ADDRESSING OBSERVATION BIAS WITHIN A GPS-TELEMETRY STUDY OF COASTAL MOUNTAIN GOATS

By

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ABSTRACT

Mountain goats (*Oreamnos americanus*) in coastal British Columbia and Alaska use lower elevation forests during winter relative to other seasons. Although conventional radiotelemetry is one potential method for studying coastal goats, signal reflection, reliance on clear weather for relocations, and potential harassment of goats during critical winter or kidding periods, all present shortcomings. Global Positioning System (GPS) wildlife collars offer a potential solution to these problems, yet introduce other problems. Some of the most challenging environments for acquisition of GPS fixes, namely incised, heavily forested valleys, are typical within coastal goat habitat. Even in less demanding environments, observation bias exists. Although habitat researchers are aware of this bias, the problem may be underestimated within particular environments. I collared 4 mountain goats within the Stafford River Valley on the mainland coast of B. C. to test GPS wildlife collar performance in challenging terrain and to examine the consequences of GPS observation bias for habitat-selection studies. I also tested the repeated fix success of similar collars placed at sites that differed in forest canopy and topographical relief. After leaving these stationary collars to attempt fix locations over a 24-h period, I determined the percentages of fixes in 2D, 3D and unsuccessful fix classes. I combined digital elevation models with a Geographic Information System (GIS) script to quantify available windows of satellite "sky" that were accessible from each test location. This "window" index, combined with surveyed and digitised habitat variables, allowed me to parameterise multiple regression equations that successfully predict the likelihood of receiving a GPS fix of various fix classes at a given location. From these ground truthing equations and spatially-explicit GIS projections of fix likelihood, I determined the likelihood of obtaining a GPS fix within any portion of the Stafford River study area. I was therefore able to match each individual goat's locations directly to a GPS fix probability. A significant correlation between mean predicted fix

likelihood and observed seasonal fix success of collared animals was observed. I then applied a simple and conservative correction factor to each fix location before conducting a habitat-selection analysis. Analyses of corrected and uncorrected data show that the consequence of failing to correct 3D data for observation bias can be severe. My analyses of uncorrected data indicate significant selectivity for habitats that differ from those which mountain goats are actually selecting.

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INTRODUCTION

The interest in telemetry systems based on the Global Positioning System for studying wildlife habitat has increased greatly in recent years and potential advances in GPS technology (Hulbert 2001) will likely ensure that this trend continues (Rodgers 2001). GPS collars have recently been used on a wide variety of wildlife species, often primarily for evaluating the collars' use. Increasingly, studies have used GPS collars to generate management recommendations such as for determining woodland caribou (*Rangifer tarandus caribou*) avoidance of industrial development (Dyer *et al.* 2001), or for studying habitat use of reintroduced elk (*Cervus elaphus nelsoni*) (Springborn and Maehr 2001) - reflecting the recent commercial development of this technology (Rodgers 2001). Researchers evaluating these collars have documented decreases in both location accuracy (Moen *et al.* 1997, Rempel and Rodgers 1997, Dussault *et al.* 2001), and more recently, in fix location probability (Dussault *et al.* 1999, Biggs *et al.* 2001, D'Eon *et al., in press*) with increasing amounts of forest vegetation and topography. Differential probabilities of obtaining GPS fixes, or observation biases, therefore probably exist within different wildlife habitats.

In a recent summary, Rogers (2001) states that traditional telemetry methods may be subjected to as much or more observation bias as GPS. Rogers (2001) also states that because of recently improved GPS collar observation rates, the consequences of this potential bias are reduced. Although these statements are most likely true, they may understate the consequence of observation bias for certain study environments. As Rogers (2001) acknowledges, observation bias is a potentially serious source of error that must be considered in all habitat use-availability studies. This may be especially applicable to studies of species such as mountain goats that inhabit complex mountainous and forested environments.

GPS offers several potential advantages, relative to conventional telemetry, that are particularly relevant for studying the habitat of mountain-dwelling species. The advantages include the ability to provide more continuous and higher accuracy tracking data (Haller *et al.* 2001) and a greater flexibility in sampling schedule. The proximity needed to obtain repeated, and accurate aerial VHF-telemetry locations may have negative effects on animals (Côté 1996). Aerial telemetry surveys are also restricted to clear-weather flying during daylight hours and can create a bias towards habitats used during those times. For these reasons, the use of GPS offers important advantages; however, as in studies for other mountainous species, topography and forest cover present GPS with a challenging environment for obtaining accurate and unbiased results.

The acquisition of GPS satellite signals by a collar is an important factor in GPS-location quality. Precision is positively affected by the number of satellites (Rempel *et al.* 1995, Moen *et al.* 1997). Accurate GPS locations are those which are precise and non-biased. In other words, an accurate sample of estimates for a location has low variability and its mean location is a short distance from the true population value - e.g., close to the true geographic location (Ratti and Garton 1996). This thesis, however, is concerned primarily with observation or fix-likelihood bias, that is the differential probability of obtaining a GPS location within one habitat relative to another.

For wildlife location data, obtaining signals from 4 or more satellites is important because the collar unit receives a three-dimensional (3D) fix mode location in which an elevation, and thus a relatively more accurate location, is estimated (Moen *et al.* 1997). If a collar acquires signals from only 3 satellites, a two-dimensional (2D) fix results which provides a lower accuracy location. This is because the GPS unit relies on previous calculations for elevation, which can introduce error in the horizontal position estimate (Rempel *et al.* 1995). Location fix attempts are unsuccessful if they acquire < 3 satellite signals within a critical period of time (Moen *et al.* 1996).

My thesis places greater emphasis on analyses of 3D data. In mountains, relatively small error in horizontal accuracy can potentially lead to large errors in vertical location estimates, so researchers may be tempted to drop 2D data from habitat analyses to improve location accuracy (D'Eon *et al., in press*). I do not specifically address issues of accuracy other than horizontal accuracy. Instead, I determine the bias in observation when 3D data are used exclusively for habitat-selection analyses.

Another important collar parameter pertaining to accuracy is dilution of precision (DOP). DOP relates to expected location accuracy based on satellite-configuration geometry. If dense canopy or topography causes the GPS collar to use satellites with a sub-optimal configuration from which to triangulate (low dispersion; e.g., a tight group of satellites directly overhead or to one side), DOP increases, expected position precision decreases, and accuracy may decline (Rempel *et al.* 1995). It is also important to note that the configurations of Navigation Signal Timing and Ranging System (NAVSTAR) GPS satellites vary over approximately a 24-h period. The orbital period of NAVSTAR satellites is about 12 h, however, the spatial constellation of satellites does not realign until 23 h and 56 min (Wells 1986). This change in spatial distribution of available satellites must be recognised when determining the likelihood of acquiring a successful GPS fix (R. Moen, Center for Water and the Environment, personal communication).

Differential correction is a method to increase location accuracy by removing effects of selective availability (SA - a degradation of GPS accuracy) using ephemeris data (list of satellite locations as a function of time) shared by a base station and particular GPS collar (Moen *et al.* 1997). Differential correction was especially useful for correcting locations to counteract the effect of SA before its discontinuation in May, 2000 (Lawler 2000) by the U.S. Department of Defense. While SA was in effect, locations were limited in accuracy to within 100 m of their true location 95% of the time (Rempel *et al.* 1995). With its removal, accuracy increased to within 20 m of the true location 95% of the time (Wells 1986). In Ontario, Rempel and Rodgers (1997) found that differential correction caused their location error for 3D fixes to decrease from 80 m to 4 m ($P<0.0001$). For some purposes, differential correction is still beneficial even without the effects of SA, because ionospheric and tropospheric signal interference corrections can result in locations within 10 m of their true location 95% of the time (Janeau *et al.* 2001).

Recent technological progress has resulted in wildlife collars being able to increase the frequency in which they fix locations. Greater proportions of successful fixes are related to improved antennas and search algorithms that allow collars to acquire satellite signals in a relatively shorter period (Rodgers 2001). However, fix-success rate is still negatively affected by multiple factors including habitat, season, topography, animal behaviour and collar movement.

Habitats that differ in their likelihood of receiving satellite signals will show biased results in studies of animals' habitat use. Variables decreasing the probability of obtaining a GPS fix location are mostly associated with trees, particularly tree height (Rempel *et al.* 1995, Moen *et al.* 1996), density (Rempel *et al.* 1995), canopy cover (Rempel *et al.* 1995, Edenius 1997), and basal area (Rempel *et al.* 1995, Edenius 1997).

Few studies have tested for the effect of topography on fix likelihood. Some have found that topography, and topography indexed by slope, are not significant factors in explaining fix success (Gamo *et al.* 2000, Biggs *et al.* 2001). However, these studies have occurred within relatively subdued topography. One study within truly mountainous terrain found that topographic relief reduced fix success only when interacting with canopy cover (D'Eon *et al., in press*).

Seasonal effects on GPS fix success have been reported with the highest success in winter (Edenius 1997, Dussault *et al.* 2001), and lowest in summer (Dussault *et al.* 2001). The trend is partially explained by changing levels of defoliation within deciduous forests, however Dussault *et al.* (2001) also showed an increase in fix success from summer to winter from identical locations within purely-coniferous forests. This result was observed even though dense snow was present in the canopy, which has been shown to have no effect (Dussault *et al.* 2001) or have a significant negative effect on fix success (Janeau *et al.* 1999).

Animal behaviour is another factor cited as affecting GPS fix success. Lower daily fix rates compared to nightly fix rates in moose were thought (Moen *et al.* 1996, Dussault *et al.* 1999) to be due to the animals using forests to avoid warm daytime temperatures (Schwab and Pitt 1991, Demarchi and Bunnell 1995). Similar reduced fix success was suggested to be due to them seeking shelter from precipitation under forest canopy (Biggs *et al.* 2001). Fix success is also significantly reduced when collar antennas are horizontal (Moen *et al.* 1996), when animals are bedded (Moen *et al.* 1996, Bowman *et al.* 2000), and when animals move (Edenius 1997, Bowman *et al.* 2000).

Clearly, diverse factors can limit the acquisition of satellite fixes, and decrease fix success, therefore, varying observation rates within different habitats can bias studies of habitat use. Habitats consisting of relatively high GPS fix likelihood may be over-represented relative to those with low likelihoods. Of the various factors, those related to topography and vegetation seem to be the most readily quantifiable and therefore predictable. These biases may be especially pronounced and consequential where animals such as coastal mountain goats inhabit narrow valleys and use varying elevations and amounts of forest.

Mountain goats in coastal areas of B. C. and Alaska depend on forest cover and steep bluffs at relatively low elevations for winter habitat (Hebert and Turnbull 1977, Schoen *et al.* 1980, Fox 1983, Smith 1994). These same forests are also commercially important, so it is essential for forest and wildlife managers to understand the habitat needs of goats, particularly during winter. Within B. C.'s coastal forests, only one telemetry study of goat habitat use (K. Brunt, B. C. Ministry of Water, Land and Air Protection, personal communication), and a limited number of observational studies (e. g., Hebert and Turnbull 1977, Demarchi *et al.* 2000, Gordon and Reynolds 2000) have been conducted. Given the habitat characteristics of coastal mountain goats, and that they may be especially sensitive to aerial traffic (Côté 1996), this species is probably ideal to test the impacts of forest cover and mountain topography on the effectiveness of GPS collars.

As a further step in our understanding of GPS observation bias for studies of mountain species such as goats, researchers need to develop spatial fix-likelihood models and test them against the fix success received by collared animals. To date, no reported studies have determined the practical ability for a model to accurately predict the fix success of a collared animal over a landscape. Here, I conduct such an analysis for mountain goats, and further explore the magnitude and consequences of observation bias by determining forest selection by goats before and after bias correction.

The predictions that I make include:

1) Field-sampling results will show fix success for 3D data to decrease with increasing topographical constraint, and increasing forest height, density, volume and crown cover variables.

2) Mountain goat collars will receive a lower proportion of fixes within winter ranges relative to fall ranges because goats spend relatively greater periods of time in lower elevation forests during winter.

3) Seasonal 3D fix-success values from collared mountain goats will be significantly correlated with predicted 3D fix-likelihood values.

4) Correction for observation bias will result in significant changes in mountain goat habitat-selection interpretations, especially in use of forested habitat.

METHODS

Study sites

The main study area where mountain goats were collared is located within the northernmost drainage of the Stafford River at the head of Loughborough Inlet (Figure 1). This is approximately 80 km north of Campbell River, and is located within Western Forest Products Tree Farm License # 25, Block 2. The ground testing of GPS collars involved 3 additional valley sites located within the Lower Mainland, including the Seymour River, the Coquitlam River, and the Malcolm Knapp Research Forest. The 3 ground-testing sites and a substantial portion of the Stafford River study area are located within the CWHvm1 biogeoclimatic variant (Submontane Very Wet Maritime Coastal Western Hemlock Variant) (Krajina 1976). Common tree species present within the 3 test valleys include western hemlock (*Tsuga heterophylla*), Douglas-fir (*Pseudotsuga menziesii*), amabilis fir (*Abies amabilis)* and lesser amounts of western redcedar (*Thuja plicata*), Sitka spruce (*Picea sitchensis*), and bigleaf maple (*Acer macrophyllum*). Within the Stafford River valley, common tree species include cypress (*Chamaecyparis nootkatensis*), western hemlock, amabilis fir, Douglas-fir and Sitka spruce.

