VHF signals reflected off buildings, making triangulation difficult.

Long-distance movements that occur over a short period of time are difficult to track from the ground and animals may be “lost.” Emigration may be difficult to distinguish from animals that cannot be located or whose radios have failed (McCann et al. 2010). Translocated animals may also move rapidly and make large exploratory movements after release (Herr et al. 2008). These movements are difficult to track with ground-based telemetry and are best monitored with aerial or satellite telemetry. Other concerns regarding the use of ground telemetry include biases toward road networks or other access routes, limited nocturnal tracking because of safety concerns, and smaller sample sizes from the censoring of animals not located frequently enough. Area-observation curves suggest a minimum of 22–30 locations are needed for *Martes* species (Chapin et al. 1998; Fuller and Harrison 2005; Koen 2005); where reported, home ranges could not be calculated for 21–46% of the animals studied (Johnson 1984; Mazzoni 2002; Dumyahn et al. 2007).

Current research and development associated with VHF transmitters is limited because of the emphasis on satellite-based systems; however, 3 areas of current technological development that may benefit *Martes* researchers include battery technology, signal-processing technology, and the combination of digitally encoded signals and automated receiving systems. The development of lithium-ion batteries greatly increased the lifespan and range of transmitters, and new battery chemistries on the horizon may continue this advancement. For example, lithium thionyl chloride batteries can provide significantly more power than lithium-ion batteries; however, they are extremely corrosive, and the necessary casing materials increase the weight of transmitters beyond what is acceptable for *Martes* species (U.S. Geological Survey 1997).

Advances in signal processing may benefit *Martes* researchers in 2 ways, through range estimation and the filtration of reflected signals. Range estimation (i.e., calculating the distance from the observer to the transmitter) would eliminate the need for triangulation, thereby greatly reducing the error of telemetry locations and the need for multiple bearings. This may be possible by measuring the time delay between signal generation and reception, and research is ongoing regarding incorporating accurate time stamps into VHF signals (U.S. Geological Survey 1997). More precise signal-processing techniques may also allow observers to better differentiate between direct and reflected signals. This would facilitate the use of higher frequency transmitters, which are currently limited in use because of problems with signal reflection. The benefit of higher frequency transmitters is that they require smaller transmitter antennas, and a closer match of the frequency with the antenna length will greatly increase reception range (U.S. Geological Survey 1997).

Finally, the recent development of digitally encoded VHF signals allows an observer to monitor multiple animals on a single frequency. A unique digital “tag” is incorporated into the VHF signal, and signals are then sorted by a digital receiver. This capability greatly increases the efficiency of scanning receivers because only a single frequency is monitored, reducing observer fatigue and eliminating the risk that a brief appearance by a study animal will be missed by either a fast-moving (e.g., aerial) scanner or an automated monitoring system (Lotek Wireless, <http://www.lotek.com/radio.htm>).

Aerial VHF Telemetry

Background

The unique ability of observers in aircrafts to rapidly search and locate radio-collared animals over large and inaccessible areas, while allowing for nearly line-of-sight reception between transmitter and receiver, makes aerial radiotelemetry an attractive research technique (Gilmer et al. 1981). It is particularly appropriate for studying *Martes* species that occur in remote areas with limited access (Weir and Corbould 2008). Wildlife biologists have used aircraft for monitoring American martens and fishers in North America since the early to mid-1970s (Mech 1974). Kelly (1977) used a fixed-wing airplane to monitor the movements of fishers in the White Mountain National Forest of New Hampshire and Maine, and Mech (1974) reported detection distances from fixed-wing airplanes of 3.2 and 8 km for martens and fishers, respectively. In comparison, current projects report detection distances of 11–15 km in the direction of flight using a forward-mounted 3-element Yagi antenna, and 8–11 km using side-mounted directional H-antennas (R. Sweitzer and R. Barrett, University of California at Berkeley, unpublished data). Helicopters have been used infrequently for monitoring American martens (Latour et al. 1994; Potvin et al. 2000; Hearn 2007), and 1 project used an ultralight aircraft (M. Cheveau, Université du Québec en Abitibi-Témiscamingue, unpublished data). Notably, we were unable to locate any studies of *Martes* species in Europe or Asia that reported using aerial telemetry.

The most common use of aerial telemetry for studies of *Martes* species has been for assessing movements and home range use. Other common uses include assessment of habitat use/selection (Potvin et al. 2000) and survival (Koen et al. 2007). Typically, aerial telemetry has been used in association with ground-based telemetry, most often as a backup method for finding animals that were difficult to locate from the ground. Because of the high cost of flight time, few projects were able to conduct aerial surveys more than once per week. Of the 37 studies we identified that used aerial telemetry to track study animals, 14 used it as the primary monitoring technique. The remaining 23 studies used aerial monitoring to supplement or inform ground-based telemetry efforts.

Tracking Techniques

The most common method for tracking animals from fixed-wing airplanes involves the use of H-style antennas mounted on both the right and left wing struts, linked to a switchbox and receiver. Once a signal has been detected, the biologist begins alternating which antenna is active/audible with the switchbox and works with the pilot to orient the flight path toward and then over the animal; the pilot then circles back, and the biologist marks the estimated location using a handheld or aviation GPS receiver based on peak signal strength (Gilmer et al. 1981; Seddon and Maloney 2004). Although helicopters are much more expensive to operate than fixed-wing airplanes, they have 2 distinct advantages: the ability to fly at slow speeds and to hover. Gilmer et al. (1981) recommend searching for radio-collared animals from helicopters outfitted with a forward-pointing antenna at an elevation of about 200 m, then obtaining signal directionality on approach by occasionally yawing left and right; however, excessive noise and windwash disturbance is a concern with low-level helicopter (<100 m) approaches to radio-collared animals. In addition, although the accuracy of positions may be improved by helicopter-based radiotelemetry, the relatively short cruising radius will limit the number of animals that can be tracked and positioned, especially in remote areas (Gilmer et al. 1981).

Accuracy

A large number of factors influence location error when tracking radio-collared animals from aircraft. In general, location error increases with flight speed, elevation above ground level (AGL), and signal reflection in rugged topography, and decreases as the experience levels of the pilot and biologist increase. Problems associated with signal reflection in steep topography or around large expanses of exposed rock are a common issue for both ground and aerial telemetry. One advantage of locating animals from an airplane in those situations is that the area can be thoroughly examined until a direct line-of-sight signal is acquired (Gantz et al. 2006).

We identified 34 different studies that used some type of fixed-wing aircraft to study American martens or fishers in North America. Fourteen of the studies provided estimates of location error. Two of these studies simply estimated location error at <10 m (Arthur et al. 1989) and <500 m (Slough 1989), without providing details on how the errors were estimated. Two studies reported location error in terms of error ellipses: 2.7 ha (Fuller and Harrison 2005) and 3.5 ha (Gosse et al. 2005). Eleven studies reported error in terms of the distance between the estimated and actual location of test transmitters, which averaged 207 ± 188 m (range: 30–729 m).

