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RELATIONSHIP BETWEEN HOME RANGE CHARACTERISTICS AND THE PROBABILITY OF OBTAINING SUCCESSFUL GLOBAL POSITIONING SYSTEM (GPS) COLLAR POSITIONS FOR ELK IN NEW MEXICO

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ABSTRACT.—We compared the ability of global positioning system (GPS) radio collars deployed on elk (*Cervus elaphus nelsoni*) to obtain valid positions (position acquisition rate [PAR]) in seasonal home ranges with differing vegetation and topographical characteristics. We also compared GPS collar PARs under varying levels of cloud cover and within differing daily time periods. We recorded a mean PAR of 69% (n = 10 elk, s = 14%) for collared elk. Multiple regression analysis of seasonal home range characteristics indicated that vegetation cover type and slope, either as individual variables or in combination with one another, were not significant predictors of GPS collar PARs. We did not observe statistical differences in position acquisition rates between cloud cover classes or varying cloud base heights. PAR was significantly higher between 1600 h and 2000 h (mountain standard time) compared to 0000 h–1200 h, which may have been due to elk behavior. We believe using GPS collars is a more effective and efficient method of tracking elk in our study area than using very-high-frequency (VHF) collars since GPS collars can be programmed to obtain fixes automatically, have fewer logistical problems, and are more economical with long-term data collection efforts.

Key words: radio collar, global positioning system, position acquisition rate, elk.

Radio telemetry has provided increased opportunities to examine activity patterns, habitat use, and behavior of wildlife species (Samuel and Fuller 1994). At present there are 3 methods of telemetry used for tracking large mammals: (1) mobile very-high-frequency (VHF) radio-telemetry systems, which consist of a receiver that picks up transmissions from a radio-collared animal via triangulation from the ground or that is located by aircraft (Samuel and Fuller 1994); (2) VHF receivers attached to permanent tracking stations in a defined study area (Deat et al. 1980, Loft and Kie 1988, Hansen et al. 1992); and (3) satellite telemetry.

Satellite systems were developed in the 1980s and also use radio collars implanted with transmitters (platform transmitter terminals, PTT), but the signal is picked up via satellites orbiting the earth and data are relayed to a servicing center. This system requires that the elevation of the PTT be estimated before its location is calculated and, as a result, large errors in the estimated location can occur if the specified elevation is incorrect (Keating 1995). Error can also be introduced into these systems by frequency stability of the transmitters, temperature, topography, and animal movement (White and Garrott 1990). Due to these influences, mean errors of locations can range from 0.5 to 1.5 km and may exceed 8 km. These systems are best suited for tracking large-scale movements of highly mobile animals rather than detailed habitat or resource utilization (Rodgers et al. 1996, Kennedy et al. 1998).

A recent development in satellite tracking is attaching geographic positioning system (GPS) units to radio collars. Whereas PTTs transmit signals to receivers on satellites to calculate a position, GPS systems receive signals transmitted from 3 or more satellites to calculate a position. The system utilizes onboard microelectronics that calculate GPS locations from a set of 24 orbiting satellites (Wells et al. 1987). In addition, GPS telemetry, depending on the manufacturer and model, offers 3 basic methods of data retrieval: (1) collar stores all location data until the collar is retrieved and data are downloaded; (2) collar stores and transmits location data to a storage satellite for data retrieval by a data management center (discussed in this paper); or (3) collar stores data and provides a local point-to-

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point communication link for retrieval (Rodgers and Anson 1994, Rodgers et al. 1996).

Availability of satellites and environmental factors can influence both the accuracy and ability of GPS systems to acquire a location. Until May 2000 the most important signal error was related to selective availability (SA). SA was the intentional degradation of the satellite signal by a time-varying bias that was controlled by the Department of Defense to limit the accuracy of GPS to non-U.S. military and government users (Trimble Navigation 1996). The effect of SA was minimized through the use of differential correction (correct the bias at one location with measured bias errors at a known position). However, on 1 May 2000, President Clinton ordred the U.S. military to cease the intentional degradation of satellite signals. This order will enable the GPS user to obtain more accurate non-differentionally corrected positions. Accuracy can also be affected by the number of satellites available to calculate the location. A GPS receiver must simultaneously receive signals from at least 3 satellites to calculate a location. The number of satellites used in calculating the position determines whether a 2-dimensional (3 satellites) or 3-dimensional (4 satellites) position is obtained. Altitude is fixed in 2-dimensional locations and based on the previous 3-dimensional location. Therefore, 2-dimensional locations can have an increase in horizontal error compared to 3-dimensional (Moen et al. 1997). If 4 simultaneous signals are received, a 3-dimensional location can be calculated and horizontal error is decreased.