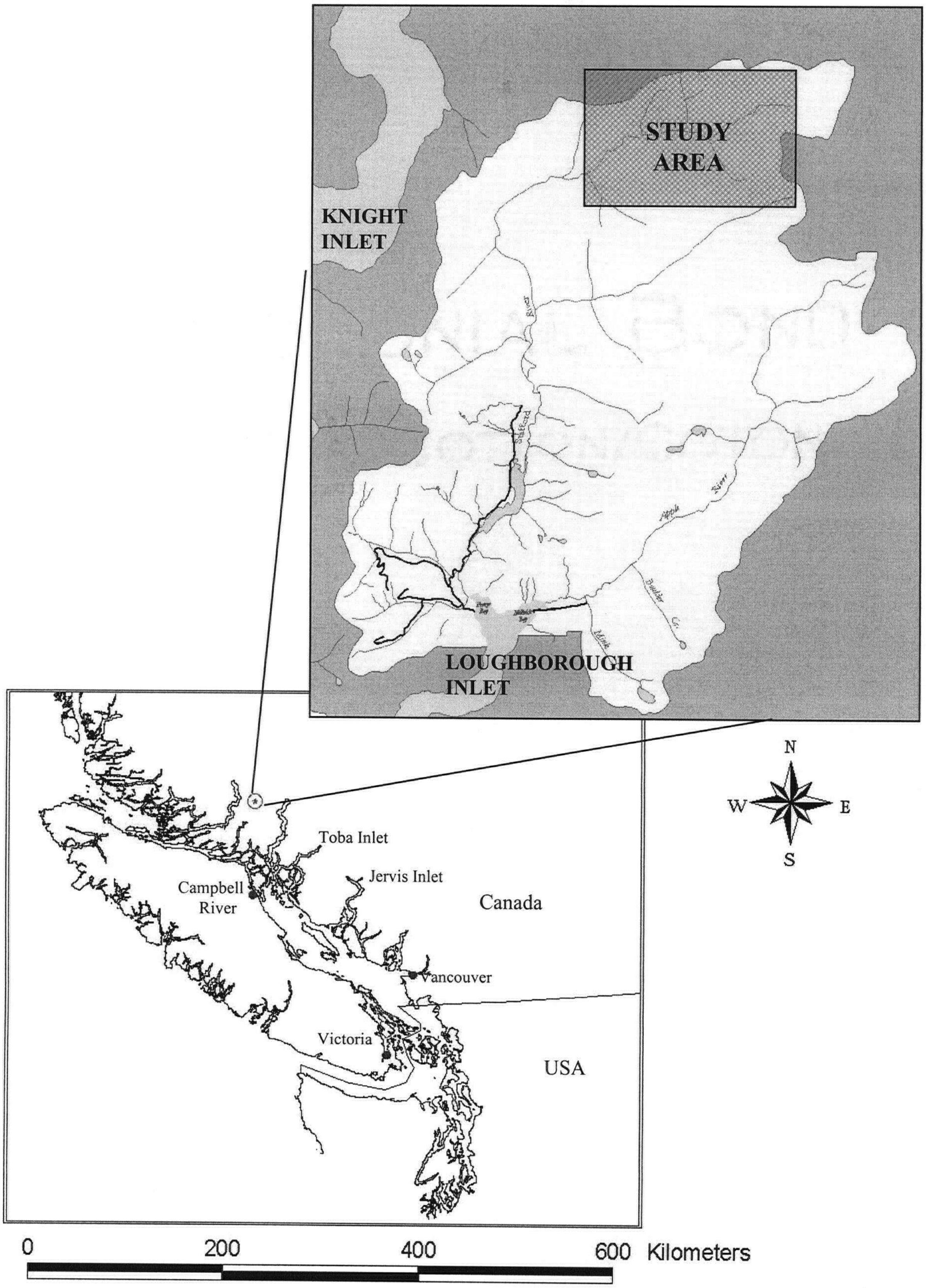

Figure 1. Overview of Stafford River study area where 4 mountain goats were collared with GPS units.

GPS collars

Using a netgun deployed from helicopter, 2 adult male and 2 adult female mountain goats were captured and collared with Lotek 2000L GPS units (Lotek 2001) on September 23, 1999 (Animal Care Certificate #A98-0276). I programmed the 4 collars to attempt to record geographic fixes at a rate of 6 locations per day (every 4 h) and retrieved the collars on June 19, 2000. The collar attempted to receive a fix for 140 sec. If unsuccessful, a reattempt was not made until the next scheduled fix time.

I conducted aerial telemetry surveys on 20 October of 1999, and 29 January, 31 March, and 15 June of 2000, to verify collar function and check for animal mortality. Animal recapture was avoided through use of a remotely activated drop-off mechanism for collar retrieval, thereby reducing animal stress.

I differentially corrected GPS locations using Lotek's N4 Post-Processing Software (Version 1.1895) and base station data collected from TerraPro at Burnaby, British Columbia. Recorded DOP was positional (PDOP) for 3D fixes and horizontal (HDOP) for 2D fixes. The post-processing differential-correction software used a default threshold setting of DOP =10.

This means that a 3D fix with a PDOP value higher than 10 degraded to a 2D fix with a lower HDOP value (A. Gyulay, Lotek Wireless Communications, personal communication). I discarded all 2D non-differentially corrected data (Norquay 1999) and filtered any data locations that were composed of a DOP value greater than 10 to maintain consistency with the differential correction program.

I subdivided my animal locations into seasonal periods based on approximate goat behavioural activity periods determined through literature and local expert opinion (Brandborg 1955, Geist 1964, Stevens 1983). Seasonal periods used were Fall (from project start at 1

October to end of rutting period at 15 November), Winter (16 November to 15 April), and Spring (kidding period for females from 16 April until time of first battery exhaustion at 3 June). To ensure that behaviour was not altered by the collaring procedure, I discarded the week of location information immediately after collaring and before 1 October.

GPS collar ground truthing

GPS collar location accuracy

To confirm that the accuracy of Lotek's 2000L GPS collars matched reports in the literature, I tested one collar's accuracy under forest canopy from a set of surveyed positions at the UBC Malcolm Knapp Research Forest in Haney, British Columbia. GPS fix attempts were made from 32 fixed locations between 19 and 20 February, 1999. In total, 86 location attempts were made. The collar was programmed to fix locations every 5 min and the collar was placed on a tripod 1 m above the ground at each station to simulate the collar height on a goat. Forest Engineering Research Institute of Canada (FERIC) surveyed and marked fixed locations with metal pegs. Base station data for 19 February, acquired from Terrapro GPS surveys Limited in Burnaby, British Columbia, were used to differentially correct GPS location information. Base station information for 20 February was unavailable. Location data from this day were therefore used to determine mean errors of uncorrected data. The UTM (Universal Transverse Mercator) location survey coordinates provided by FERIC were transformed into geographical coordinates (decimal degrees) using a program called CORPSCON (Corps Convert, created by TEC - U.S. Army Topographic Engineering Center). This transformation allowed me to compute location errors by fix-success category, using the Pythagorean Theorem to calculate the resultant error distance from the known x–y coordinates.

Testing GPS fix success

To estimate GPS fix likelihood within forested coastal mountains, I placed 3 Lotek 2000L GPS collars at the centre of 72 plots within 3 forested valleys of the Lower Mainland, British Columbia. The same type of collar was later used on 4 goats. I placed the GPS collars on stakes 1 m above the ground, with the antenna housing in a vertical, upright orientation. The collars were programmed to attempt location fixes every 30 min over a 24-h period to afford each collar an equal chance of satellite acquisition. Therefore, the 72 observations represented the percentage of fix locations from 48 fix attempts at each plot.

Collar fix information was downloaded after each sampling day to a laptop computer via a download link unit, before reinitialising the collar for a new sampling session in a different plot. I uploaded each collar with a new GPS almanac of available satellites, biweekly.

I assigned plots to 3 valleys and 5 forest cover classes. I attempted to conduct 6 replicates per forest-valley category on different days between 6 March and 24 May, 2000. I relocated GPS collars to a new valley test site each consecutive field day. I randomly chose plot locations from the available area within each forest-valley combination, except to ensure that plots were ≥ 30 m from another forest stand, or ≥ 50 m from a road surface. I used these restrictions to minimise confounds of multiple forest stands or road influence on fix success. To maintain accuracy, travel distances within and to plots were adjusted for necessary slope correction.

I selected 3 valleys that differed in topographical relief for collar ground-truthing study areas. The Seymour River (SR) site was chosen as the narrowest valley (*ca.* 5 km wide), the Coquitlam River (CR) site was chosen for an intermediate level of topographical exposure (*ca.* 7-12 km wide), and the Malcolm Knapp Research Forest (MK) was chosen to provide the greatest satellite access. Topography in the MK study area blocked satellite views from primarily the northeast direction. The SR and CR valleys were situated in a north-south orientation. To determine if these valleys truly differed in topographical access, I calculated and compared Topex measurements (see "Measuring GIS variables") from each ground-truthing plot.

Plots were assigned to different forest cover classes (Table 1) to represent different environments including Clearcut, that was considered equivalent to alpine environments in satellite view, and Short, Moderate, Tall Dense and Tall Open forest classes. Tall Dense and Tall Open plots were within canopies with above and below 66% canopy closure, respectively. Tall Dense stands were not available within the SR study area, and Clearcut was available only within the MK. I also tested 3 collars from a rooftop with no obstructions at the University of British Columbia, to simulate clearcut or alpine environments with zero topographical constraint to satellite view.

Table 1. Description of GPS sampling classes used to test the impacts of forest cover on fix likelihood of Lotek 2000L GPS collars.

Forest cover class	Age class (yr)	Height class (m)
Clearcut	1-5	0-1.3
Short (short height forest)	21-40	10.5-19.4
Moderate (moderate height forest)	41-120	19.5-37.4
Tall Dense (tall height forest >66% crown closure)	121-250	37.5-55.4
Tall Open (tall height forest <66% crown closure)	121-251	37.5-55.5

Georeferencing plot locations

For later GIS calculations involving topographical satellite access, I referenced GPS ground truthing plots to available 1:5 000, 10 000 and 20 000 hard copy maps, using a ruler and Douglas protractor. To georeference plots from these maps without geocoordinates, I scanned and digitally conflated (rubber-sheeted) the images (Demers 2000) to a 1:20 000 projection scale equivalent to B. C. Terrain Resource Inventory Management (TRIM) mapping using an Avenue script (#1 in Appendix 1) from Environmental Systems Research Institute (ESRI). Identifiable features common to both maps, such as road and river-road intersections, were then used as control points for the conflation procedure. My plots were viewed as a separate visible GIS layer, and I could thereby extract UTM coordinates from them. I could have used averages from the most accurate class of GPS collar locations, however I needed an independent estimate of collar location.

I tested a sample of 14 plot coordinates from the MK for accuracy against the coordinates obtained from an Ashteck backpack GPS unit used in the field, with realtime differential correction. I could not obtain further field coordinates because of GVRD access limitations. I calculated a mean mapping location error of 15.8 m (SEM=4.7).

Predicting GPS fix likelihood

Measuring plot variables

Within the area surrounding test collars, I measured habitat attributes that could potentially affect the reception of GPS satellite signals. I chose fixed-radius plots within specific forest categories to consistently include a minimum of 5 trees except within the Clearcut class. I chose plots with radii of 7.8 m for Moderate and Tall forest plots, and a shorter radius of 5.6 m for Short forest plots because they were higher density stands.

I measured the following plot variables: Collar # (2 indicator variables), Leading Tree Species (2 indicator variables for leading plot tree species by volume), Aspect, Slope, Percent Shrub, Crown Closure (measured by densiometer), PCG (gap percentage of plot area), Volume/ha (volume per hectare), Crown vol/ha (crown volume per hectare), Basal area/ha (basal area per hectare) and Height (90^{th} percentile plot tree height) (Table 2).

Table 2. Summary of abbreviations for independent (measured plot and GIS) variables and dependent variables for multiple regression to predict GPS fix success.
[1] = variables used for final regression equations.