Although helicopters have been used extensively for tracking other wildlife species, we found only 3 studies that used helicopters for tracking radio-collared *Martes* species. Latour et al. (1994) used a Bell 206B helicopter to

monitor the movements and home ranges of American martens in the Mackenzie Valley of the Northwest Territories, Canada. They reported an average location error of 242 ± 100 m. Potvin (1998) used both a Bell 206B helicopter and a Cessna 185 fixed-wing airplane to track American martens in western Quebec, Canada, and reported average errors of 9 m for the helicopter and 223 m for the airplane. Finally, Hearn (2007) used both a Bell 206B and an Aerospatial A-star helicopter to track American martens in Newfoundland, Canada. Although he did not report an estimate of location error, he did report hovering <10 m above the canopy and visually observing collared martens (Hearn 2007).

Although it may be possible to improve the accuracy of some locations by operating aircraft closer to the ground, as a general rule, it should not be necessary to fly a fixed-wing aircraft below 150 m AGL. Indeed, most federal and state agencies and the U.S. Federal Aviation Administration (FAA) require that aircraft not operate below 150 m, except in special circumstances (Gilmer et al. 1981). Safety must remain the highest priority when using helicopters or light aircraft to track radio-collared wildlife; there is no situation when improving the accuracy of positions for radio-collared animals is more important than the safety of the pilot and biologist. In our experience, the optimal elevation AGL for locating radio-collared fishers is between 150 and 230 m; lower-level flying significantly detracts from the concentration needed to interpret variation in signal strength, and it is more difficult to pinpoint locations when flying much above 450 m.

Efficiency

Seven studies provided sufficient information to evaluate the efficiency of aerial telemetry. Studies that relied exclusively on aerial telemetry averaged 1961 total locations on 39 study animals, or 50.3 locations per animal ($n = 4$). Projects that used aerial telemetry to supplement ground efforts averaged 447 total locations on 24 animals, or 18.6 locations per study animal ($n = 3$).

Current and Future Applications

The primary benefit of aerial telemetry is the ability to consistently locate a large number of study animals and to monitor long-distance movements (e.g., dispersals, male breeding activities) in inaccessible terrain. In North America, *Martes* species exist at relatively low densities in rugged terrain, use large areas, and are capable of making rapid long-distance movements—all characteristics that make ground-based telemetry difficult. If flights are frequent, detecting and locating mortalities quickly can help establish the cause of death. The primary weaknesses of aerial telemetry are reduced location accuracy, the loss of additional insights and data gleaned by tracking animals on the ground, and the high cost of flight time. Koen (2005) compared the accuracy of aerial and ground-based telemetry and found that aerial locations

were 57% less accurate, making them largely unsuitable for investigating habitat use or selection at fine spatial scales. Aerial telemetry also precludes the identification of specific habitat elements, such as resting or denning sites. For this reason, most studies combine aerial and ground-based monitoring. Although aerial telemetry facilitates the monitoring of larger numbers of study animals, this often translates into fewer locations collected per study animal as a result of reduced tracking efforts (e.g., weekly flights vs. daily ground-tracking).

A relatively recent innovation in wildlife radiotelemetry is the use of ultralight aircraft. The ultralight classification includes motorized aircraft weighing <115 kg with a power-off stall speed of 25 knots (Quigley and Crawshaw 1989). Advantages of using ultralight aircraft compared with larger fixed-wing airplanes or helicopters include lower cost and extended flight time (better fuel economy), flexibility of use (e.g., transport into remote areas), and relatively slow flight speeds, which can translate into more precise locations. Disadvantages of ultralight aircraft include relatively high sensitivity to weather conditions (especially wind) and the potential for reduced safety compared with fixed-wing airplanes (Quigley and Crawshaw 1989).

For locating radio-collared jaguars (*Panthera onca*) from an ultralight, Quigley and Crawshaw (1989) used 2 H-antennas mounted approximately 2 m from each wing tip and angled downward at 45°. M. Cheveau (unpublished data) used an ultralight aircraft equipped with skis to track radio-collared martens in a remote area of northwestern Quebec. Cheveau mounted one 4-element Yagi antenna pointing forward on the front of an ultralight aircraft, with a second antenna oriented sideways on the left side of the ultralight. Using this arrangement, she reported locating study animals daily with an average location error of 33 m (median = 12 m) based on blind tests.

GPS Telemetry

Background

In 1988, the Ontario Ministry of Natural Resources unveiled an ambitious program to double the number of moose (*Alces alces*) in the province over the next 20 years through a combination of timber management and habitat conservation (Ontario Ministry of Natural Resources 1988). As part of this program, they reviewed all available and potential technology for wildlife tracking and settled on the (then) new NAVSTAR GPS satellite constellation as the most efficient and cost-effective way to meet their monitoring needs (Rodgers et al. 1996). In 1992, Lotek Engineering (Newmarket, Ontario, Canada) was contracted to design and develop a GPS-based wildlife telemetry system (Rodgers 2001), and by 1994, the first 1.8-kg GPS collar was available commercially (Rodgers et al. 1996). Since then, steady advancements in GPS telemetry technology such as the miniaturization of

GPS chips, the addition of remote-download and solar-recharging capabilities, and improvements in antenna design have resulted in collars as small as 5–7 g.

Currently, the most appropriate GPS units for tracking *Martes* species range from 40 to 75 g in weight, which includes the battery, epoxy, and collar material. This means that current GPS transmitters weigh approximately 1–8% of a study animal's body weight, depending on the species and sex of the animal. Solar-powered units, while significantly smaller, are generally considered inappropriate for research on *Martes* species because of their preference for areas of dense canopy, tendency to rest in tree cavities or other protected structures, and nocturnal or crepuscular behavior.

The first deployment of a GPS collar on a *Martes* species occurred in February 2009, when both the USDA Forest Service, Pacific Southwest Research Station and the University of California at Berkeley, Sierra Nevada Adaptive Management Project (SNAMP) began field-testing units manufactured by Telemetry Solutions (Concord, California, USA) on fishers in the southern Sierra Nevada of California. To date, 45 miniature GPS collars have been deployed on fishers by these 2 research organizations. One additional GPS collar was deployed on an adult male American marten in 2010 on the Sagehen Experimental Forest in the central Sierra Nevada (K. Moriarty, Oregon State University, personal communication).

Tracking Techniques

Most miniaturized GPS collars contain “store-on-board” transmitters, meaning that data are stored in the unit until it can be retrieved, after the animal either sheds the collar or is recaptured. A VHF beacon operating on a separate power supply allows the collar to be found if it is shed by the animal. Because electronic drop-off mechanisms add 20–40 g of weight, most researchers have used homemade inserts in the collars to facilitate eventual drop-off (see below). Store-on-board units are a risky proposition for most *Martes* researchers, because the collar must be recovered to retrieve the data. Should the collar be dropped in a tree cavity, underground burrow, or roof space where the VHF beacon is suppressed, or the collar is not retrieved prior to failure of the VHF signal, all data are lost. For this reason, researchers typically add the remote-download feature to their collars. This feature operates from the GPS battery and allows a researcher to wirelessly connect with the collar to download the data or reprogram the collar when within 200–400 m of the animal; for example, data can be downloaded from the base of a rest or den tree when it is occupied by a study animal. If the animal is using an area that is difficult to access, tends to flee at the researcher's approach, or is part of a larger project with multiple animals, stored data can be downloaded from an aircraft properly outfitted with a UHF antenna by either circling or hovering at 150–230 m AGL (R. Sweitzer, personal communication).