Environmental factors that could affect the position accuracy and position acquisition rate (PAR; percentage of locations that a GPS collar successfully acquires from roving satellites based on total number of attempts) are primarily related to topography and plant cover (Rodgers et al. 1995) but may also include weather as it relates to animal behavior (i.e., animals seeking shelter during heavy precipitation events). Because the use of GPS collars is such a newly evolving technique, few studies have investigated its usefulness and effectiveness in tracking animals under various environmental conditions (Rempel et al. 1995, Moen et al. 1996, Rodgers et al. 1996, Edenius 1997).

The objective of this study was to evaluate position acquisition rates of GPS collars deployed on elk inhabiting montane ecosystems in north central New Mexico under different levels of cloud cover, in differing vegetation cover and terrain types within animal home ranges, and within various daily and seasonal periods.

STUDY AREA

The study area is located within and around Los Alamos National Laboratory (LANL). LANL is located in north central New Mexico on the Pajarito Plateau and the east Jemez Mountains, approximately 120 km north of Albuquerque and 40 km west of Santa Fe. Stretching 33–40 km in a north–south direction and 8–16 km from east to west, the plateau ranges in elevation from about 1680 m to 2250 m and slopes gradually eastward from the edge of the east Jemez Mountains. Elevations reach approximately 3050 m within 1.6 km of the LANL boundary. Intermittent streams flowing southeastward have dissected the plateau into a number of fingerlike, narrow mesas separated by deep, narrow canyons ranging in depth from 15 m to 330 m.

A variety of vegetation communities cover the study area as dictated by the wide range of elevational zones. The Rio Grande floodplain borders the east edge of LANL and contains the lowest elevations in the area. It is characterized by a Plains and Great Basin Riparian-Deciduous Forest (Brown 1982) with cottonwood (*Populus* spp.) and willow (*Salix* spp.). Piñon pine (*Pinus edulis*) and juniper (*Juniperus monosperma*) are common at higher elevations (1860–2070 m) and occur on much of the mesa tops. Ponderosa pine (*Pinus ponderosa*) is common on the higher mesa tops and along many of the north-facing canyon slopes, and species of fir (*Pseudotsuga menziesii* and *Abies* spp.) can be found along the higher north-facing slopes intermixing with ponderosa pine. Species of the Rocky Mountain Subalpine Conifer Forest and Woodland occur along the extreme western edge of LANL and are more prevalent at the higher elevations of the nearby Jemez Mountains.

Most canyon stream channels in and adjacent to LANL are ephemeral and therefore not considered wetlands. However, permanent flows from springs and laboratory facility outfalls result in a small number of permanent or near-permanent streams within short stretches of certain canyons. The area that is now LANL has not been exposed to livestock grazing or hunting since the mid-1940s.

METHODS

We collared 6 elk (5 cows and 1 bull) during March and April 1996 using clover traps. We retrieved collars from all 6 animals within 6 to 18 months following collar deployment. Four collars were refurbished by the manufacturer and deployed on different animals (3 cows and 1 bull) in either 1997 or 1998, resulting in a total of 10 collared animals from which data were collected. No animals died or were injured during capture. Estimated age of cow elk ranged from 1 to 7 years. The 6 animals collared in 1996 were captured either in shallow canyons dominated by piñon pine–juniper or on a mesa top dominated by ponderosa pine. Animals collared in 1997 and 1998 were captured either on mesa tops dominated by ponderosa pine or on a mesa top dominated by piñon pine and juniper.