Independent variables	
Measured plot variables	**Description**
Collar #	One of 3 collars (each was matched to a dedicated battery)
Leading Tree Species	2 indicator variables for leading tree species by volume within each plot (describing Western Hemlock, Douglas-Fir or Other)
Aspect	Categorical variable describing north facing (315°-45°) aspect or other
Slope	Average of 2 slopes as percentage (from 0° and 180° relative to aspect)
Percent Shrub	Estimated visual cover percentage within plot from 0 m to 3 m high
Crown Closure	Measured by spherical densiometer
[1]PCG	The percentage of canopy gap within the plot area
Volume/ha	Tree volume per hectare
Crownvol/ha	Crown volume per hectare
Basal area/ha	Basal area per hectare
Height	The 90th percentile of all tree heights within plot
Measured GIS variables	
[1]GISage	Stand age class from forest cover description
GISheight	Stand height class from forest cover description
GIScc	Stand crown closure class from forest cover description
[1]Forclear	Describes the presence or absence of forest
[1]Topex	Sum of 8 “line of sight” angles in ° from plot to highest horizon point
Meansat	Mean number of satellites theoretically accessible from plot within each respective 24-h sampling period
[1]Plot Type (I-IV)	4 indicator variables to describe 5 forest classes
Dependent variables	
Percentage 2D Fix Likelihood	The percentage of fix locations which were unable to acquire a satellite configuration to calculate a new elevation estimation
Percentage 3D Fix Likelihood	The percentage of fix locations able to record an estimate for elevation, and requiring a minimum of 4 satellites
Percentage Overall Fix Likelihood	The percentage of fix locations that were either 2D or 3D

I enumerated every tree whose stem-centre fell within the plot, except for dead trees with diameter at breast height (DBH, measured at 1.3 m in height) less than 7.5 cm. All live trees at least 1.3 m tall were measured. When the number of plot trees was low, I measured most of the dominant and subdominant tree and canopy heights within plot. When the number of plot trees was relatively abundant, I measured tree heights at various canopy levels, and estimated the remainder of heights based on adjacent tree height measurements. I measured an average of 6.6 tree heights (from within the dominant or subdominant canopy layer) per plot. All measured and estimated tree heights were used to calculate Height.

I recorded tree species and measured DBH for each tree. For use in later multiple regression analyses, I classified Leading Tree Species into 2 indicator variables to describe the species Western Hemlock (*Tsuga heterophylla*), Douglas-Fir (*Pseudotsuga menziesii*) and Other to maintain relatively large group sizes. I measured tree heights using a clinometer, fibre measuring tape and trigonometry equations. I measured maximum crown widths with fibre tape by estimating the edge of each tree's canopy and estimated canopy density using 2 variable estimates. Firstly, I used a spherical densiometer to measure Crown Closure (Lemmon 1956). Secondly, I estimated canopy gaps within plots (PCG) by measuring the longest axis and corresponding perpendicular width of any visible canopy gaps estimated to be at least 2 square metres. I then calculated the elliptical area of this gap. The volume of each tree was calculated using growth curve regression equations specific to tree species and the Lower Mainland Forest Inventory Zone (Watts 1983). I calculated Crownvol/ha (m^3/ha) using a parabolic volume equation.

Measuring GIS variables

I included 4 GIS forest cover variables, GISage, GISheight, GIScc (crown closure) and Forest (presence or absence) as independent variables to predict fix likelihood. I also included 2 variables related to collar satellite access: Topex and Meansat, the mean number of satellites available during the 24-h sampling period.

To estimate the window of potential satellite constellations available to a GPS collar at a test plot, I calculated Topex values. This measure of topographical constraint combined digital elevation models with an Avenue (ArcView software' object-oriented scripting language) GIS script. Topex is the sum of "line of sight" angles in degrees for 8 directions. A plot in a narrow valley bottom would have a relatively high Topex score; one on a ridgetop would have a relatively low score. From some ridgetop locations, a negative declination for a direction can be obtained because the declination is measured from the plot to the highest elevation point within 2 km; in some cases, the highest elevation point can be below the actual plot elevation. I edited Topex scores to ensure that no one value was <5 ° because the Lotek GPS 2000L collars were programmed to ignore signals lower than this declination from the horizon (A. Gyulay, Lotek Wireless Communications, personal communication). Therefore, the lowest possible cumulative total for Topex was 40°. Because the ArcView method used an unknown procedure to interpolate elevations from digital elevation models, a new script was developed for future topographical calculations (A. Moy, Centre for Conservation Research, personal communication).

To calculate a potentially more informative measure of satellite access within the respective 24-h sampling period, using aspect and topographical constraint information derived from Topex calculations, I estimated the mean number of satellites theoretically visible from each plot using a utility called Curtains (Pathfinder Office).

The GIS variables act on the stand scale level, however I considered my sampling unit to be sample plots, not forest stands, because Topex and Meansat measurements, variable within stands, were calculated from plot centres.

GIS analysis

I used ArcView (version 3.2) for all GIS analyses. B. C. TRIM coverages (1:20 000 scale) were translated from compressed Spatial Archive and Interchange Format files (SAIF) to Arc shape files with Feature Manipulation Engine (FME) translator. I used a UTM projection of datum North American Datum (NAD 83, zone 10) to display goat locations and other GIS coverages. Mountain goat location data were converted from geographical co-ordinate information (datum 186 WGS 1984) to UTM projection using Blue Marble Geographics software. Forest-cover polygon data was typed in 1971 by K. C. Hoel from 1:15 000 black and white aerial photos taken in 1969. The mapsheets of TRIM and forest cover were merged using ArcView's Geoprocessing Wizard. No forest harvesting occurred since vegetation typing was conducted within the study area. Because the majority of forest cover classes were mapped as age class 8 and 9 (> 141 yr old), the consequence of the dated forest cover mapping is relatively minor.

I created digital elevation models for each of the study valleys. For the ground-truthing valleys, I applied a GIS extension (Topex) to calculate the amount of sky exposure visible from all plot locations. I overlaid a GIS grid onto the Stafford Valley and calculated point values of Topex from the grid centroids to map satellite-viewing access. GIS vector coverages including forest cover, age and Topex point values, were rasterised into 50-m by 50-m cells using identical reference locations. I reclassified forest cover to a dichotomous variable: forest or non-forest. I then entered grid values into regression equations developed from ground truthing, using ArcView's Map Calculator function. The Percentage 3D Fix Likelihood, Percentage 2D Fix Likelihood and Percentage Overall Fix Likelihood (likelihood of obtaining a 2D or 3D fix) was thus estimated for each grid cell over the entire Stafford River study area. Values less than 0% likelihood within the Percentage 3D Fix Likelihood category were reclassified to 0%.

To associate GPS fix likelihood values with every goat location within a seasonal range, I converted the maps of "floating point" grid-likelihood data to point values using Avenue (#2 in Appendix 1). Expected GPS likelihood values were assigned to goat location data using ArcView's "assign data by location" procedure within its Geoprocessing Wizard.

Before either habitat selection or a more accurate estimation of mean Percentage 3D Fix Likelihood per animal season was calculated, data were corrected for observation bias. A greater number of locations and fix likelihood values were considered when goat locations were found in low fix likelihood environments. This procedure used a correction factor based on detection probability (Table 3) and normalised data to a more equal probability of obtaining GPS locations. After correcting for observation bias I averaged the Percentage 3D Fix Likelihood values in each season and compared them with the observed seasonal Percentage 3D Fix Success values for each animal.

Because of the variability of elevations used by goats during Spring, I focused my analyses of seasonal bias on differences between the high Percentage 3D Fix Success of Fall, versus the lower Percentage 3D Fix Success of Winter. I could then determine if lower Winter Percentage 3D Fix Success was mostly attributable to poor collar performance associated with winter weather, or to goat behaviour, in that the Percentage 3D Fix Likelihood values within the habitats frequented by goats were lower than that during Fall. I tested for significant differences between the correspondence of Percentage 3D Fix Likelihood and Percentage 3D Fix Success for all seasons and for all collars.

Habitat selection for Female #2 was omitted from forest selection analyses because the mapped forest cover within this animal's range was inadequate. The forest cover map shows no forest polygon near this goat's range, where forest is visible above a centrally-used cliff face (Figure 2).

Table 3. Correction factors used to determine seasonal Percentage 3D Fix Likelihood and to calculate forest habitat selection by goats.

Range of Percentage 3D Fix Likelihood	<0 - 25	>25 - 50	>50 - 75	>75 - 100
Midpoint	12.5	37.5	62.5	87.5
Probability detection function	1/12.5 = 0.08	1/37.5 = 0.03	1/62.5 = 0.02	1/87.5 = 0.01
Multiplication factor	8	3	2	1

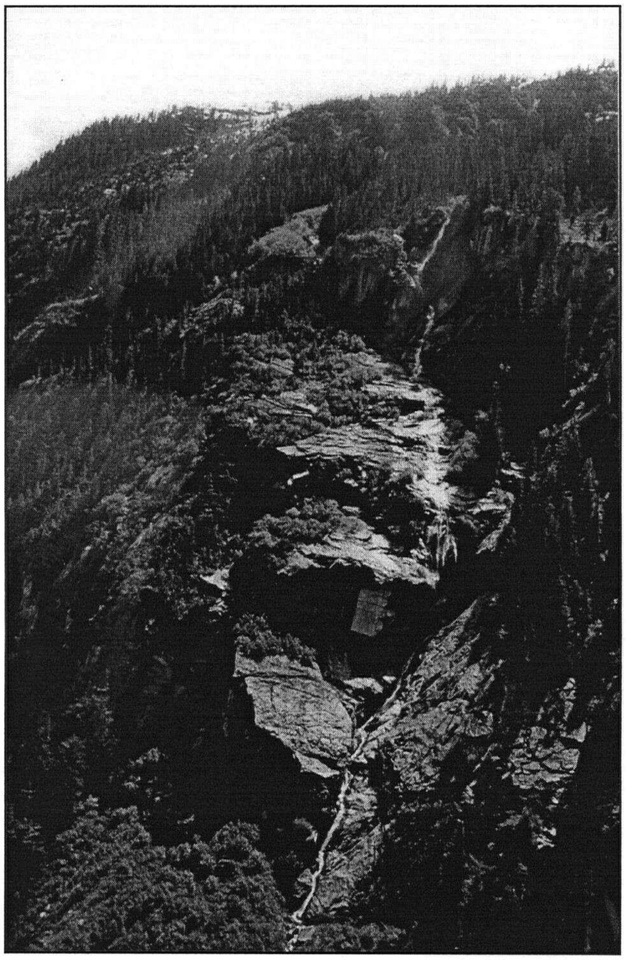

Figure 2. Photo showing presence of forest above north-facing cliff used by Female #2, another adult female mountain goat and young of the year.

Forest cover processing

To match forest cover data to more current TRIM information, I shifted forest coverages 112.9 m west and 202.0 m north using Avenue (#3 in Appendix 1). I determined the shift distances by measuring the discrepancy between the location of the Stafford River in the forest cover layer and the TRIM data. Mean average x and y shift distances were calculated from 5 x-y pairs of offset distances determined from ArcView's measuring tool.

Habitat-selection analysis

I determined selection of forest habitat by goats at 2 scales, before and after correction of location data, for GPS fix observation bias. I calculated the goats' selection of seasonal ranges within the study area (second order selection), and selection of habitat components within the home range (third order selection) (Johnson 1979). For second order selection, I estimated forest availability from the study area. For third order selection, I framed the estimation of availability within the overall home range of the 3 goats for which I was determining selection patterns. A 100% minimum convex polygon (MCP), estimated from locations filtered for accuracy from the 3 goats, was used for this overall annual range (*ca.* 8-month period). I determined selection using a modified chi-square analysis (Neu *et al.* 1974) to compare goat use versus habitat availability.

Home ranges were calculated using 50% and 95% adaptive kernel estimates (Worton 1989). Home range size differences by sex were evaluated descriptively. All range analyses were conducted with Animal Movement (ArcView extension) (Hooge *et al.* 2002).

Statistical analyses

SPSS (9.0 for Windows) was used for multiple regression analyses, and JMPIN (SAS Institute version 4.0) was used for other statistical analyses. Non-parametric tests were used for statistical comparisons where data did not meet necessary assumptions (Zar 1996). Goodness-of-fit tests (Sall *et al.* 2001) were used to test the assumption of normality, and Levene tests (Sall *et al.* 2001) were used to test for equality of variances. An alpha level of 5% was used for all analyses, where alpha is the chance of a Type I error ($\alpha = 0.05$).

I compared Fall and Winter Percentage 3D Fix Success values for each collared animal using a 2-tailed Fisher exact test (Zar 1996). I used Wilcoxon 2-sample tests (Zar 1996) to compare the accuracy of different fix classes received from GPS collars, and to test for significant differences between Winter and Fall Percentage 3D Fix Likelihood values for 3 mountain goats. Kruskal-Wallis tests (Zar 1996) were used to test for significant differences between the 3 valley scores of Topex, and Crown Closure, and to compare the correspondence between seasonal Percentage 3D Fix Likelihood and Percentage 3D Fix Success. Tukey tests (Zar 1996) were used to determine which groups were significantly different.