Accuracy

Accuracy and efficiency are significant concerns when applying GPS technology to tracking *Martes* species. These species typically live in structurally complex habitats where GPS accuracy and fix rates may be compromised. The 2 primary research projects using miniaturized GPS collars on *Martes* species have evaluated their accuracy in 2 ways. The USDA Forest Service, Pacific Southwest Research Station's Kings River Fisher Project (KRFP), in the Sierra Nevada of California, tested collar accuracy by placing a GPS collar on a scat-detector dog during surveys. Scat-detector dogs are trained to locate the scats of a target species (see Long and MacKay, this volume), and over the course of a month, the dog and a handler could survey the majority of the study area. To test the accuracy of the GPS collar while moving through brush and varying forest conditions, researchers compared locations collected by the collar with a tracklog generated by a standard Bluetooth GPS unit carried by the handler. The average distance between the GPS collar and the handler was 12.4 ± 18.6 m ($n = 165$) (C. Thompson and K. Purcell, unpublished data); 90% of all errors were <28 m.

Researchers with the University of California at Berkeley SNAMP project placed collars in multiple fixed locations and allowed them to collect locations for up to 24 h (R. Sweitzer and R. Barrett, unpublished data). They compared recorded locations with those taken from handheld GPS units, categorizing errors by canopy cover, slope, and aspect. Average error varied from 12 to 42 m, with no obvious relation to cover or topography.

Efficiency

To date, 46 miniaturized GPS collars have been deployed on 13 fishers in the SNAMP project, 8 fishers in the KRFP project, 24 fishers in a USDA Forest Service, Pacific Southwest Research Station fuel-reduction project, and 1 American marten in the Oregon State University, Sagehen Creek study. Because collars are user-programmed, fix rates are highly variable and data presented here should be taken as suggestive of potential collar performance. Based on multiple remote-download attempts for all collars, the average performance of 75-g collars was 152 points collected over an average of 58 days. The average performance of 50-g collars was only 16 points collected over 27 days. The average fix success for both collar types was 28%. Two 75-g collars were successfully removed from recaptured adult male fishers after the GPS batteries were drained, allowing for an accurate assessment of actual lifespan and productivity. One unit lasted 77 days, attempting 711 fixes during that time and successfully acquiring 182 locations (25.6% success rate). The second lasted 85 days, attempting 766 fixes and successfully acquiring 281 locations (36.7% success rate; C. Thompson and K. Purcell, unpublished data). A 45-g collar placed on a male American marten collected 179 fixes at

5-min intervals over 2 days, for a success rate of 39% (K. Moriarty, personal communication). Comparatively, manufacturer specifications indicate that collars collecting 1 location per day should last 331 and 114 days for the full-AA (75 g) and half-AA (45 g) configurations, respectively.

Current and Future Applications

GPS-tracking technology has now advanced to the point where it is appropriate for the largest *Martes* species and individuals, namely fishers and males of other species >2 kg in weight; however, GPS collars are still too heavy and bulky for use on smaller animals. Their use can greatly expand research capabilities through increased accuracy, potentially greater numbers of locations in remote terrain, greater spatial coverage in rugged or roadless areas, collection of locations during times when aerial or ground telemetry may not be feasible (e.g., at night, during severe weather), collection of sequential locations indicating routes of travel, and elimination of the need for an on-the-ground researcher who could potentially disrupt the behavior of study animals. Nonetheless, use of GPS technology has many limitations; for example, data on the cause of mortality and other real-time information are unavailable without additional effort, because the VHF frequency is not monitored consistently. Another concern of particular relevance to *Martes* researchers is the possibility of habitat-related biases resulting from unequal satellite reception within a study area. *Martes* species typically move rapidly through complex landscapes, and a careful assessment of potential biases is necessary. Finally, GPS collars currently have much shorter lifespans than VHF collars, typically on the order of 2–3 months vs. 2–3 years.

Significant advances in GPS technology will undoubtedly be made in the near future that provide greater reliability and longevity. GPS chips will continue to decrease in size, though this will likely mean more storage and functionality, rather than lighter collars, because chips are already an insignificant component of transmitter weights. Lighter collars are most likely to result from improvements in battery technology, which is currently the limiting factor for collar weight, lifespan, and fix attempts. Another area where further advancement is possible is antenna technology; a \$4 GPS chip can achieve greater accuracy than a \$19,000 GPS receiver, if the antenna used is of significantly higher quality (van Diggelen 2010).

One active focus area for current research and development is the transmission of data back to the user. Currently, collars suitable for use on *Martes* species must either be retrieved or their data downloaded remotely from within 400 m. With the explosion of cellular technology worldwide, new and innovative options are emerging. Currently, features are available to remotely download data from larger GPS collars whenever an animal comes within range of a cellular tower using GSM (Global System for Mobile communications) technology, and it is only a matter of time before this technology is in-

corporated into smaller collars. Although this may not be useful in North America, where most *Martes* populations inhabit remote terrain with limited cellular phone coverage, it could vastly improve tracking capabilities in Europe or Asia, where *Martes* species inhabit rural and urban areas, and cellular coverage is widespread. Similar proposals have been made to use either unmanned aerial vehicles (Schulte and Fielitz 2001) or other collared animals (Markham and Wilkinson 2008) as download relay stations. At least 1 manufacturer is currently working on a remote-download station that, when placed in conjunction with a bait station, will download data from any collared animal that comes within 100 m (Q. Kermeen, Telemetry Solutions, personal communication).

The most likely area of rapid technological advancement will be through GPS+, a reference to supplementation of the GPS satellite constellation with additional satellite or terrestrial networks. In 1993, Russia announced the functionality of its version of the GPS satellite constellation, known as GLONASS, and China, Japan, and the European Union are developing similar networks (Compass, QZSS, and Galileo systems, respectively). The creation of products capable of communicating with multiple satellite systems will greatly increase coverage and reduce the time-to-fix, resulting in more successful locations and overall power conservation. Similarly, technology is available to supplement GPS location data with data from terrestrial Wi-Fi or GSM networks. These networks provide supplemental location information and increase the speed of communications between the satellite and collar, resulting in more successful locations and overall power conservation. Although this technology may be slow to work its way into wildlife applications, its prevalence in navigation and cellular-phone technology ensures its development and eventual availability.