Collar Programming

We collared each animal with a Telonics, Inc. (Mesa, AZ; use of company name does not imply endorsement by the U.S. Department of Energy) model ST14GPS receiver equipped with a VHF beacon transmitter with an estimated battery life of 12 to 14 months. To maximize battery life while still obtaining sufficient hourly data throughout a 24-hour period, we programmed each collar to attempt to acquire a GPS position every 23 hours. A 23-hour interval allowed the collar to attempt to make a GPS fix each day 1 hour earlier than the previous day. All data (usually 3 to 5 positions) were uplinked from the collar to a data-storage satellite every 3 to 4 days and subsequently retrieved by a servicing center (e.g., Argos Inc.; use of company name does not imply endorsement by the DOE). Raw data (stored in a compressed format using an absolute fix followed by historical fixes relative to the absolute fix) were sent to us from Argos via e-mail, after which they were stored on a PC computer for processing, which was required to convert the data into longitude, latitude, Julian Day, and Greenwich Mean Time (GMT). Longitude and latitude were converted into UTMs using the projection command of ARC/INFO (ESRI 1991). GMT was represented in hours and minutes. Because of data storage limitations of the collar, the following information was not stored on the collar: type of GPS fix (either 2-dimensional or 3-dimensional), specific satellites used in the calculation of the position, and current satellite geometry as indicated by the position dilution of precision (Trimble Navigation 1996). Therefore, differential correction of GPS collar data and determination of 2-dimensional versus 3-dimensional positions were not conducted during this study. While SA was enabled, accuracy of nondifferentially corrected GPS collar location data could vary from <1 m to as much as approximately 100 m, while differentially corrected data can provide consistently accurate estimates of true locations to within several meters (Rodgers et al. 1996). Because SA was enabled during our study, locational error was calculated using an ST14GPS collar placed in different habitats and terrain throughout LANL property (Bennett et al. 1997). The mean locational error was 108 m, and no significant differences were found in the mean error between mesa tops and canyons. There were no significant differences ($\alpha = 0.05$) in locational error for the test collar with respect to vegetation cover type and topography; therefore, we assume a similar error rate for collars deployed on elk. Bennett et al. (1997) reported that 95% of the time a position was obtained from the GPS collar, it was within 122 m of the actual location. This was higher than the 100 m expected by U.S. military design specifications for units operating in 3-dimensional mode, suggesting an influence of 2-dimensional locations.

Position acquisition rates were calculated by dividing total number of successful fixes acquired by each collar by total number of fixes attempted by the collar. Number of fixes attempted was based on the preprogrammed interval rate of 23 hours during the life of the collar while deployed on the animal. Length of the data collection period was determined by collar battery life or death of the animal as a result of vehicle collision or hunter harvest.

Vegetation/Topography Analysis

Because we could collect habitat data only at locations of successfully acquired GPS locations and because we did not know locations of animals when fixes were not obtained, we used a combination of seasonal home range polygons and GIS vegetation and topographical coverages to compare PARs in each collared animal's seasonal home range to vegetation and slope characteristics of each home range. Seasons were defined as follows: spring (March–April), calving (May–June), summer (July–August), fall (September–October), and winter (November–February). These periods are most representative of the differing seasonal movement and resource-use patterns observed in our study area (White 1981, Allen 1996, Long et al. 1997, Biggs et al. 1999) and coincide with other on-going studies of elk on LANL property. Most individuals migrating onto LANL property do so in late fall (i.e., November), and calving in our study area generally takes place during May and June. During these periods home range polygons can be highly variable and encompass a greater area compared to other seasonal periods. Additional information used in defining these periods was taken from previous elk studies on movement patterns and habitat use in other mountainous regions of New Mexico and western states where terrain and plant species composition are relatively similar to our study area (Findley et al. 1975, Hoffmeister 1986, McCorqoudale et al. 1986). We used the adaptive kernel method of program CALHOME (Kie et al. 1994) to estimate each collared animal's home range using 95% of all animal locations (95% utilization distribution). Based on a visual inspection of each animal's home range, the polygon boundaries did not appear to be dictated by cover type or terrain; therefore, we assume that at least 95% of the unknown locations where fixes were not obtained fell within the home range polygon. Optimum grid cell size and bandwidth (a smoothing parameter) were automatically determined by the program. The program also produces a least-squares cross-validation (LSCV) score, which is a measure of how well the bandwidth fits the data; the lower the LSCV, the better the fit (Worton 1989, Kie et al. 1994). In a few cases grid cell size and bandwidth were manually altered to produce a lower LSCV (Kie et al. 1994), resulting in what is believed to be a better representation of the home range polygon. Once home range polygons were calculated by CALHOME, the output data set of X,Y UTM coordinates was imported to the GIS.