Fix likelihood regressions

From test plot results, I used independent variables associated with satellite access, GIS forest cover and measured plot attributes, in multiple regression equations to predict Percentage GPS Fix Likelihood values. Dependent variables included were Percentage 3D Fix Likelihood, Percentage 2D Fix Likelihood and Percentage Overall Fix Likelihood (likelihood of obtaining either 2D or 3D GPS fixes). I focused more attention on models that predicted Percentage 3D Fix Likelihood because I later used this estimate to correct biases. Finally, for each GPS fix class, I chose 1 model that was most practical for projecting Percentage Fix Likelihood values in the study area.

I conducted multiple regression analyses using several explorative techniques such as step-wise, backward and logical combinations of variable entry, to derive potential candidate models (Neter *et al.* 1996). I plotted residuals of candidate models against predicted values to check for normality, homoskedasticity, autocorrelation, and lack of fit (Neter *et al.* 1996). The model was retained as a candidate if residual plots did not indicate departure from multiple linear regression assumptions. Final chosen models were those that provided the highest explanatory power as determined by the adjusted R-squared, and lowest standard error of the estimate.

RESULTS

Ground truthing

Location accuracy

Mean location error under canopy at the MK site decreased significantly with use of differentially corrected data both for 2D and 3D data (Wilcoxon 2-sample tests, P=0.0006, 0.002). Mean error varied with differential correction from 52.6 m to 9.5 m for 3D data, and from 18.6 m to 14.6 m for 2D data (Table 4). For differentially corrected data, no significant differences between 2D and 3D were observed (Wilcoxon 2-sample test, P=0.28). Observation of a lower mean accuracy for uncorrected 3D data compared to uncorrected 2D data was unexpected; however, differences between the 2 categories of data were not significant (Wilcoxon 2-sample test, P=0.57). The DOP values for the 3D data are lower than that of the 2D data, which may explain the larger inaccuracy.

Table 4. Summary of location errors under forest canopy by fix category.

Fix category	Sample size	Average DOP	Mean error (m)	95% Confidence limits
2D	25	3.6	18.6	(0.0 < mean error < 52.6)
2D Dif[1]	20	5.5	14.6	(1.1 < mean error < 28.2)
3D	18	5.5	52.6	(13.6 < mean error < 91.6)
3D Dif[1]	9	5.7	9.5	(0.0 < mean error < 20.0)

[1]Dif = differentially corrected data.

Differences between valley-forest categories

Topex and Crown Closure differences were observed between Lower Mainland valleys and forest classes. These differences are relevant for further comparisons of fix success among categories of forests and valley-widths.

GIS Topex measurements from each plot showed an expected trend of increasing sky visibility from the narrow SR valley, through the CR valley, to finally the open MK valley (Figure 3). No overlapping values were observed between Topex scores of the widest valley MK and the 2 narrower valleys, however values from SR and CR did overlap. Valley Topex values were significantly different overall (Kruskal-Wallis test, P<0.0001), and the range of values from each valley was significantly different from each other.

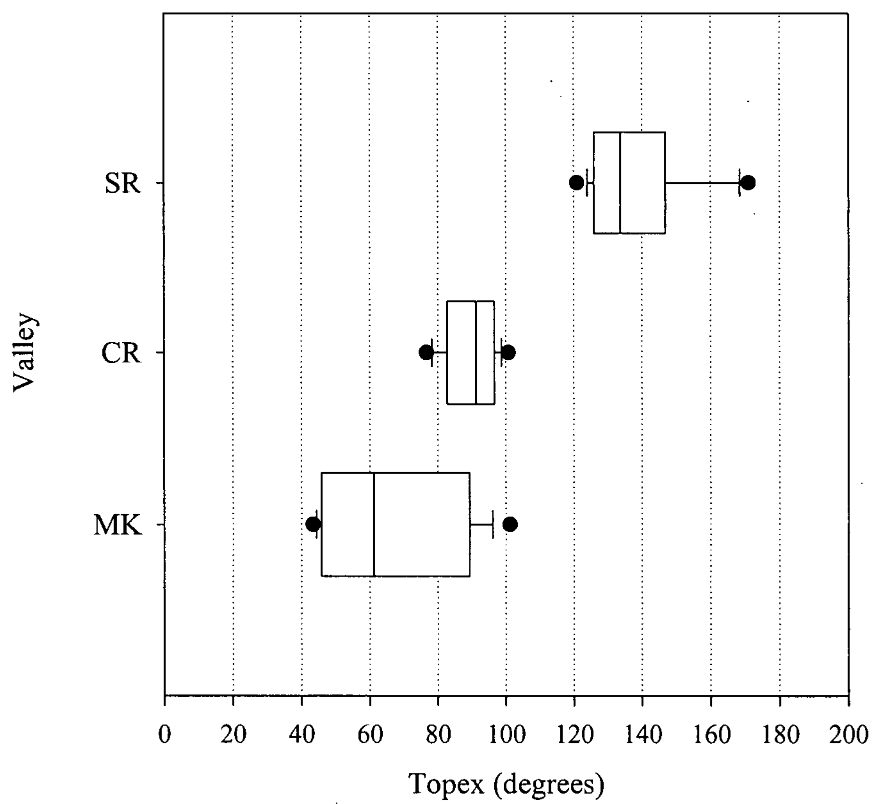

Figure 3. Comparison of Topex values (topographical constraint) in the 3 study valleys (SR=Seymour River, n=18; CR=Coquitlam River, n=22; MK=Malcolm Knapp Research Forest, n=28). Boxplot measures from left to right: the 5th (circle), 10th and 25th percentiles, median (inside the box), 75th, 90th and 95th (circle) percentiles.

Crown Closure, as measured by spherical densiometer, was highest within the Short forest category (mean = 88.79%). Standard error bars showed Crown Closure was greater than in Moderate forests (mean = 79.38%). Mean values for Tall Closed and Tall Open were 81.45% and 85.05% respectively. However, the difference between all forest classes was not statistically significant (Kruskal-Wallis test, P=0.08). Another measure of canopy closure, PCG, showed Short forests had lower percentages of canopy gap when standard error bars were compared. Nonparametric analysis showed no statistical difference between PCG of any forest classes (Kruskal-Wallis test, P=0.12).

Fix-success variation among categories of valleys and forest

A large range of values was observed for Percentage 3D Fix Success (Figure 4) from stationary collar testing in the Lower Mainland. The mean Percentage 3D Fix Success for plots within Tall Open of the narrow SR valley was 15.7%, while that of the Tall Closed sites of MK, the most accessible valley, received 44.6%. Clearcut in the same valley received 75.1%. A smaller range of values from 80.5% to 95.8% were observed for Mean Percentage Overall Fix Success in forested valley sites, while Clearcut received 99.7% (Figure 5).

In valleys where there were lower amounts of topographical constraint Percentage 3D Fix Success was often higher. An increasing trend in Percentage 3D Fix Success was observed with increasing valley width in 3 of 4 forest classes. From standard-error estimates, mean Percentage 3D Fix Success was greater in MK relative to CR within the Short forest category, greater in both the MK and CR compared to SR in the Tall Open forest category, and greater in MK relative to CR in the Tall Closed forest category. These observations lent some support to the hypothesis that Percentage 3D Fix Success decreases with increasing topographical constraint.

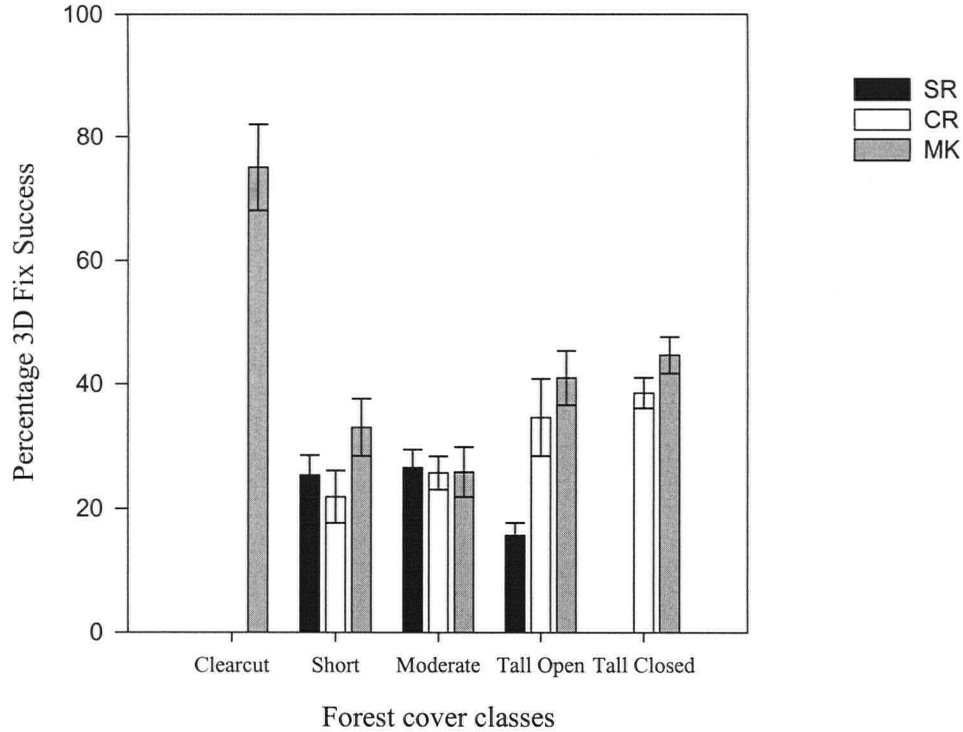

Figure 4. Mean Percentage 3D Fix Success by forest cover class in 3 valleys (SR=Seymour River, CR=Coquitlam River, MK=Malcolm Knapp Research Forest). Error bars represent standard errors. Sample sizes are 6 observations per group bar except for Tall Open forest in CR which was 5.

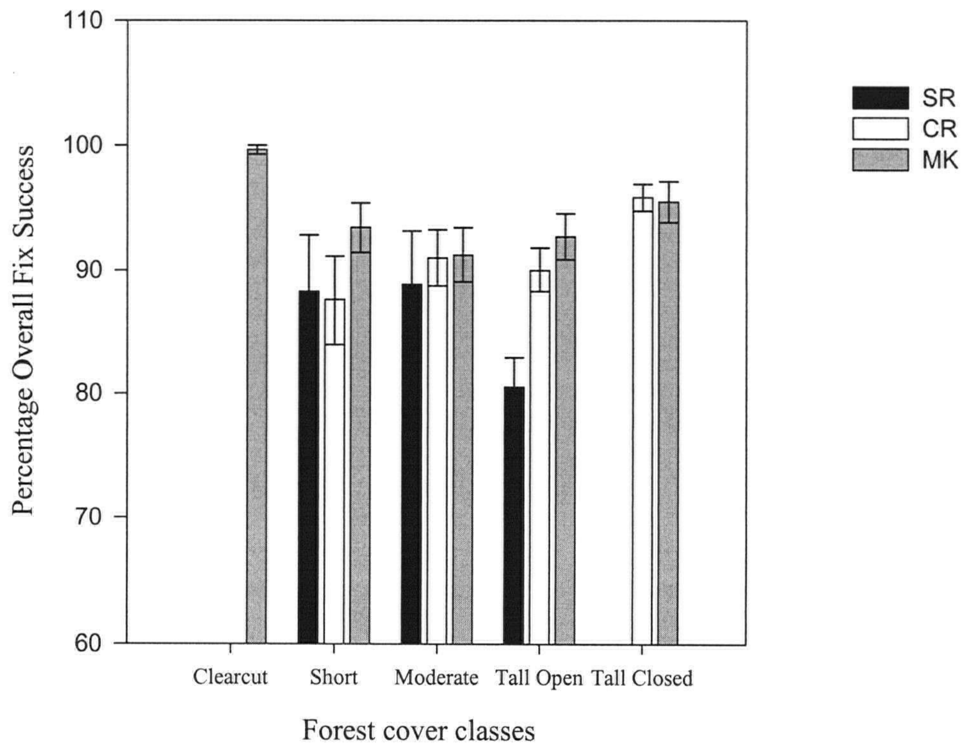

Figure 5. Mean Percentage Overall Fix Success (2D & 3D) by forest cover class in three valleys. Clearcut was only available within CR and there was no Tall Closed forest available within SR. Sample sizes are 6 observations per group bar except for Tall Open forest in CR which was 5.

Percentage 3D Fix Success was very high when both factors of vegetation and topographical constraint were removed. A mean of 95.8% was recorded from tests on a rooftop unobstructed by terrain.

An inconsistent trend was observed when comparing Percentage 3D Fix Success amongst forest categories. Unexpectedly, only the Tall Open forest category of the SR showed taller forest having lower Percentage 3D Fix Success than shorter forest categories. In contrast, the Percentage 3D Fix Success within both the CR and MK was greater for taller categories of forest than for shorter ones. This was contrary to the hypothesis that taller height forests should receive poorer GPS fix success. However, Height could decrease Percentage 3D Fix Success when other variables such as Crown Closure are accounted for.