Argos Telemetry

Background

Originally conceived as a collaborative project between the United States and France to improve meteorologic and oceanic information (CLS America 2011), the Argos Satellite System has expanded markedly since its inception >30 years ago. Currently, movements of >300 species are monitored by >6500 Argos Platform Terminal Transmitters (Argos PTTs; D. Stakem, CLS America, personal communication). Although many biologists are familiar with the mechanics of GPS telemetry, Argos satellite telemetry works quite differently. Unlike GPS telemetry units that receive signals from orbiting satellites and internally calculate a location, Argos units broadcast a signal into space that is picked up by polar-orbiting satellites. Signals from the PTT received by the satellite are relayed to a ground processing station; if ≥ 4 signals are received by a satellite during a pass, a location and an estimate of that location's accuracy

are calculated using the Doppler-shift principle. For more-detailed descriptions of the Argos system, the principles behind the calculation of locations, and current data options, see Fancy et al. (1988) and CLS America (2011).

Much of the initial research into Argos telemetry concluded that the moderate location accuracies of this system limited its suitability to studies of species that moved long distances (Harris et al. 1990; Keating et al. 1991; Britten et al. 1999). Accordingly, much of the wildlife research that has used Argos telemetry has focused on large-scale movements, particularly of birds (e.g., Higuchi et al. 1998; Soutullo et al. 2006), marine mammals (e.g., Baumgartner and Mate 2005; Blix and Nordoy 2007) and large terrestrial mammals (e.g., Walton et al. 2001; Mauritzen et al. 2002; Ito et al. 2006). Over the past 10–15 years, however, the evolution of transmitter design, satellite configuration, and data-processing techniques have significantly improved Argos satellite telemetry performance (J. Sauder, unpublished data). Recent research suggests that Argos telemetry can be suitable for smaller-scale analyses of space use and habitat selection by species that do not move large distances, if appropriate techniques and units of analysis are used (Moser and Garton 2007).

Tracking Techniques

One of the unique characteristics of Argos telemetry is that data collection is entirely automated and coordinated through CLS America. Signals received by the satellites are relayed to a ground-based processing station, where a location and accuracy assessment is calculated. These data are made available to the researcher in multiple formats. Data are accessible in near real-time on the Argos Users website (<http://www.argos-system.org>), where tools for mapping, downloading, and working with the data can be found. Alternatively, data can be delivered daily or at other intervals to the owner via e-mail. This facilitates data collection in traditionally difficult research situations (e.g., at night, in wilderness areas, during inclement weather), though at significantly increased cost. The initial cost of Argos PTTs can exceed \$2500, and additional data-delivery fees are charged by CLS America, based on the number and timing of signals received by the satellites.

The weight and size of Argos PTTs designed for deployment on *Martes* species are mainly a function of battery and collar configurations. Collars built for fishers have generally had about 15 mm-wide nylon-belted collar material and were powered by 1, 2, or 3 AA batteries, resulting in collar weights of approximately 75, 97, and 120 g, respectively (K. Lay, Sirtrack Ltd., personal communication). Lifespan is a function of 4 parameters: repetition rate (how often the transmitter broadcasts a signal), duty cycle (hours per day the transmitter is functioning), output wattage (strength of transmission), and battery size. For a 3 AA-battery collar with a repetition rate of 45

seconds, duty cycle of 12 h “on” in each 72-h period, and output wattage of 0.5 watts, the manufacturer’s projected lifespan is approximately 400 days. For identically configured transmitters with 2 and 1 AA batteries, the projected life span is approximately 265 and 135 days, respectively. In practice, however, effective collar life may not meet the manufacturer’s estimate. Low temperatures ($<10^{\circ}\text{C}$) are known to diminish the lifespan of Argos collars. Also, at the end of a transmitter’s life, performance often becomes more variable, because the unit’s voltage may hover around the minimum required to emit a signal.

Ground- or aircraft-based tracking of Argos collars is possible but difficult, requiring specialized equipment. Argos transmitters broadcast their signals at approximately 401.65 MHz, a frequency that most VHF receivers do not pick up. Police scanners have been used to locate PTTs (Bates et al. 2003), but the slow repetition rate of signals makes homing-in on the signal difficult. Recently, specialized receivers with highly directional antennas have been designed to detect PTTs. Some of these Argos PTT receivers have an internal meter that indicates signal strength audibly. Using such a receiver makes recovering stationary collars fairly simple, but locating a collar still on a study animal is difficult because the 45 sec between signals is long enough for the animal to leave the area.

Accuracy

When 4 or more signals from an Argos PTT are detected by a satellite during 1 pass, a location and accuracy assessment are calculated. The accuracy assessment assigns the location to 1 of 4 “location classes” (LC) ranging from 0 (least accurate) to 3 (most accurate). The Argos Users Manual states that 68% of locations assigned to LC 3 have an error radius of ≤ 250 m, increasing to ≤ 500 m for LC 2, ≤ 1500 m for LC 1, and ≥ 1500 m for LC 0 (CLS America 2011). Independent testing of these assessments has shown them to be fairly accurate (J. Sauder, unpublished data). If fewer than 4 signals are received by the satellite during a pass, a location may be calculated with auxiliary data processing; these are assigned to location classes A, B, or Z, but no accuracy assessment is provided by Argos for these locations. Such data points are of variable accuracy and probably of little value to *Martes* researchers, with the possible exception of using them to document long-distance dispersals. In addition to the location class, CLS America recently began providing an error ellipse, an angle of orientation, and a metric called geometric dilution of precision (conceptually similar to positional dilution of precision for GPS telemetry). This additional information on location error may improve the accuracy of error evaluations for analyses of Argos telemetry data. The 95% error ellipses for LC 3, 2, and 1 locations from collars deployed on fishers were 6.0, 23.1, and 186.1 ha, respectively (J. Sauder, unpublished data).

The effects of topography and canopy cover on Argos telemetry performance have not been as widely studied as they have for GPS telemetry. Recent research suggests that Argos telemetry is generally robust to the negative effects of topography and canopy cover (J. Sauder, unpublished data). This is different from GPS telemetry, where environmental variables are known to bias acquisition rates and the accuracy of locations (D'eon et al. 2002; Frair et al. 2004; Lewis et al. 2007; Kochanny et al. 2009). The effects of weather and behavior on Argos PTT performance remain poorly understood.

Efficiency

Because Argos telemetry is entirely automated, rates of data collection are mainly a function of the duty cycle programmed into the collar as well as the random effects of animal behavior and weather. Since Argos transmitters blindly broadcast a signal into the sky, it is impossible to calculate fix rates, as for GPS telemetry. Instead, quantifying transmitter performance as a function of time-in-operation is suggested. Stationary Argos collars tested in typical fisher habitat in north-central Idaho averaged 7.8 ± 3.8 LC 2 and 3 locations per 24 h of operation. Identical collars deployed on fishers averaged 3.6 ± 1.5 LC 2 and 3 locations per 24 h of operation (J. Sauder, unpublished data). This approximate 54% reduction in performance is presumed to be due mainly to the effects of animal behavior, but weather could also play a role. Accordingly, the 3-, 2-, and 1-AA collars described above should average 237 ± 99 , 159 ± 66 , and 81 ± 34 LC 3 and 2 locations, respectively, over the manufacturer's estimated lifespan when deployed on a fisher. In reality, collar performance can be more variable for unknown reasons. Reasons for poor collar performance are difficult to evaluate, as they are confounded by animal behaviors, defective collars, and damaged antennas. Projections about collar performance must also be tempered by potential temporal autocorrelation among points. Multiple satellites can detect a single animal several times in a short time period. Depending on the analysis techniques used and the project's objectives, a specified minimum interval between points may require that some data be censored, reducing the number of locations available for analysis.