We conducted vegetation analyses using GIS and a land cover map developed at LANL (Koch et al. 1997). A 1992 Landsat thematic mapper image was classified into 30 classes using the Iterative Self-Organizing Data Analysis Technique (ERDAS 1994). These 30 classes were aggregated into 10 land cover types through field surveys, aerial photo interpretation, and incorporation of topographic information. Resulting cover types also included developed and other nonvegetative coverages, as well as cover types not occurring within the study area. Therefore, only 4 cover types were used in our analysis: ponderosa pine forest, open cover (grass/shrubland), mixed-conifer/spruce-fir forest, and piñon-juniper/juniper woodland. In addition to these cover types, small isolated patches of aspen (*Populus tremuloides*) occur within the study area, but because these represent a very small amount of total cover (<1.0%), this cover type was omitted from further analysis. Each seasonal home range polygon was intersected with the vegetation cover type polygons. The total amount of each cover type was then calculated for each home range.

The same method for calculating PARs by cover type was used for calculating PARs by slope type. The percentage of each home range that consisted of each of 8 slope categories (0–5°, 5–10°, 10–15°, 15–20°, 20–25°, 25–30°, 30–40°, and >40°) was calculated. We used a multiple linear regression to test the interaction of slope and habitat characteristics of each seasonal home range with the PAR in that home range.

Cloud Cover

Data on hourly cloud cover during 1996–97 for Los Alamos County were obtained from the National Climate Data Center, Asheville, North Carolina. Cloud cover data were reported primarily on the hour and were matched by date and time to GPS collar fix attempts (programmed to collect on the hour). However, in some cases no cloud cover data were available during the time a GPS collar fix was attempted. In these cases the closest cloud cover data available to within 1 hour of the GPS collar fix attempt were used. Data from elk collared only in 1996 were used in this analysis. To minimize the potential influence of steeper terrain and heavier vegetation canopy cover associated with some portions of the study area, we restricted the analysis to animals with home ranges that occurred primarily on LANL property and overlapped the location at which cloud cover data were collected. Position acquisition rates were analyzed by cloud ceiling (height of base of cloud cover at <1000 m, 1000–2000 m, and >2000 m) and sky cover (clear; scattered = 1/8–1/2 cloud cover; broken = 5/8–7/8 cloud cover; overcast; obscured = foggy conditions). Because PARs are proportions, they can be described by binomial distribution (Freund and Walpole 1987). Therefore, to determine whether PARs were significantly different between cloud cover classes, we constructed 95% confidence intervals (CI) around each cloud cover class PAR to see if CIs overlapped. If they did not overlap, they were considered significantly different (Freund and Walpole 1987).

Hourly Period

Position acquisition rates were analyzed by day based on 6 hourly blocks within a 24-hour period: 0000–0400, 0400–0800, 0800–1200, 1200–1600, 1600–2000, and 2000–2400 h. Analysis was conducted on data from all 10 animals combined. To determine if PARs were significantly different between hourly periods, we constructed 95% CIs around each hourly period PAR to see if CIs overlapped.

RESULTS

Of 10 collared elk, 5 were harvested and 3 died as a result of vehicle collisions. The GPS collar operational life (calculated for animals that survived beyond the operational life of the GPS collar) averaged 15 months (n = 5, range = 11.6 –17.7 months). Over 1900 fixes were obtained between March 1996 and June 1998 for all 10 elk combined. Approximately 69% (s = 14%) of GPS location attempts were successful and ranged from 54% to 96% for individual animals. Mean yearly PAR ranged from 59% in 1996 to 81% in 1998, was highest in spring (77%) and winter (74%), and was lowest in fall (45%; Table 1).