Because these forest age/height categories were not experimentally controllable, varying factors may have obscured true relationships (Clark *et al.* 1993) between variables and GPS fix success. For this reason, a multivariate approach was needed to further clarify the effect of habitat variables on fix success.

Multiple regression formulas

Multiple regressions showed the topographical measure Topex to be the highest single variable predictor of all classes of fix likelihood. The coefficient of determination for the equation of Topex predicting Percentage 3D Fix Likelihood was 0.39. The only measured habitat variable to significantly add to fix likelihood predictability, and that met multiple regression assumptions when combined with Topex, was PCG (Equation #1 in Table 5). The next most significant measured predictors were Height followed by Crownvol/ha, however, a poor fit of residuals was observed for models using these variables combined with Topex.

Table 5. GPS fix likelihood equations and parameterisation of multiple regression coefficients.

Equation	Intercept	Topex	PCG	Forclear	GISage	Plot Type I[a]	Plot Type II	Plot Type III	Plot Type IV	R^{2b}	SEE	P value
1	49.81	- 0.23	42.51							0.45	15.78	<0.0001
2	92.09	- 0.19				- 46.36	- 46.39	- 36.65	- 42.92	0.77	10.28	<0.0001
3	93.79	- 0.22		- 45.83	0.04					0.76	10.50	<0.0001
4	10.94	0.13		40.40	- 0.04					0.73	8.95	<0.0001
5	104.73	-0.09		- 5.46						0.30	6.49	<0.0001

Note: Regression equations #3, #4, and #5 were used to spatially estimate fix likelihood within the Stafford Valley. All equations predict Percentage 3D Fix Likelihood except for #4 (Percentage 2D Fix Likelihood) and #5 (Percentage Overall Fix Likelihood). Equation #3 was used to calibrate goat habitat data for fix likelihood and to test for habitat selection by goats within the Stafford Valley.
[a] = Plottypes I - IV are indicator variables for the following 5 categories of forest (each category is followed by its corresponding coefficient for the indicator variables): Short forest (1000), Moderate (0100), Tall Closed (0010), Tall Open (0001), and Clearcut (0000).
[b] = Adjusted R^2

The best fitting equation (Equation #2 in Table 5) used Topex and Plot Type to explain 77% of the variability in Percentage 3D Fix Likelihood. However, predictions from this equation were precluded to a specific complement of forest age and height classes. The equations chosen for practical analysis (Equations #3, #4, and #5 in Table 5) used GIS variables exclusively, including Forest, Topex, and GISage, and were not restrictive to certain classes of forest. Leading Tree Species did not significantly improve predictions of Fix Likelihood.

GPS fix likelihood within the Stafford Valley

Expectedly, GPS fix likelihood values predicted from GIS ranged greatly over the Stafford Valley study area. Percentage Overall Fix Likelihood was shown to range from 70.7% to 101.0%. The highest predicted values occurred on relatively high elevation ridgetops, while the lowest predicted values occurred within forest polygons at lower valley positions (Figure 6). A similar trend was observed for Percentage 3D Fix Likelihood values with respect to topographical relationships (Figure 7). Values for Percentage 3D Fix Likelihood were expectedly lower relative to that for Percentage Overall Fix Likelihood, and ranged from less than 0% to 84.8%.

A complementary relationship was observed for Percentage 2D Fix Likelihood values in relation to Percentage 3D Fix Likelihood and Percentage Overall Fix Likelihood. Where high-value grid cells of Percentage 3D Fix Likelihood and Percentage Overall Fix Likelihood occurred, lower Percentage 2D Fix Likelihood values were observed, and vice versa. The highest Percentage 2D Fix Likelihood grid cells were within forest polygons at lower valley positions, while the lowest values occurred on ridgetops. The range of predicted values for Percentage 2D Fix Likelihood was 16.1% to 90.5%.

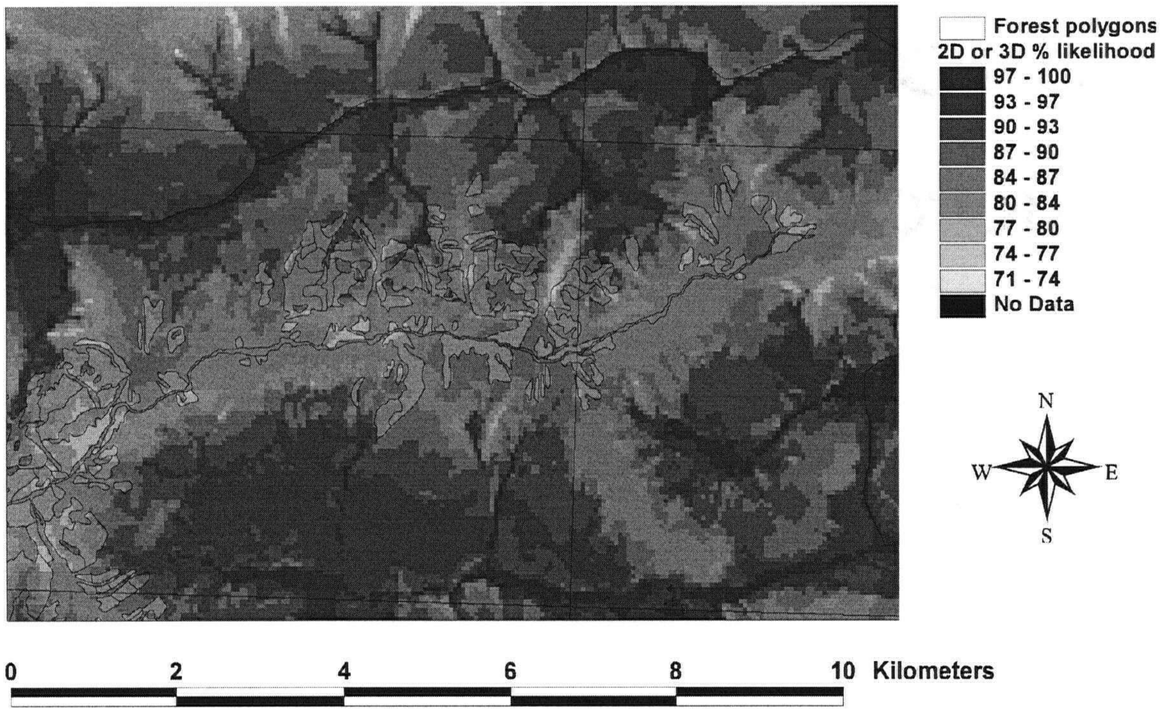

Figure 6. Percentage Overall Fix Likelihood in the Stafford River study area. Darkest grid cells are generally associated with ridgelines, while the lightest cells are found in forest polygons near valley bottoms.

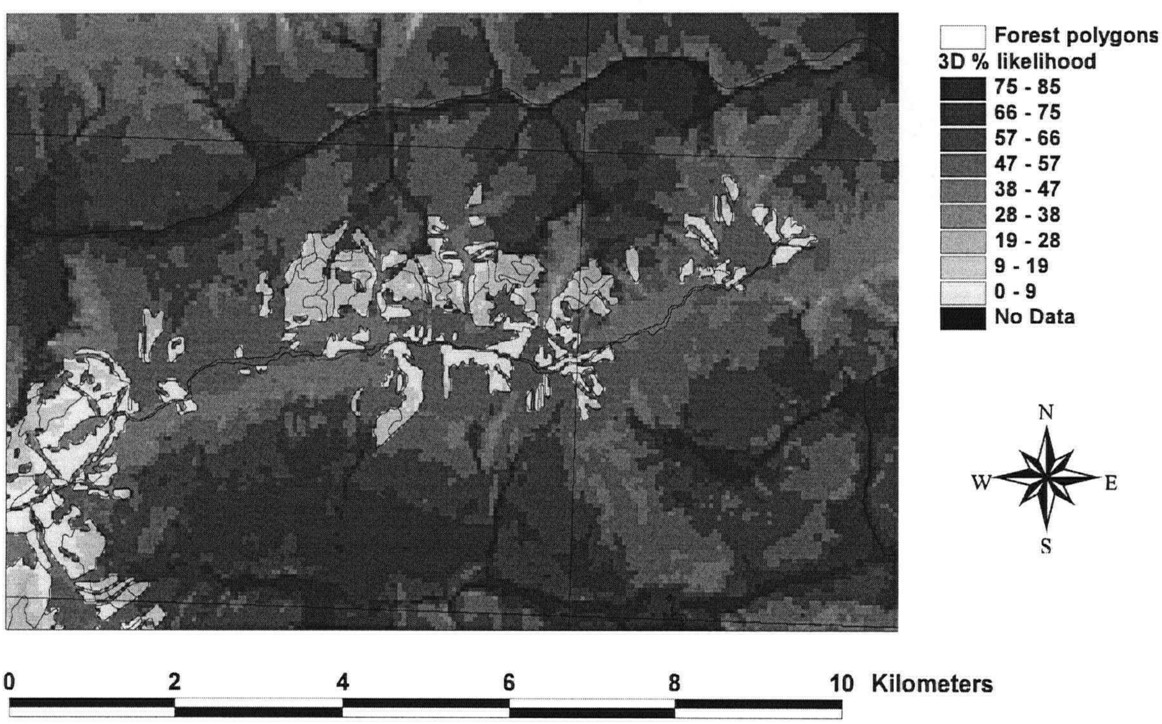

Figure 7. Percentage 3D Fix Likelihood in the Stafford River study area and its variation with forest cover polygons. Highest likelihood values are found at ridgetops while lowest values are found at lower elevation sites, particularly under forest cover.

Assessing collar performance from collared animals

GPS collars received a varying number of animal locations, ranging from 379 to 940 over approximately an 8-month period (Table 6). Percentages of GPS locations that were successfully fixed ranged widely between collared animals. The lowest Percentage Overall Fix Success was 23.5%, while the highest was 62.0%. A relatively low number of fixes fell within the highest accuracy fix class (Percentage 3D Fix Success). The lowest Percentage 3D Fix Success was 5.4% while the highest was 12.9%.

Table 6. Number of GPS collar fix attempts and Percentage Fix Success (Overall and 3D) for 4 collared mountain goats. Percentages of fix success are calculated from total fix attempts per individual. Means are calculated from each individual animal's fix success.

Collared animal	Total # fixes	Total # fix attempts	Percentage Overall Fix Success	Total # 3D fixes	Percentage 3D Fix Success
Male #1	379	1616	23.5	87	5.4
Male #2	901	1508	59.8	189	12.5
Female #1	940	1517	62.0	195	12.9
Female #2	579	1561	37.1	123	7.9
Average			45.6		9.7

A wide range of fix performances was observed among collared goats and among seasons (Figure 8). Percentage 3D Fix Success was especially low during Winter and Spring. The lowest Percentage Overall Fix Success was observed for Male #1 during Spring and Winter (20.8% and 17.4% respectively). Percentage 3D Fix Success for this collared animal was only 2.0% during Spring and 4.4% during Winter. The highest Percentage Overall Fix Success was 74.6% for Male #2 during Fall. Percentage 3D Fix Success in the same period for this animal was 23.6%. Fall consistently showed greater Percentage 3D Fix Success relative to the 2 other seasons. For Male #1 and Female #2, which showed the largest Percentage Failures (unsuccessful fix attempts), highest failure rates were observed during Winter. The 2 other animals showed slightly higher failure rates within Spring followed by Winter.