Current and Future Applications

The strengths of Argos telemetry revolve mainly around its automated data collection and the number of locations generated. These features make it possible to simultaneously monitor many individuals and helps ensure that data are collected evenly across seasons, days, and hours without high operating costs or exposure of employees to potentially dangerous situations. Furthermore, unlike GPS or VHF telemetry, where an animal may move far enough to make relocation or recapture unlikely or problematic, animals fitted with Argos collars should always provide data if the transmitter continues to function.

Locations from Argos telemetry are inherently less accurate than GPS and VHF locations, and analyses at spatial scales finer than 500 m are probably not appropriate. Furthermore, because data collection is automated, there are no opportunities to improve location accuracy through additional effort, as there is with VHF telemetry. Physically walking in on an active collar is also impractical with Argos telemetry because the study animal could leave the area during the 45 seconds between signals. However, recovering stationary collars, either mortalities or slipped PTTs, is fairly straightforward with new receivers designed for this task, particularly when the collar has been stationary for several days.

To date only 1 field study has used Argos telemetry extensively on a *Martes* species (J. Sauder, unpublished data). Researchers deployed 35 Argos collars on male and female fishers in northern Idaho to evaluate resource selection by fishers within both landscapes and home ranges. Two other projects, 1 in Washington (USA; J. Lewis, Washington Department of Fish and Wildlife, personal communication), and 1 in California (A. Facka, North Carolina State University, personal communication), are testing the application of Argos telemetry in fisher reintroduction projects. The application of Argos telemetry to *Martes* species is currently limited to fishers because of the current minimum weight and bulk of Argos radio-collars. The use of Argos telemetry on smaller *Martes* species will require the additional miniaturization of battery technology.

In early 2011, CLS America implemented a major change in the way locations are calculated. Argos telemetry locations are no longer calculated using a least-squares technique; instead, a Kalman filtering process is being used (CLS America 2011). Depending on the habits of the species being studied, as well as transmitter configuration and duty cycle, location quality and quantity are expected to improve dramatically. Reprocessing of a fisher telemetry dataset by CLS America resulted in a 20% increase in location-class 3 and 2 points (J. Sauder unpublished data) as a result of implementation of the Kalman filtering process. This is expected to dramatically improve performance of Argos transmitters, with up to 40% more locations and 65% improved accuracy, depending on the configuration and duty cycle of the radio-collars.

Alternative Attachment Techniques

Since telemetry was first used in 1972, collars have been the overwhelming choice of attachment method by *Martes* researchers. Of the 131 telemetry-based research projects we identified, 120 (92%) used collars exclusively, and another 9 used a combination of collars and transmitters implanted into the peritoneal cavity. Only 2 studies relied exclusively on implanted transmitters (Davis 2008; Weir 2009). Two studies tested the use of harness transmitters on American mink (*Neovison vison*; Eagle et al. 1984) and black-footed

ferrets (*Mustela nigripes*; Biggins et al. 2006); in both projects, the researchers concluded that animals easily removed the harness unless it was attached so tightly that it caused severe neck irritation. One researcher experimented with gluing transmitters between the shoulder blades of 2 stone martens, but the transmitters were shed within 24 h (Herr 2008).

Risks to Study Animals from Telemetry-based Research

Before telemetry-based projects are implemented, researchers should weigh the potential risks associated with capture, handling, and radio-tagging of animals against the benefits of the data to be collected and the status of the population of interest (Kenward 2001; Casper 2009). The attachment of radio transmitters to any wildlife species can potentially lead to injury or mortality during the trapping and handling process or after release (Casper 2009). However, appropriate training in animal handling, a thorough investigation of previous related studies, and some forethought about how transmitters might interact with the morphology and behavior of individual species can, in most cases, minimize adverse effects on study animals (Millspaugh and Marzluff 2001). Limitations on collar weight as a percentage of body weight (3–5%) are commonly adhered to for most mammals (Kenward 2001; Gannon et al. 2007), but the potential effects of the shape and flexibility (especially ability to stretch) of radio-collars relative to the focal species' body shape and habits has received relatively little attention for medium-sized mammals. Because of their long and slender bodies, affinity for tight spaces (e.g., tree cavities, subnivean passages, rock crevices, roof spaces), and tendency to move through vegetation that could snag collars, *Martes* species are likely to be more susceptible than others to collar-related injuries. In this section, we discuss the potential negative effects of transmitters on *Martes* and related species, options to minimize injuries, and results of alternative transmitter attachments to date.

There are 3 primary ways that radio-collars can negatively influence animal safety and research objectives: (1) collars can get caught on external objects, (2) collar fit may change over time, and (3) collar attachment can alter behavior and result in biased data. Although options exist for dealing with these concerns, each involves a trade-off of some kind; thus, the most appropriate choices for each project will vary depending on the species of interest, research goals, study area, time frame, and budget. When initially planning a telemetry-based study on *Martes* species, researchers should consider these 3 points, determine whether concerns about transmitter attachment differ among sex or age groups, talk to other biologists about their experiences, and then decide which techniques are most appropriate for their situation. Finally, if injuries or mortalities occur in association with transmitter attachments,

researchers should take the time to review the details of the incident, attempt to improve their methodology, and share the outcome with the larger scientific community to help prevent similar problems for other researchers.

The first concern with attaching radio-collars to *Martes* species is that they can potentially get caught on objects (e.g., sticks, splinters, wire fencing) or wedged in confined spaces (e.g., rock crevices, tree cavities) in natural or human-altered environments. These situations could result in injury, asphyxiation, or vulnerability to predation for individual animals. One American marten in Oregon died after getting its collar caught on a splinter inside a hollow tree (Bull and Heater 2001). Evidence at the scene of 2 separate fisher mortalities in Canada suggested that individuals died as a result of collars getting hung up in branches associated with debris piles (R. Weir, Artemis Wildlife Consulting, personal communication).

A second potential problem with radio-collars is that they are not generally constructed to adjust to changes in neck size associated with age, weight gain or loss, or season. As a result, collars may cause discomfort, lesions, injuries to skin or muscle, and even death if the neck becomes constricted or infected. For most (if not all) *Martes* species, subadult males and juveniles of both sexes present the greatest challenges for balancing the trade-offs between fitting a collar loosely enough to allow for growth, but secure enough that it will not be easily shed or snagged. Neck injuries associated with tight-fitting collars have been documented for fishers on several projects (Weir 1999; Mazzoni 2002; C. Thompson and K. Purcell, unpublished data; M. Higley, Hoopa Tribal Forestry, personal communication). In the reported instances, collars of recaptured individuals were found embedded in the neck (Figure 13.4). The animals were treated and released without collars, and at least 3 had recovered fully by the time they were recaptured. To reduce the risk of neck abrasion, one researcher substituted flexible nylon webbing for the typically stiff collar material but found that the webbing became stiff and abrasive with the accumulation of oil and dirt, contributing to the death of 4 fishers (Heinemeyer 1993). Similar neck injuries associated with radio-collar attachment have been recorded for other carnivores, including the American mink (Zschille et al. 2008) and black bear (*Ursus americanus*; Koehler et al. 2001). Because recapture and the removal of radio-collars from all study animals on a project is often not feasible, the documentation of injuries associated with long-term collar wear is undoubtedly underrepresented.