Vegetation Cover Type

GPS position acquisition rates were highest during spring and winter, at which times the relatively open cover types (grass/shrubland, piñon-juniper/juniper woodland) were more prevalent in home ranges than were taller forested cover types (ponderosa pine, mixed conifer; Table 2). Open cover types also made up a relatively large amount of the overall vegetative cover within fall home ranges (47%) when PARs were at their lowest (45%). However, composition of taller forested cover types was relatively similar (45%) to open cover types during that period. Ponderosa pine and mixed conifer constituted >50% of cover during calving and summer, during which time PARs were also low. Although lower PARs were observed in seasonal home ranges that had a greater composition of tall forest cover types, multiple regression analysis showed that cover type was not a significant predictor of GPS position acquisition rate ($R^2 = 0.19$, 37 df, $P = 0.09$).

Topography

Over 50% of all seasonal home ranges consisted of 0–5° and 5–10° slopes (Table 2). However, there was a greater composition of slopes above 5° in home ranges during calving, summer, and fall, at which times GPS collar PARs were lowest. Analysis using multiple regression showed that slope was not a significant predictor of PAR ($R^2 = 0.19$, 34 df, $P = 0.26$). Furthermore, addition of cover type to the model did not improve it ($R^2 = 0.25$, 30 df, $P = 0.48$).

Cloud Cover

We did not observe any statistically significant differences ($\alpha = 0.05$) in PARs between cloud cover classes nor did we observe any significant differences in PARs between varying cloud base heights. However, PAR was generally lower during overcast conditions and when cloud base heights were <1000 m.

Hourly Period

We observed a significant difference ($\alpha = 0.05$) between PARs of hourly time periods (Fig. 1). PAR was significantly higher during the period 1600–2000 h than during 0000–1200 h. PAR was generally higher from noon to midnight compared to the period from midnight to noon.

DISCUSSION

We compared position acquisition rates of GPS collars deployed on Rocky Mountain elk in north central New Mexico with respect to

TABLE 1. GPS position acquisition rates[a] (PARs) for radio-collared elk by season and year, Los Alamos National Laboratory, New Mexico, March 1996–June 1998.

Year	Season	Number of animals	Total number of locational fixes	PAR (%)
1996	Spring	5	137	64.3
	Calving	6	227	59.1
	Summer	6	191	50.0
	Fall	5	151	47.2
	Winter (1996–97)	4	371	72.8
	Mean PAR			58.7
1997	Spring	4	204	79.7
	Calving	4	148	57.8
	Summer	2	96	73.8
	Fall	1	21	32.8
	Winter (1997–98)	1	98	76.6
	Mean PAR			68.0
1998	Spring	4	186	84.9
	Calving	2	99	77.3
	Mean PAR			81.1

MEAN SEASONAL PAR (%)

Spring	Calving	Summer	Fall	Winter
76.6	61.7	55.2	44.8	73.5

[a]PAR is defined as the percentage of locations that a GPS collar successfully acquires from roving satellites based on total number of attempts.

TABLE 2. Vegetative cover and slope composition of elk seasonal home ranges, Los Alamos National Laboratory, New Mexico, 1996–1998.

	Season				
	Spring (n = 13)	Calving (n = 12)	Summer (n = 8)	Fall (n = 6)	Winter (n = 5)
COVER TYPE[a]					
Open cover	11.6	15.9	12.3	11.9	9.1
Piñon-juniper/ juniper woodland	40.5	24.6	23.9	35.6	57.6
Ponderosa pine	35.6	30.6	25.6	23.7	18.7
Mixed conifer	4.3	22.3	31.0	21.7	6.0
SLOPE CLASS					
0–5°	40.4	25.7	26.1	26.9	35.7
5–10°	31.3	26.5	24.7	24.5	27.0
10–15°	13.5	15.9	16.8	17.5	16.6
15–20°	8.6	13.5	14.4	14.9	11.1
20–25°	3.9	10.1	10.4	9.7	5.9
25–30°	1.6	5.3	5.1	4.6	2.4
30–40°	0.9	2.9	2.7	1.9	1.3

[a]Certain cover types were omitted from analysis; therefore, the sum of cover types for home ranges does not equal 100%.

cloud cover and seasonal home range habitat characteristics. We also compared PARs between seasonal and hourly periods.