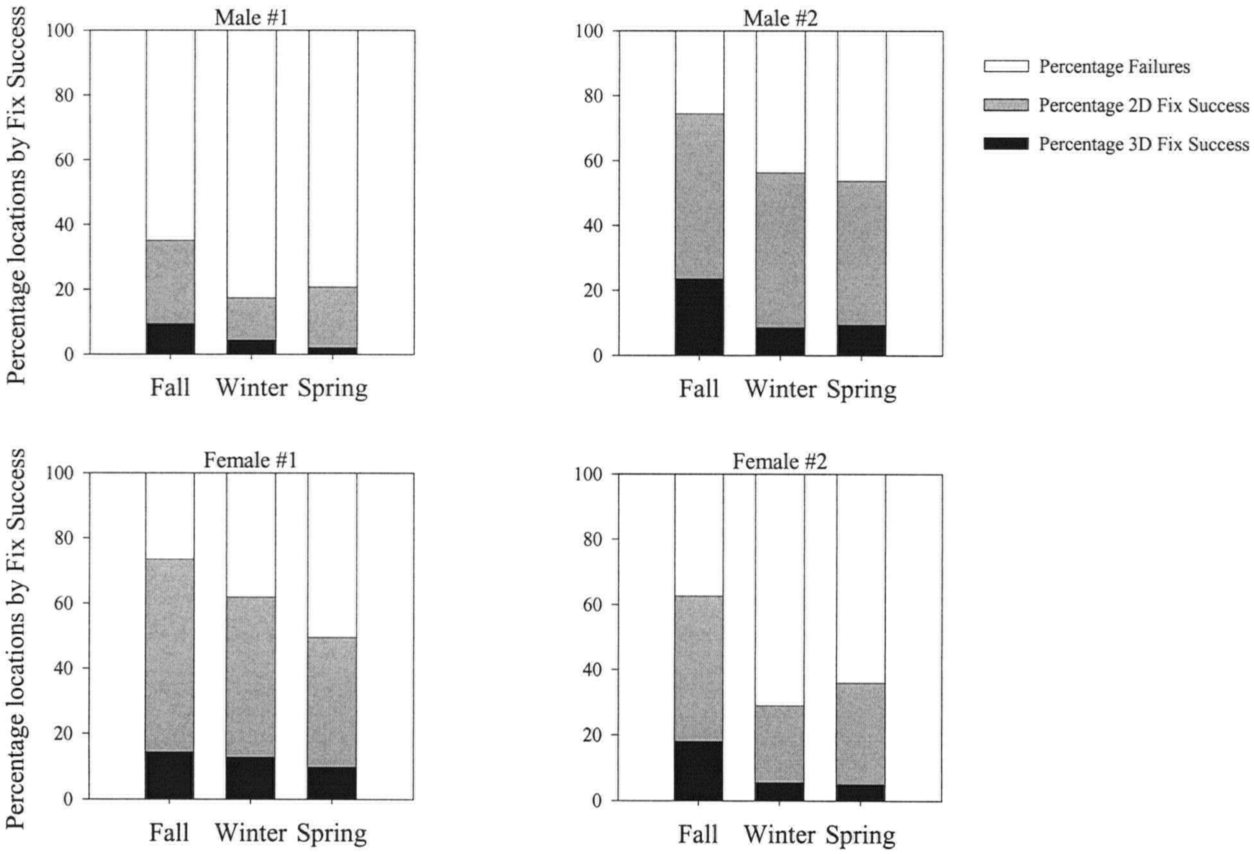

Figure 8. Seasonal comparisons of Percentage Failures, Percentage 2D Fix Success, and Percentage 3D Fix Success received from each collared goat over an 8-month period.

Consistently higher Percentage 3D Fix Success and Percentage Overall Fix Success was received during Fall compared to Winter (Figure 9). Significant differences between Fall and Winter Percentage 3D Fix Success were observed for Male #2 and Female #2 (2-tailed Fisher exact test, P=0.006, 0.007, respectively). Significant differences in seasonal Percentage Overall Fix Success were observed for Male #1 and #2, and Female #2 (2-tailed Fisher exact test, P=0.006, 0.01, <0.0001 respectively). Mean Percentage 3D Fix Success increased 10.1% from Winter to Fall, and the average increase for Percentage Overall Fix Success from Winter to Fall was 20.1%.

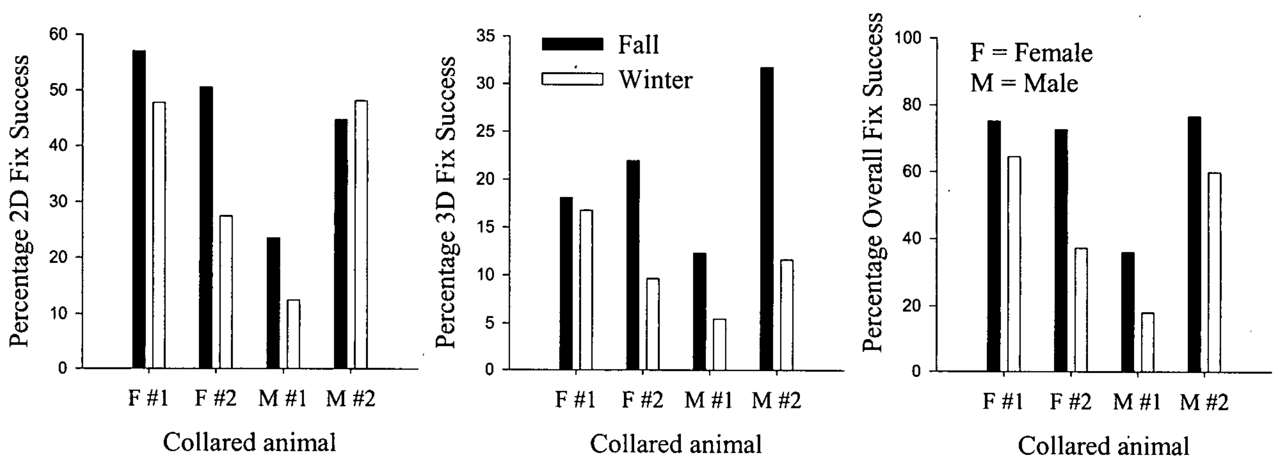

Figure 9. Comparison between Fall and Winter Percentage Fix Success .

These observed differences in seasonal fix success could be caused by differential goat habitat use during each season. For example, Fall ranges associated with higher Percentage 3D Fix Success grid cells were at relatively higher elevations where GPS signal reception is facilitated by lower canopy cover and less topographical constraint. However, the relatively low Percentage 3D Fix Success values for Winter could also be caused by unmeasured factors associated with the season itself. For example, low temperatures and winter snow accumulation in canopy could decrease signal reception.

Analysis of GPS fix predictions

Comparison of seasonal predictions

By matching goat locations with predicted values of Percentage 3D Fix Success, I could compare mean Percentage 3D Fix Likelihood from Fall and Winter ranges. For each of the 3 animals tested, the uncorrected Percentage 3D Fix Likelihood values were significantly greater during Fall compared to Winter (Wilcoxon 2-sample tests, Male #1, $P<0.0001$; Male #2, $P<0.0001$; Female #1, $P=0.006$). Therefore, differences in Predicted 3D Fix Likelihood appear to be sufficient in explaining differences between Fall and Winter Percentage 3D Fix Success from collared animals.

Observation bias was evident from stationary-collar field testing, from predictions of animals' seasonal ranges, and from collared goats. Ultimately, I would like to correct this bias to determine if habitat-selection interpretation is affected. To validly correct for location bias, I must accurately predict the fix success of both stationary collars and collared animals.

Correspondence of fix likelihood with goat collar fix success

I observed a moderately high correlation between Percentage 3D Fix Likelihood and the observed Percentage 3D Fix Success for goats during all seasons (Figure 10). Percentage 3D Fix Likelihood accounted for 60% of the variability in Percentage 3D Fix Success ($R^2 = 0.60$, $P = 0.01$). For the 9 animal seasons, observed values were consistently less than those predicted by the stationary ground-truthing collars. The overall difference between the predicted and observed 3D fix success was 25.8% (SE=2.3). The differences of fit ranged from 13.7% to 37.7%.

The correspondence between the observed and expected fix success was not significantly different for any of the 3 goats (Kruskal-Wallis test, P=0.67, Figure 11). However, a trend was observed for winter seasons to correspond more closely to predictions relative to other seasons (Kruskal-Wallis test, P=0.06, Figure 12).

Habitat-selection analysis

Forest availability

The determination of landscape forest availability depended largely on the scale of analysis (Figure 13). In the study area 8.5% of the land area was forested, whereas 27.0% of the landscape was forested at the home range scale for the 3 goats tested for habitat selection.

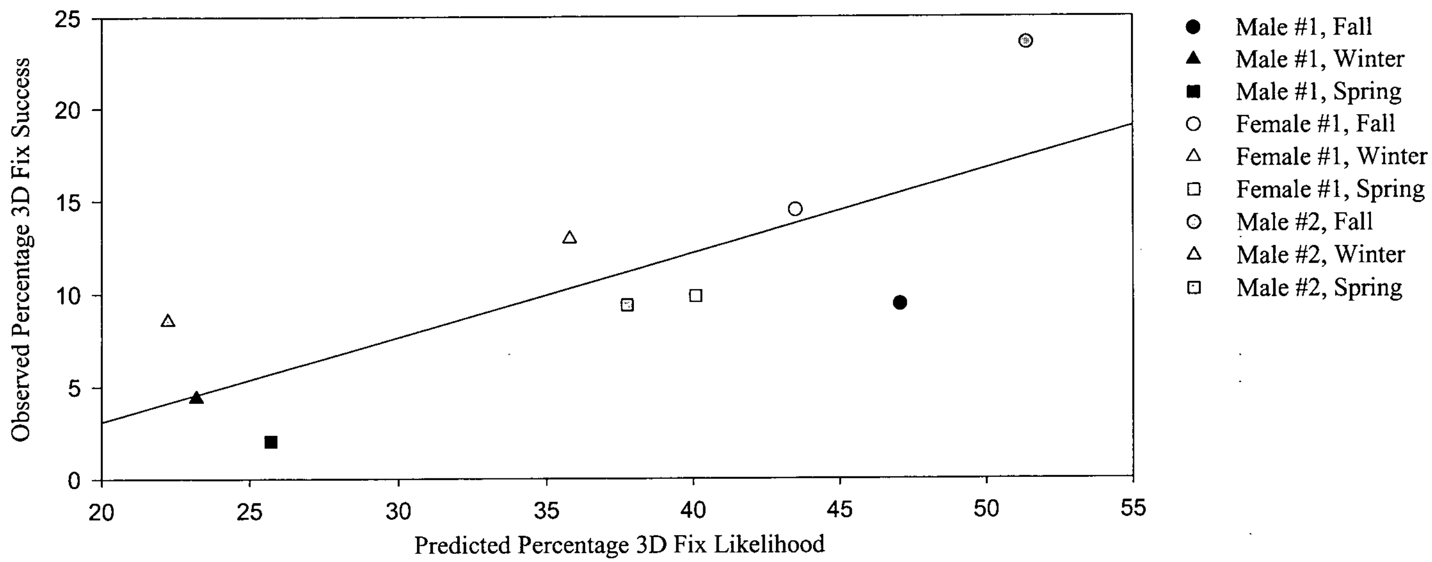

Figure 10. Correlation between seasonal mean Percentage 3D Fix Likelihood and Percentage 3D Fix Success for 3 collared mountain goats.

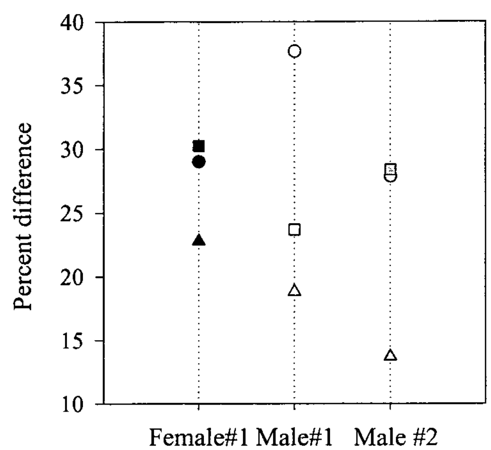

Figure 11. Collar comparison of correspondence between Percentage 3D Fix Likelihood and Percentage 3D Fix Success for 3 collared goats.

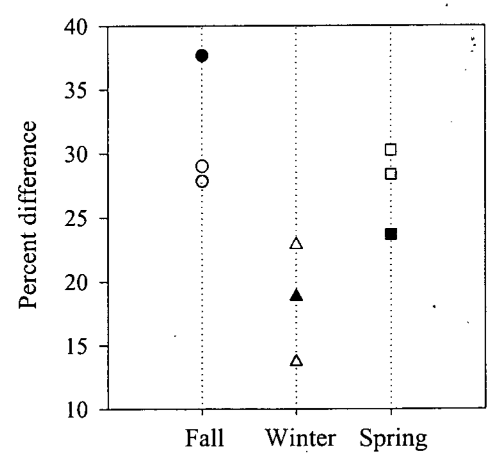

Figure 12. Seasonal comparison of correspondence between Percentage 3D Fix Likelihood and Percentage 3D Fix Success for 3 collared goats.