Finally, transmitter attachments can present problems for study animals and researchers if the device alters behavior, limits habitat-related choices, or increases the risk of predation. For example, a radio-collar with a bulky shape may limit the size of cavity openings that females can use during the denning season, which is not the case with implanted transmitters (R. Weir, unpublished data). Often, these potential adverse effects are difficult to assess



Figure 13.4. Ingrown collar removed from a juvenile male fisher. Animal was treated, released, and later recaptured showing no signs of the injury (photo J. Garner).

or quantify for species that are infrequently seen in the field; however, consideration of the species' ecology and morphology can help inform the selection of collar shape, size, material, and color. For example, species that use circular cavities may be least impeded in their movements by small cylindrical canisters, and dark-colored collars are likely the best choice for animals with dark pelage. Two primary options exist for minimizing problems associated with attaching radio-collars to *Martes* species: collar alterations and intra-peritoneal implants.

Collar Alterations—Break-aways and Spacers

In this chapter, we refer to a *break-away* as a weak point on a radio-collar that is designed to break under pressure or deteriorate over an extended period of time, or both. A *spacer* represents an expandable portion of the radio-collar that provides some allowance for growth, weight gain, or increase in muscle mass around the neck. These options are not mutually exclusive and can be combined in a single collar. These types of alterations have been most commonly designed for use with large mammals, such as white-tailed deer (*Odocoileus virginianus*; Diefenbach et al. 2003), elk (*Cervus canadensis*; Smith et al. 1998), and black bears (Koehler et al. 2001), but the same general

ideas are appropriate for use with *Martes* species. To our knowledge, Paragi (1990) was the first to insert a small piece of leather into a collar to ensure that it would eventually drop off. Weir (1999) used cotton firehose spacers in fisher radio-collars with mixed results; the cotton material on 2 collars rotted away after only 4 months, but remained intact on another collar that had become embedded in the tissue of a male fisher's neck. On the Hoopa Reservation in northern California, a piece of soft leather was added to some collars to provide a degree of stretch and a long-term breaking point (S. Matthews, Wildlife Conservation Society, unpublished data).

Two ongoing research projects in California's southern Sierra Nevada have incorporated the objectives of break-aways and spacers into their VHF and GPS radio-collar designs for use on fishers (C. Thompson and K. Purcell, unpublished data; R. Sweitzer and R. Barrett, personal communication). After testing several designs, the Kings River Fisher Project researchers settled

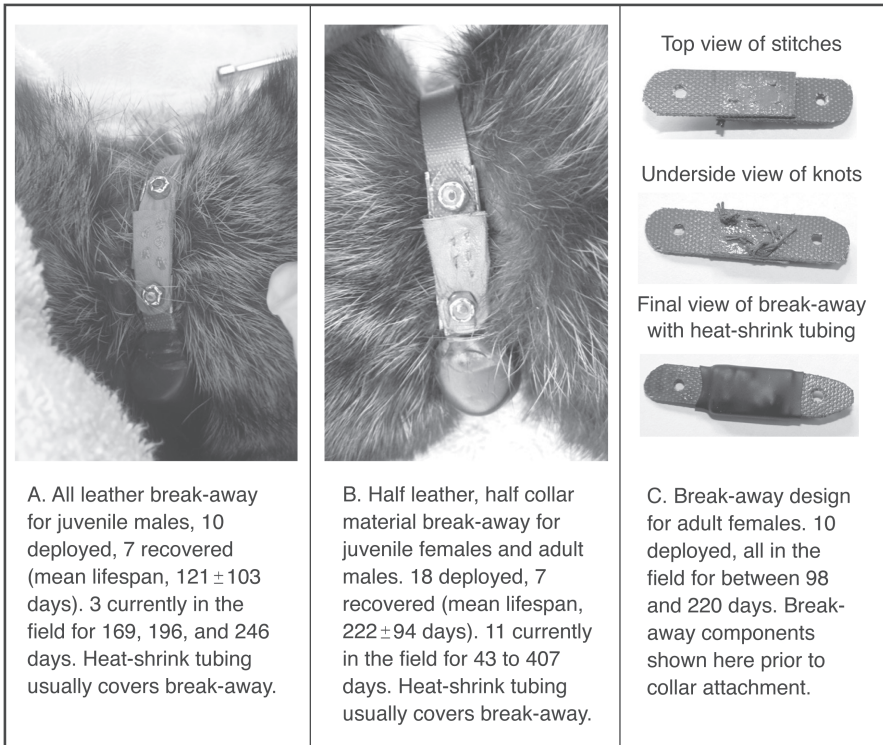


Figure 13.5. Examples of break-away devices being used on the U.S. Forest Service's Kings River Fisher Project (Thompson et al. 2010). Break-aways guarantee that the animal will be able to shed the collar eventually, if it is not recaptured, and provide a weak point for breaking loose if the collar gets entangled.

on 1 pattern and 3 combinations of materials to accommodate animals in different sex and age groups (Figure 13.5; R. Green, unpublished data). The basic design involves 2 short pieces of material stitched together by hand. The stitches are then coated with nail polish and covered with heat-shrink tubing. The break-aways are made in advance, bolted to VHF collars during handling, and can be replaced easily if an animal is recaptured. Materials used in making this break-away include soft leather, neoprene-impregnated polyester straps (used in radio-collars), cotton thread, cotton-polyester thread, nail polish, and heat-shrink tubing. The combination of materials used depends on the likelihood of the animal's neck increasing in size. Two pieces of soft leather allow for the greatest amount of stretch (best for juvenile males; Figure 13.5A), 1 piece of polyester strap combined with 1 piece of soft leather will permit some stretching (suitable for juvenile females, subadult males, and adult males; Figure 13.5B), and 2 pieces of polyester strap are unlikely to stretch (appropriate for adult females; Figure 13.5C). Although these break-away/spacer designs may not prevent all possible injuries associated with collars in *Martes* species, they are inexpensive and easy to make, can be adapted to different collar designs and materials, provide some room for growth, and decompose over time. Furthermore, although it is rarely possible to document the success of a break-away insert, there have been at least 2 instances where collars were recovered from sites where entanglement was possible (e.g., exposed root mass, narrow rock crevice) and the break-away was found split open, as anticipated.

Intraperitoneal Implant Transmitters

History

Implanted transmitters (implants) were first used on *Martes* species in the early 1980s, when Skirnisson and Feddersen (1984) implanted transmitters in 9 stone martens in Germany. The authors compared the function of the intraperitoneal implants with 5 radio-collars, and found that the implants worked without malfunction, whereas the collars all failed prior to the end of the manufacturer's predicted lifespan. They also reported that 1 implanted animal died after the sutures tore loose, but 1 implanted female successfully gave birth to and raised 3 kits while carrying the implant.