We elected to compare position acquisition rates of GPS collars in elk seasonal home ranges to assess the relationship between home range habitat characteristics and the general effectiveness of using GPS radio collars in our study area. An alternative method of assessing the effectiveness of GPS collars in varying terrain and cover types would be to compare PARs within specific vegetation cover types and slope categories based only on successfully acquired GPS positions. We chose not to apply this method since we did not know where the animal was during an unsuccessful attempt, thus preventing us from comparing habitat characteristics of successfully acquired GPS positions with unsuccessful attempts. If we were to assess PARs of specific cover and slope

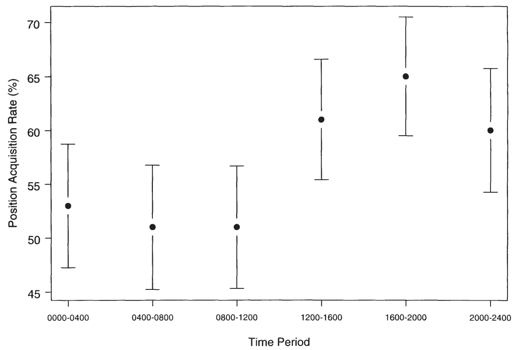

Fig. 1. Position acquisition rates by hourly time period. Significant differences between hourly time periods were determined by calculating 95% confidence intervals; nonoverlapping confidence intervals indicated a significant difference.

types based only on successfully acquired GPS positions without accounting for missing GPS positions, we could over- or underestimate specific habitat (slope, cover) PARs. Furthermore, potential error associated with each point (108 m) could result in inaccurate interpretation since the location could occur within any 1 of 4 GIS coverage pixels (a pixel is 30 × 30 m), each of which could contain different cover and slope types. Unless we have a very high PAR within a relatively homogenous habitat type with respect to vegetation and terrain, we will be unable to accurately identify PARs for a specific cover or slope type. One way to correct for this would be to program a collar to attempt to acquire a fix in very short time intervals (i.e., ≤10 minutes), thereby allowing the researcher to fill in the voids of missing data based on successfully acquired positions. In this study we programmed collars to acquire a fix every 23 hours. As a result, animals could move large distances between position fix attempts through multiple habitat and slope types, making it virtually impossible to identify what type of terrain and cover type the animal was in when a fix was not successfully acquired.

We calculated PARs for individual animals ranging from 54% to 96%, similar to what has been found in other studies of GPS collars (Rodgers et al. 1995, Moen et al. 1996, Rodgers et al. 1996, Edenius 1997). PARs of about 86% in the study area have been reported using a test collar (Bennett et al. 1997), and in this study we report a mean PAR of 69% for collared animals. The difference between rates in this study and rates found with the test collar may be a result of several factors. First, if animals are moving at a pace greater than normal walking while a GPS position is being attempted, a fix may not be obtained within the allotted receiving time. Backpack trial tests performed by Edenius (1997) in northern Sweden indicated that a movement rate of 3–4 km · h^{-1} may reduce PAR under forest canopy. We observed a reduction in PAR during studies of the test collar as it was in the process of being transported by a vehicle at speeds above 8 km · h^{-1} between test locations. In contrast, Moen et al. (1996) reported that movement by GPS-collared moose did not affect PAR. Second, the test collar was placed on an elevated stand simulating the height of an adult elk with the collar situated in a normal position (dorsal GPS antenna, ventral transmitter). If a collar shifts when a GPS fix is being attempted (such as when an animal is bedded down), the GPS unit may be out of “sight” of the roving satellites and thus might be unable to successfully acquire a fix (Rodgers et al. 1995). This interference may also occur with VHF collars. However, the user has the option of altering position for further location attempts, whereas the amount of time a GPS collar attempts a fix is preprogrammed into the collar and minimized to reduce battery use (e.g., 3 minutes). Third, analysis of the test collar data tested only a single type of error, that of acquiring a GPS position. Because a hand-held uplink receiver was used to obtain position data in the collar testing, PAR error (or data loss) associated with satellite uplink and data transmission was untested. However, this would not appear to be a significant source of data loss since the collar continuously uplinks data over the course of an extended period of time (6 hours on every 3 days in the case of this study), thus providing multiple opportunities for successful data transmission. Although we report a lower overall mean PAR for collared animals compared to the test collar, PAR increased considerably following refurbishment of the collars (1996 vs. 1998). This may be due partially to advancements made in the antenna system following initial deployment of collars on the animals. Technological advances in collar components, particularly the antenna, may have resulted in higher PARs in the collars deployed on animals after 1996 (Stan Tomkiewicz, Telonics, Inc., personal communication), thus affecting overall results of the data analysis. More extensive comparisons of future generations of these collars to current versions of the collar should be performed.