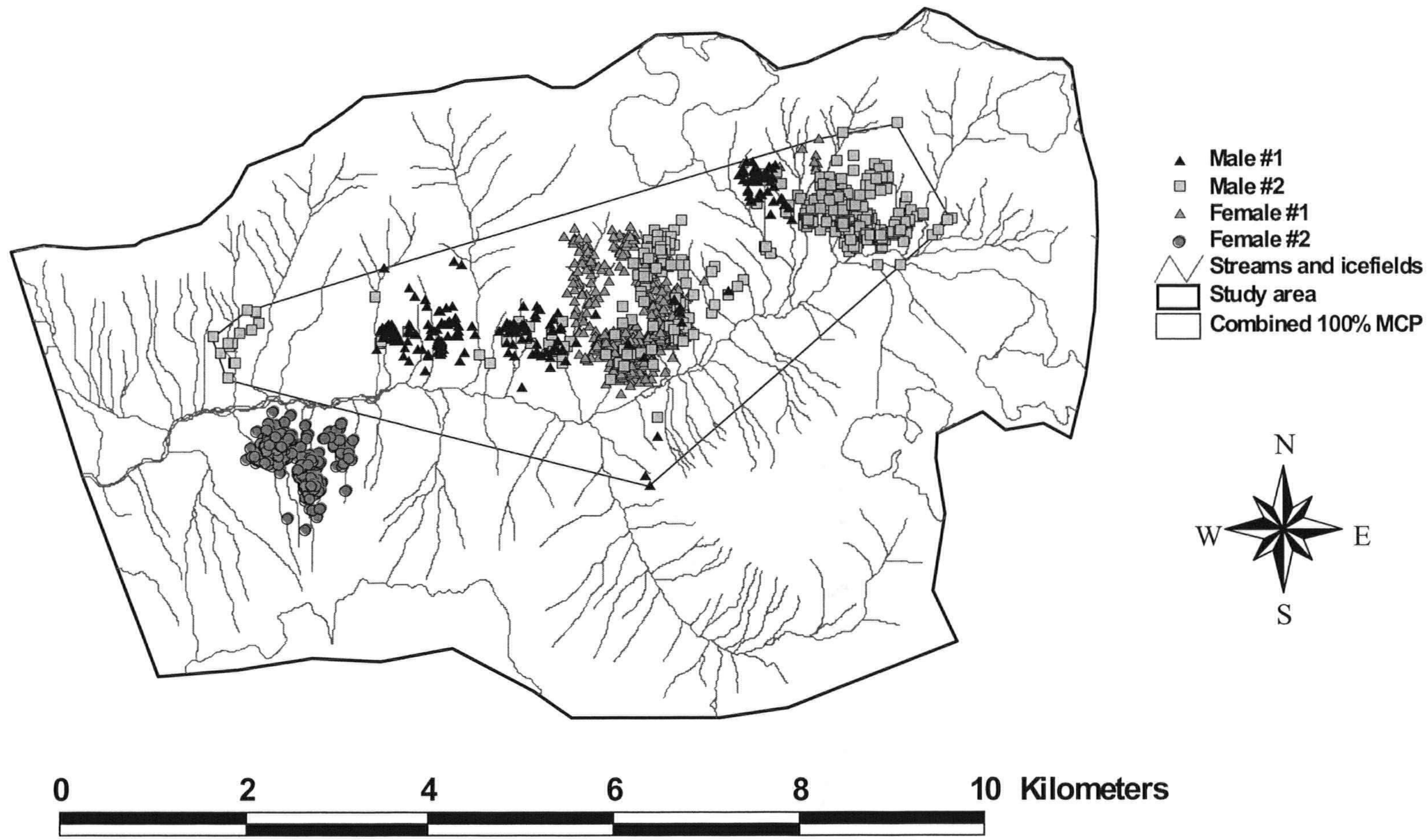

Figure 13. Two boundaries for determining forest availability and goat habitat selection within the home range (based on 100% MCP annual range of 3 mountain goats) and within the study area. Female #2 was not included in analysis because of forest cover deficiency. All locations were filtered for DOP values.

Effects of correction and fix class choice on measurements of habitat selection

Selection results varied according to the type of fix class data used and varied between corrected and uncorrected GPS data (Figure 14). The influence of data correction on interpretation of habitat selection was relatively greater than the influence of using 2D combined with 3D data versus data filtered only for 3D locations.

In 7 of 9 cases, the estimated percentage of forest use by goats decreased with the omission of 2D data. An average decrease of 3.7% was observed when only the 3D data fix class was used for selection determination. In 3 of 18 cases of selection, significant results became non-significant with the omission of 2D data. In the case of Female #2, a significant selection for forest within the study area during Spring changed to an amount of forest used that was less than availability although non-significant (Figure 14A). Changes in 3D data significance may be related to smaller sample sizes, however, the magnitudes of difference for forest use, estimated by different fix classes, are still valid.

A larger change in apparent habitat selection was observed when corrected and uncorrected 3D data were compared. For every animal, and during each season, the correction GPS-observation bias increased the estimation of seasonal forest habitat use. An average increase of 15.8% was observed when the likelihood correction factor was applied. In 10 of 18 cases, selection that was originally significant became non-significant, or vice-versa. In 4 cases, use changed from a significant forest preference or avoidance, and showed an opposite but non-significant change in selectivity. In 1 of these 4 cases, for Female #2 within her home range during winter, use changed from significantly lower to significantly greater forest use compared to availability (Figure 14B).

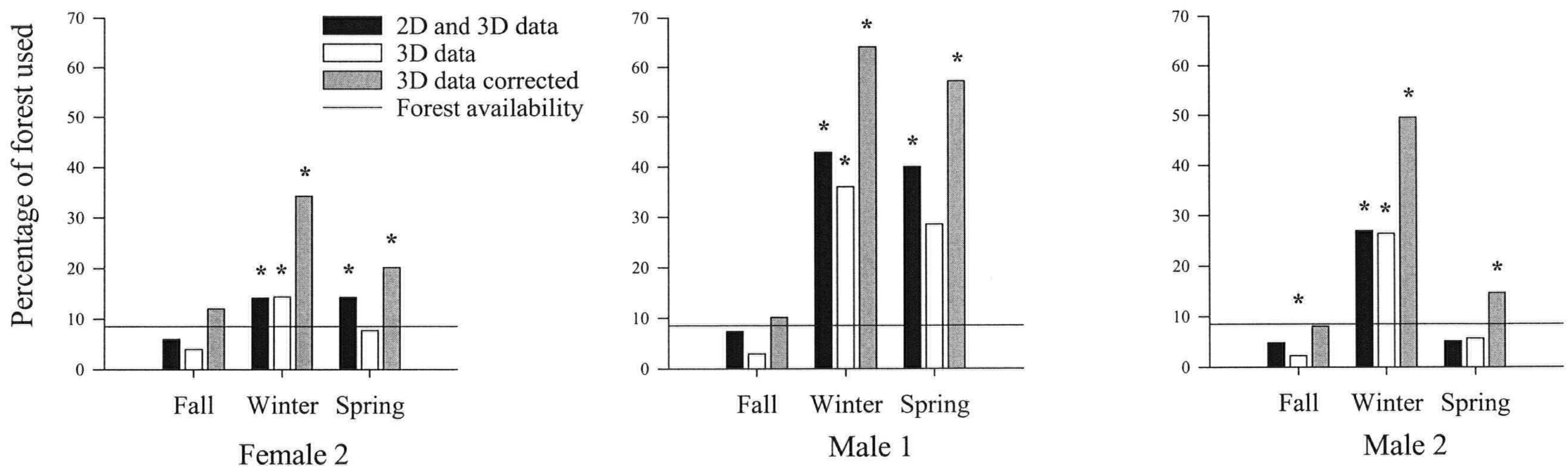

Figure 14A. Effects of correction and GPS fix-class choice on measurements of mountain goat habitat selection within the study area. * = significant difference relative to forest availability.

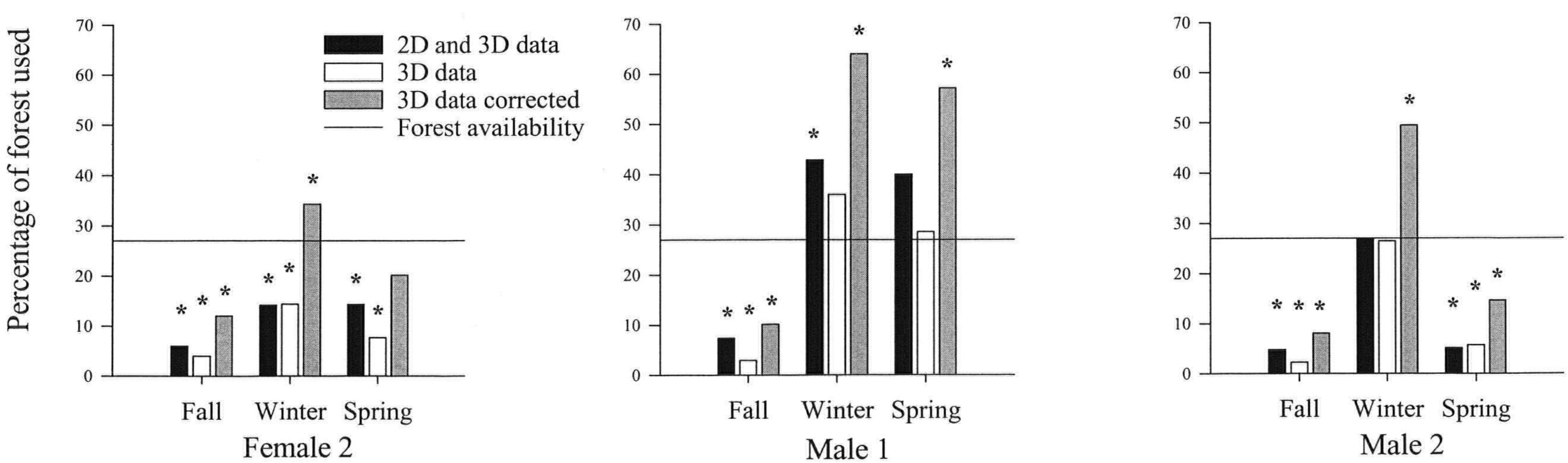

Figure 14B. Effects of correction and GPS fix-class choice on measurements of mountain goat habitat selection within the home range. * = significant difference relative to forest availability.

Summary of seasonal forest selection by goats

Results of forest selection by season were very consistent for each of the 3 goats measured (Figure 15). In fact, except for Spring selection at the home range scale (Figure 15A), each animal showed the same selection result at each scale and during each season. At both scales analysed, each goat significantly selected forest habitat during Winter.

At the home range scale of selection during Fall (Figure 15A), goats used forest habitat significantly less than availability. Goats differed in selection of forest use during Spring; Male #1 preferred forest, Male #2 avoided forest, and Female #2 used forest equal to its availability.

In selection of individual seasonal ranges, all 3 goats used forest habitat in greater proportion to its availability during Spring. At this study-area scale, use of forest was equal to availability during Fall (Figure 15B).

Some of the seasonal ranges determined for collared goats showed very concentrated habitat use and were relatively distinct from one another (Figure 16). Female #2 used an especially small area approximately 300 m wide during the kidding season (Figure 16). The home-range area for this female was only 2.9 ha when estimated by 50% adaptive kernel, and 27.7 ha when calculated with a 95% adaptive kernel.

Although my sample size is very small, females used smaller home ranges than males (n=2, Figure 17). The average male home-range area as estimated by 95% adaptive kernel, was greater than 5 times as large as that of the average female range.

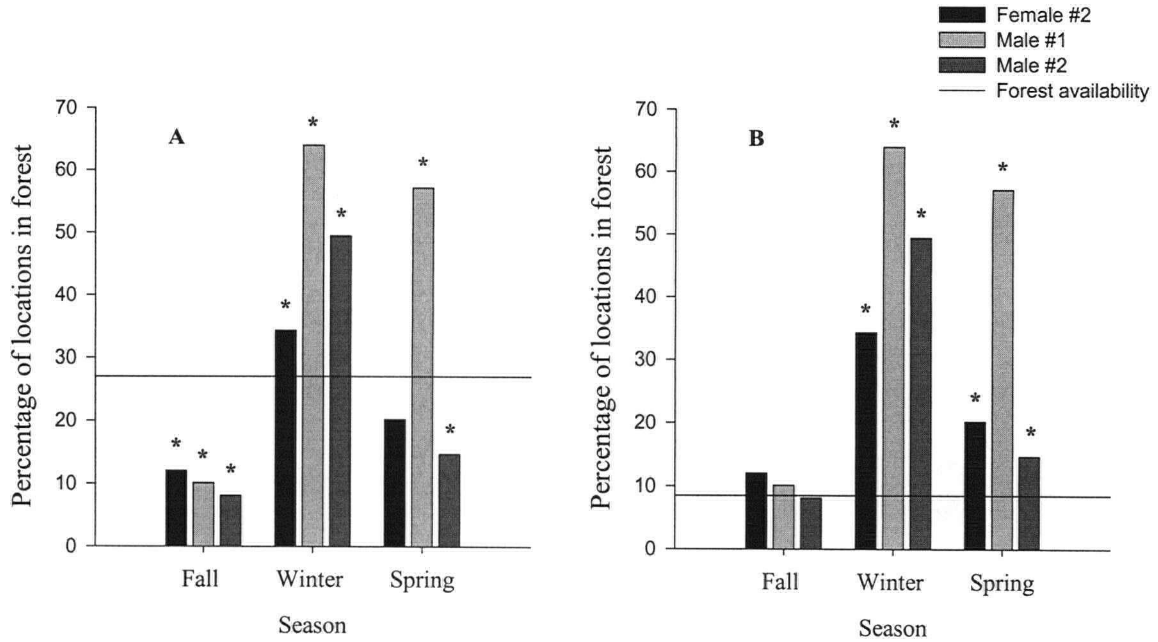

Figure 15. Summary of seasonal forest selection by 3 mountain goats. All selection data are corrected 3D data. A = forest selection at the home range scale. B = forest selection at the study area scale.