The next reported use of implants with *Martes* involved American martens reintroduced into the Yukon between 1984 and 1987 by the Yukon Department of Renewable Resources. Thirty-nine martens were monitored via radiotelemetry, 12 with collars and 27 with intraperitoneal implants. During the initial 30-day monitoring period, 17 (63%) of the implanted animals died from a variety of implant-related causes, whereas all collared animals survived (Slough 1989). During approximately the same period, Buskirk et al.

(1989) implanted 16 g temperature-sensitive transmitters in American martens in Wyoming to evaluate winter rest-site requirements, and reported no ill effects. In 1989 and 1990, 37 fishers were translocated into the Cabinet Mountains of Montana: 26 were radio-collared and 11 had intraperitoneal implants (Roy 1991; Heinemeyer 1993). Four of the collared animals, fitted with collars made of lightweight webbing (described above), developed severe neck lesions and died. Another 2 animals showed hair loss and irritation when the collars were removed, but no adverse effects of the implants were reported.

To our knowledge, implants were not used again on *Martes* species until 1998, when researchers in British Columbia (Canada) began implanting fishers (Weir and Corbould 2006) as a result of concerns about the safety and reliability of radio-collars. Since 1998, researchers in British Columbia have implanted 32 fishers on 41 occasions with no negative consequences (R. Weir, personal communication). Recently, implanted transmitters have been used in fisher reintroduction efforts in Washington (J. Lewis, personal communication) and California (A. Facka, personal communication).

Function

Early generations of implant transmitters suffered from reduced signal strength. As stated by Biggins et al. (2006: 182), “Relatively poor reception range is a well-known attribute of implantable transmitters, in part because of the compromises necessary with transmitter antennas, which can translate into reduced precision and accuracy of data.” Green et al. (1985) compared the performance of implants and collars on coyotes (*Canis latrans*) and kit foxes (*Vulpes macrotis*) and found that collars had 5–10 times greater range and a 30% longer lifespan. Koehler et al. (2001) reported that implanted black bears were more difficult to locate than collared bears because of reduced signal strength, and recommended that implants be used on animals with smaller or more dependable home ranges. These problems appear to have been resolved in current generations of implantable transmitters, and researchers currently using implants in fishers report no difference in signal strength or range (R. Weir and J. Lewis, personal communications). Most researchers also report comparable lifespans between implants and collars (J. Copeland, USDA Forest Service (retired), personal communication; R. Weir personal communication; J. Persson, Swedish University of Agricultural Sciences, personal communication), though problems with malfunctioning mortality switches in implants have led to premature transmitter failures in some cases (J. Lewis, personal communication). Additional research on brown bears (*Ursus arctos*) in Sweden has suggested that the failure of mortality switches in implant transmitters may be associated with the accumulation of moisture inside the transmitters, and subsequent corrosion

(J. Arnemo, Norwegian School of Veterinary Science, unpublished data; see below).

Potential Risks

Transmitters can be implanted either subcutaneously or into the peritoneal cavity. Many studies have found that intraperitoneal implants are preferable for mammals, because subcutaneous implants often cause abscesses, and the rate of transmitter loss or damage is high (Agren et al. 2000; Echols et al. 2004; Biggins et al. 2006).

The greatest risk associated with implanted transmitters involves the surgical procedures and the 24–48 h recovery time while the incision begins to heal. Implant surgeries often take place in uncontrolled environments where the risk of infection is high, and procuring an experienced veterinarian willing to work under field conditions can be challenging (J. Copeland, personal communication). Eagle et al. (1984) implanted 32 American minks with intraperitoneal transmitters, and attributed 3 mortalities within 2 months to infection and inexperienced personnel. Copeland (1996) reported a single implanted wolverine (*Gulo gulo*) dying after chewing out the sutures. Likewise, Zschille et al. (2008) implanted 14 American minks and reported 1 male dying after chewing out the sutures; subsequently they recommended that implanted animals be held for 72 h after surgery to ensure a full recovery.

Once an animal has recovered from surgery and the incision has healed, the risk of mortality from the implant appears to be low. We found no reports of *Martes* species dying from implant-related causes, once the sutures had healed. Van Vuren (1989) performed 300 implant surgeries on 183 yellow-bellied marmots (*Marmota flaviventris*) and reported only 2 mortalities in which the animals expired in burrows and the cause of death was unknown. Gynn et al. (1987) reported that 1 of 18 implanted American beavers (*Castor canadensis*) died after the intraperitoneal implant lodged in the intestinal tract, and Herbst (1991) reported that 1 of 18 implanted nine-banded armadillos (*Dasypus novemcinctus*) died from a similar blockage. Recently, extensive use of intraperitoneal transmitters on sea otters (*Enhydra lutris*) and Vancouver Island marmots (*Marmota vancouverensis*) has resulted in no consistent complications (Ralls et al. 2006; M. McAdie, British Columbia Ministry of Environment, personal communication).

Evidence accumulated to date suggests that intraperitoneal transmitters have no effect on reproduction. Although this is nearly impossible to prove because of their low and variable reproductive rates, numerous accounts have been published of implanted females of various *Martes* species giving birth and successfully raising kits. Weir and Corbould (2008) found similar reproductive rates between implanted and collared female fishers; 5 of 8 implanted and 7 of 10 collared females successfully reproduced. More exten-

sive evaluations of the impacts of implant transmitters on reproduction have been done on other species, with most reporting no noticeable effect. Herbst (1991) found that female nine-banded armadillos carrying intraperitoneal implants reproduced successfully, and Van Vuren (1989) reported that both growth rates and reproductive rates were similar between implanted and non-implanted yellow-bellied marmots. Reid et al. (1986) evaluated the ability of river otters (*Lontra canadensis*) to reproduce while carrying implanted transmitters and found that all stages of the reproductive cycle were successful. The authors' only caution was that surgery on adult females during pregnancy or lactation should be avoided, because many drugs used for anesthesia cross the placental barrier and may induce anesthetic effects or affect development in fetuses. This concern is complicated by delayed implantation, although the use of anesthesia while collaring female *Martes* study animals is not known to impact the development of offspring in the subsequent year.

Long-Term Implications

Very few data are available on the long-term implications of implanted transmitters for study animals. Implants are coated in inert materials and hermetically sealed, so it is generally assumed that they pose no long-term health risks for study animals, beyond the limited risks described above. However, because of the difficulties associated with locating and retrapping study animals after a project is completed, very few researchers have removed intraperitoneal transmitters, inspected them for wear or damage, or assessed long-term side effects on study animals that carry them throughout their lifespans.