Although the combination of cover type and terrain did not produce a model that significantly predicted GPS collar PAR, we observed lower rates in animals with home ranges that had a greater composition of tall forested cover types and steeper terrain, and higher PARs in animals with home ranges consisting of more open cover types and less steep terrain. Other studies have also shown a decline in PAR as tree density, tree height, and canopy closure increased (Rempel et al. 1995, Rodgers et al. 1996, Edenius 1997, Moen et al. 1997). The noticeable effect of high-relief terrain on the ability of GPS collars to acquire fixes has also been observed in other studies (Moen et al. 1997, Rutter et al. 1997).

GPS position acquisition rates tended to decrease with overcast conditions. Lower rates during overcast conditions may be related more to animal behavior than to ability of the GPS unit to observe roving satellites. Although certain meteorological conditions may diffuse the signal between satellites and the GPS collar, this would more likely affect accuracy of location fix than PAR (Trimble Navigation 1996). If we assume that greater cloud cover and lower cloud base heights indicate periods of precipitation events (i.e., snowfall, rainfall), then thermoregulatory responses may cause animals to move into more thickly forested areas and/or onto steeper slopes, either of which may result in some reduction in PAR.

We also report higher PARs between noon and midnight compared to midnight and noon, which is in contrast to what has been found in other studies. Moen et al. (1997) reported lower PARs of GPS-collared moose during daytime hours and suggested this was due to animals seeking shade during daytime increases in temperature. Although our results differed, we did find lower (but not statistically significant) PARs during warmer months when animals were likely attempting to cool themselves by seeking greater canopy cover and steeper slopes during daytime hours. Also, terrain varies dramatically within home ranges of some of the collared animals during summer months, from approximately 2100 to 3000 m, indicating that animals may utilize higher, cooler elevations during periods of warm temperatures. Lowest PARs were observed for elk that spent most of their time in more mountainous terrain within ponderosa pine and mixed-conifer habitats. These areas also consist of steep mountain slopes with narrow canyons, which may limit the satellite observation and transmission success rate of the GPS collar.

The initial high cost of GPS collars can prohibit the purchase of multiple collars, which in turn can reduce sample size of the target species being studied. Conversely, costs associated with use of VHF collars (e.g., aircraft time) may limit the number of animals that can be collared, thus reducing the quality of the study (Rodgers et al. 1996). Depending on study objectives (i.e., detailed daily movement patterns vs. general seasonal migration routes), VHF collars could be used in conjunction with GPS collars to reduce overall costs.

The preprogramming capability of GPS collars for obtaining positions provides the user an opportunity to select specific periods of the day/night during which to monitor the target animal. Although the version of GPS collar used in this study required all programming to be performed by the manufacturer prior to deploying the collar on to the animal, more recently developed versions allow the user to program the collar while in-hand. Additionally, other manufacturers' models of GPS collars allow the user to make programming changes to the collar while the collar is still on the animal via a remote radio communication link between the GPS collar and a command unit operated by the user (Rogers et al. 1996). Development and application of GPS radio collars for use in animal studies is relatively new to the field of wildlife research but shows much promise as an effective means of tracking wildlife. However, only a limited number of studies have evaluated the usefulness of these collars for tracking wildlife, particularly with respect to assessing PARs under varying environmental conditions (i.e., weather, topography, terrain).

We believe the use of GPS collars to be more effective than VHF units in tracking elk in our study area based on (but not limited to) greater estimated accuracy of locations, preprogramming capability of the collars, reduction in logistical concerns (i.e., access to remote or restricted areas), and reduction of personnel needs and costs as the study progresses.

Wildlife researchers should evaluate their data requirement needs (frequency of location positions) and labor costs of tracking animals using VHF telemetry prior to the use of GPS radio collars. Researchers should also identify potential effects that terrain and cover types within their study area could have on GPS collar PAR and locational error with respect to their study objectives.

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