To our knowledge only 1 research project has attempted to evaluate these long-term implications. Between 2004 and 2010, the Scandinavian Brown Bear Research Project (<http://www.bearproject.info/>) surgically removed 64 intraperitoneal implant transmitters (Telonics IMP/400/L) carried by brown bears for 3–9 years (Arnemo et al. 2007; J. Arnemo, unpublished data). In 30 cases (47%), the transmitter was encapsulated by connective tissue in the omentum, and histopathology showed a typical reaction to a foreign body. A detailed inspection was conducted on 49 of the implants. Thirteen of the transmitters (27%) showed visible damage, such as discoloration, wear, or melting of the exterior wax coating. One implant (2%) had cracks in the Plexiglas cylinder holding the transmitter components, and the end cap on the Plexiglas cylinder was loose or open in 6 implants (13%). Humidity levels inside the supposedly waterproof implants ranged from 5 to 20%, and condensed moisture was visible inside the cylinder in all cases. In 30 of the implants (63%), moisture had resulted in battery corrosion and 3 implants (6%) had subsequently short-circuited. Of greatest concern was the fact that 2 of the 3 short-circuits resulted in battery corrosion and breaking of the end

cap of the Plexiglas cylinder. In one case, a 5-year-old implant suffered internal corrosion, short-circuit, and breakage of the end cap, which caused significant leakage from the battery into the abdominal cavity. The implant was encapsulated by a thick wall of connective tissue and removed. Upon release, the female bear survived and had 3 cubs the following year before being legally shot by a hunter. In 2010, 10 years after implantation, another adult female brown bear was found dead. Necropsy showed that the batteries had short-circuited, the end cap of the Plexiglas cylinder had broken off, and a metal wire (the antenna) had perforated the stomach. The cause of death was peritonitis with subsequent sepsis (J. Arnemo, unpublished data).

These researchers concluded that the implant transmitters were not waterproof, were not physiologically inert, and had a high rate of technical failure attributed to the gradual accumulation of moisture inside the transmitter (Arnemo et al. 2007). Although they acknowledged that implant transmitters were a viable method for minimizing the adverse effects of radio-collars on study animals, they recommended that all implants be surgically removed during the operational life of the batteries. These concerns have yet to be addressed directly in relatively short-lived animals, such as *Martes* species, although transmitters replaced after 3 years in Olympic marmots (*Marmota olympus*) in Washington and British Columbia, and 2 years in wolverines in Sweden did not show similar levels of deterioration (M. McAdie and J. Persson, personal communication).

Conclusions

Researchers tend to have strong opinions about the viability of implanted transmitters as a research technique, based on their personal experiences. It is undeniable, however, that radio-collars add some unknown degree of risk to the safety of study animals and may influence their behavior in unknown ways. Available evidence indicates that implanted transmitters provide a viable alternative to radio-collars and, in some situations, may pose less overall risk to the study animal, if they are used responsibly. For example, in translocation efforts where animals are already being held and can be monitored after surgery, implanted transmitters may be preferable to collars. Additional guidance on implant procedures is available from studies on other species. After extensive use of implanted transmitters on Vancouver Island marmots, researchers at the British Columbia Ministry of Environment recommended that personnel implanting transmitters should (1) use liquid disinfectants instead of gas sterilization, which can damage the wax coating and result in adhesions, (2) flush transmitters well with sterile saline solution after removing them from the disinfectant, (3) avoid temperature extremes, which can damage the wax and lead to adhesions, (4) visually inspect all wax-coated transmitter packages for any surface defects or cracks prior to implantation,

and (5) handle transmitters gently with sterile gloved hands to prevent contaminating the transmitter—the use of forceps or other instruments creates small inconsistencies in the wax coating, which can lead to focal adhesions (M. McAdie, personal communication).

More information is needed on the long-term risks and potential deterioration of implanted transmitters within the body cavity. In the interim, we recommend that at the end of each study, researchers should recapture study animals and remove implanted transmitters, despite the additional cost, time, and effort this requires.

Summary

Radiotelemetry has provided essential information on the ecology of *Martes* species, and has been used extensively to study many aspects of American marten and fisher ecology. Questions addressed include demographic rates, habitat use, responses to disturbance, diet, activity patterns, movements, and spatial organization. Despite the significant contributions of individual projects (e.g., Brainerd et al. 1995; Genovesi and Boitani 1995, 1997a,b; Zalewski 1997a,b, 2000; Herr 2008), little telemetry-based data on either the European pine marten or the stone marten are available. Much of the work that has been done on these species remains unpublished, although some information is available in non-English articles and reports (e.g., Skirnisson 1986; Clevenger 1993a; Seiler et al. 1994; Simon and Lang 2007). Recent and ongoing research will help fill this void, once it becomes widely available (e.g., E. Manzo, Ethoikos, Convento dell'Osservanza, Siena, Italy; M. Mergey, Centre de Recherche et de Formation en Eco-Ethologie, Boulton-aux-Bois, France; and D. O'Mahoney, Ecological Management Group, Belfast, Ireland, unpublished data); however, many questions that are best addressed using radiotelemetry, such as density or causes of mortality, remain unanswered. Telemetry-based research on the yellow-throated marten, Japanese marten, and sable remains sparse, with only 1, 2, and 4 projects conducted, respectively; none have been conducted on the Nilgiri marten.

We have seen remarkable advances in technology since telemetry was first used on *Martes* species. As technological advances such as the miniaturization of ARGOS and GPS collars open exciting new opportunities for data collection and mesocarnivore research, it is important to clearly identify research objectives and carefully select the most appropriate tools for the questions being addressed. Although the number of accurate locations generated by a properly functioning miniature GPS collar is impressive when compared with the effort required to obtain a similar sample using ground-based telemetry, this new technology and its relatively high failure rates make it a risky choice for short-term or underfunded projects. Similarly,

ARGOS transmitters are currently appropriate only for the largest *Martes* species, the fisher.

The use, efficiency, cost, and accuracy of different monitoring techniques and technologies are summarized in Table 13.2. Ground-based telemetry, the most common technique used in research on *Martes* species, typically provides >100 locations per study animal during the course of a typical research project, but the overall cost will vary considerably, depending on terrain. In comparison, projects that used aerial telemetry monitored more animals, but collected fewer locations per animal, as a result of the reduced frequency of monitoring (e.g., weekly flights vs. daily ground-tracking). Satellite-based monitoring techniques have not been widely used, but they appear to provide higher data-collection rates and potentially reduced costs; however, there are potential trade-offs in reliability, weight, longevity, and the accuracy of locations obtained.

Selecting the appropriate technology and monitoring technique requires careful consideration of research objectives and available resources, as well as the morphology, behavior, and ecology of the focal species. When radiotelemetry is the most appropriate choice and animals must be handled, researchers should maximize available opportunities by collecting data on age, sex, reproduction, physiological state, and other covariates that may influence resulting data. Furthermore, if break-away collars are not used, researchers should consider recapturing animals to remove collars or implants while the transmitters are still functioning, even though it can be challenging, time-consuming, and expensive.

Despite its limitations and associated concerns about the invasive nature of radiotelemetry research, during the past 4 decades we have seen remarkable growth in the application of this technology to ecological research questions. Handmade beacons of the past have developed into miniature processors capable of collecting physiological, meteorological, or proximity data, and the research questions that can be addressed have evolved accordingly. The next few decades promise to be an exciting period for mesocarnivore researchers, as technological advances result in the development of ever smaller and lighter transmitter packages.

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