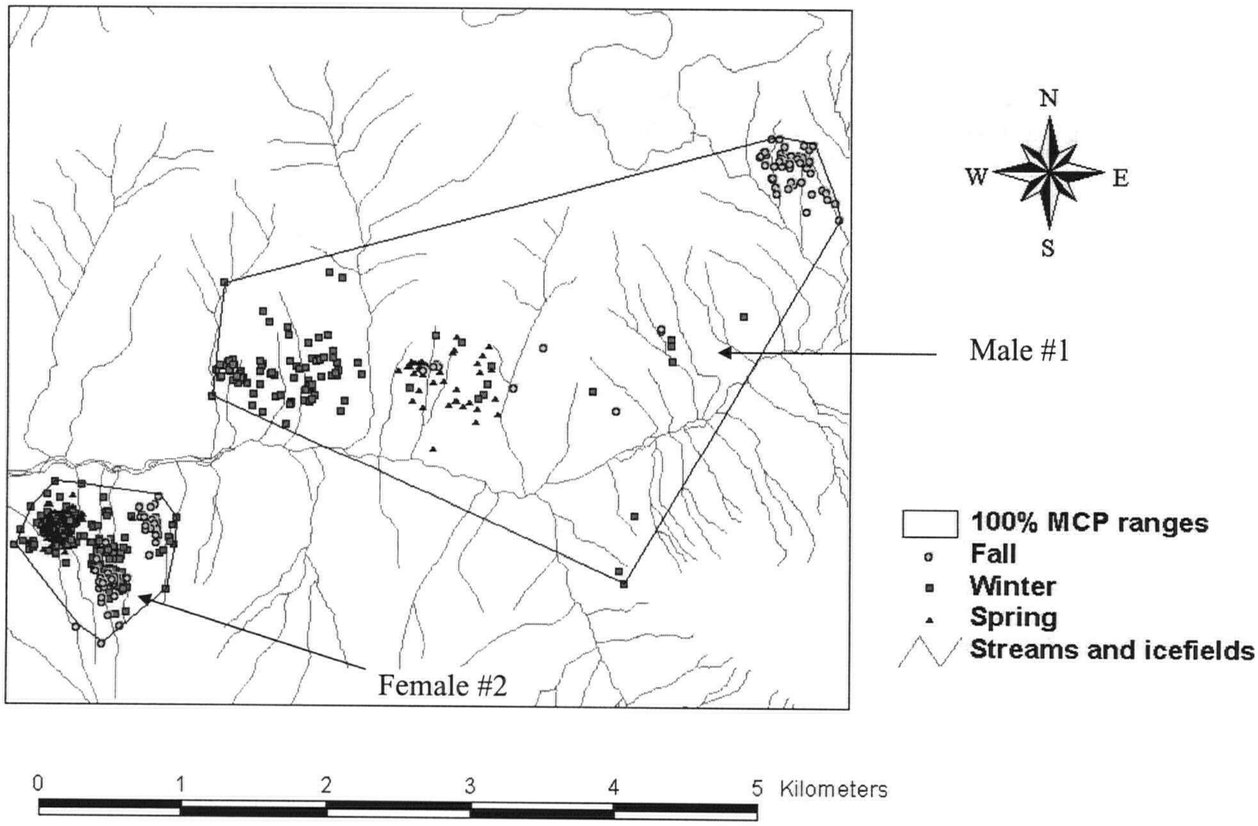

Figure 16. An example of the distinct seasonal habitat-use differences for collared mountain goats. Locations for Male #1 and Female #2 have been filtered for DOP values. Annual ranges are drawn as 100% MCP for viewing convenience.

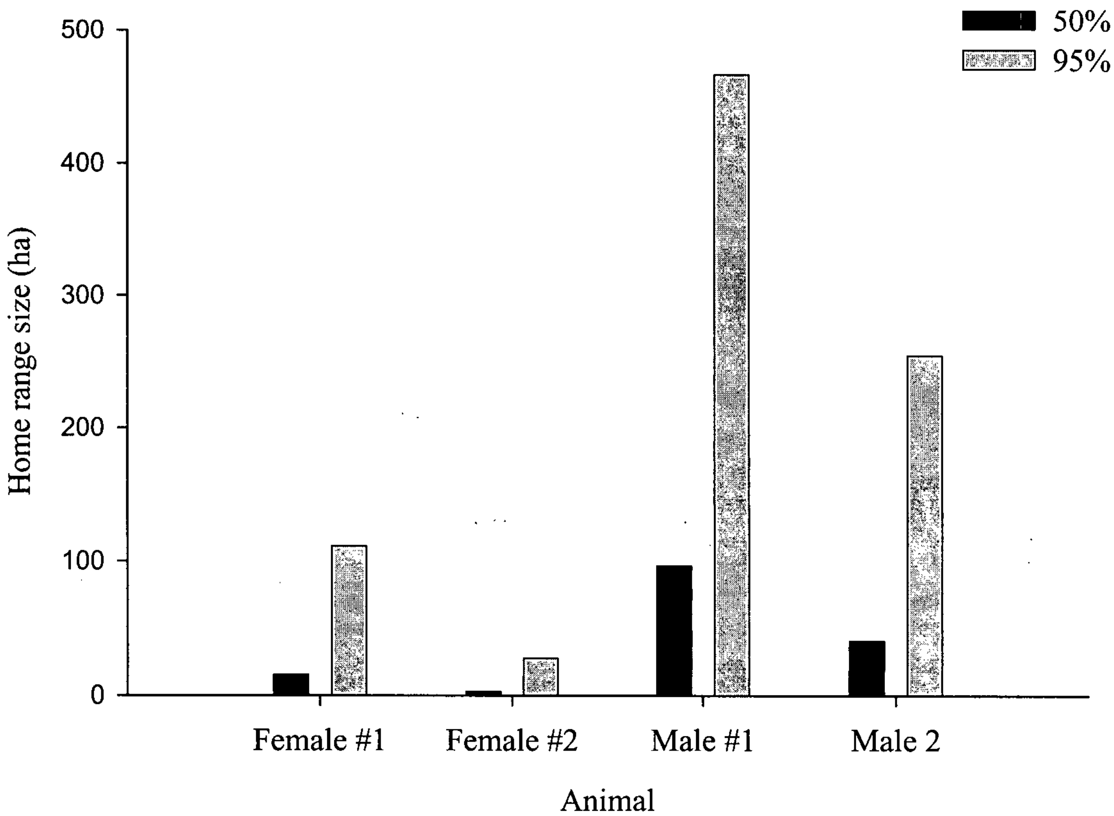

Figure 17. Comparison of home range size for female and male mountain goats. Home range size was calculated using 50% and 95% adaptive kernels from locations received over approximately 8 months during Fall, Winter and Spring.

DISCUSSION

GPS observation bias

I combined multiple regressions derived from collar field tests with a GIS analysis of Stafford River to predict the Percentage 3D Fix Likelihood for collared mountain goats. I then verified these predictions by observing Percentage 3D Fix Success for the same animals. My results confirmed the presence of observation bias both from my field testing of GPS collars and from observations of collared mountain goats.

This study is the first to show that topography alone can significantly affect GPS fix success in some environments. From multiple regression equations, I found that Topex was the single best explanatory variable in predicting Percentage 3D Fix Success, accounting for 39% of variability. Measures of canopy closure were the next most important predictor variables, particularly PCG (percentage of canopy gap). Both Topex and PCG were more important in explaining fix-success variability than were either Height or Volume/ha. Although several researchers found tree height to be the most important variable in determining fix success in forests (Rempel and Rodgers 1997, Dussault *et al.* 1999), data from my test environments did not support this finding. Fix success was redcued by increase in Height alone, but was better predicted by other variable complements.

Among categories of forest class and valley width, field testing showed weak trends related to hypotheses of Percentage 3D Fix Success. I expected relatively high variability among these categories because of the multivariate nature of the independent variables (Clark *et al.* 1993). Consistent with my hypothesis, a weak trend was observed for wider valleys to receive greater fix success. Contrary to other studies (Rempel *et al.* 1995, Rodgers *et al.* 1996, Dussault *et al.* 1999), shorter forest classes often received lower overall fix success relative to taller classes. This difference may be related to the dense, second-growth canopy found within my Short forest category.

Bias was also observed when comparing the Percentage 3D Fix Likelihood amongst the goats' seasonal ranges. For each goat, the mean Percentage 3D Fix Likelihood within its Fall locations was greater than that from Winter locations. Other studies have observed that collared animals receive relatively greater overall fix success during winter (Edenius 1997, Dussault *et al.* 2001). The difference is likely attributable to animal behaviour in relation to habitat. For example, the previous studies observed animals within deciduous forests; a forest type that is lower in crown closure during winter. In my study area, goats used coniferous forest habitat more frequently in Winter than in Fall. These differences in seasonal prediction rates were also confirmed by collared animal data. Percentage 3D Fix Success showed a trend similar to that exhibited by seasonal Percentage 3D Fix Likelihood as it was also higher for collared goats during Fall compared to Winter.

Consequences of observation bias for habitat selection

I validated my fix-success predictions by observing the fix success of collared animals. I then evaluated the consequences of bias for habitat-selection interpretations. The most important finding from this thesis is that failure to account for observation bias can lead to significant misinterpretations of habitat-selection data. From comparisons of corrected and uncorrected 3D data, significant relationships can be obscured or enhanced. Without correction of 3D data, significant results can be obtained opposite to what animals are actually selecting. Some uncorrected 3D GPS data showed goat avoidance of forest, whereas the same data corrected for observation bias showed significant goat preference for forest.

I observed interpretation differences when analysing habitat selection at both the seasonal-range and study-area scales. Uncorrected GPS habitat-selection analyses can be in error at various scales, especially for studies where animals in mountains use both forested and non-forested habitats, or where animals are within relatively heterogeneous landscapes. Habitat-patch size influences a researcher's ability to accurately interpret animal selection because the power of habitat-selection analyses decreases with increasing habitat complexity and with decreasing telemetry precision (White and Garrott 1986). If the scale of precision for data derived from GPS is larger than the scale of habitat patches, then errors in assessing habitat selection are more likely to occur. In landscapes where habitat patches are large and change little over distance, errors in assessments would be greatly diminished.

A general model could be developed in which the ratio of average patch size to GPS precision describes the likelihood of habitat-analysis misinterpretation. For example, a landscape with small average patch sizes relative to GPS error would have a high likelihood for selection misinterpretation. For studies where habitat complexity is deemed problematic, such a model could suggest an appropriate level of resolution for describing a habitat patch (e.g., finely detailed habitat polygons could be aggregated into larger, more general habitat polygons until likelihood of misinterpretation was lower).

Because topography and vegetation can reduce the relative number of acquired satellite signals, both accuracy and degree of bias can be affected. For this reason, open-habitat use by an animal can be overestimated in two different ways where patch sizes are small. As previously described, an open-habitat is more likely to receive satellite signals and therefore obtain a fix, however, forested habitats can also receive less precise locations compared to non-forested habitats. Therefore, where forested patches are small and adjacent to open patches, the proportion of estimated forest use can again be underestimated.

Although precision and observation bias are therefore both important issues in GPS selection studies, observation bias may be more consequential. As accuracy improves with digital mapping standards - e.g., new TRIM II mapping (BMGS 2002) - and GPS technological advance (Lawler 2000, Hulbert 2001), observation bias will increase in relative importance to habitat studies until GPS units obtain fixes independent of habitat. GPS collars routinely acquire large datasets, and low precision can be statistically less influential as sample size increases (White and Garrott 1986, Samuel and Kenow 1992), but this is not true for the issue of observation bias.

D'Eon *et al.* *(in press)* suggested the possibility of using only 3D data to increase location accuracy, yet acknowledge that doing so could lead to further biases. I suggest that the removal of 2D data from analyses will result in an underestimated proportion of habitats within which satellite signals are more difficult to receive. This problem can be overcome using correction methods, but, for studies in mountainous terrain that receive relatively low fix rates, rarely-used yet important habitats still could be overlooked. In the case that 3D data alone is analysed, the exclusion of 2D data certainly increases the importance of correcting for observation bias because the magnitude and consequence of bias is exaggerated.

Matching predictions and observations of GPS fix success

To correct habitat results, I needed to validate my fix likelihood predictions. Although the predictability of estimating fix success for stationary collars was high, the fix-likelihood predictions for collared animals could have been inaccurate for a number of reasons. Sources of error in predicting fix success for collared animals could include GIS mapping error, the possibility that multiple regression equations predict fix likelihood poorly within certain habitats, and variation in fix success due to animal behaviour within different habitats. I therefore linked the spatial predictions of Percentage 3D Fix Likelihood to observations of Percentage 3D Fix Success from collared animals. This validation process led to some interesting observations related to fix success versus fix likelihood, and to collar and seasonal differences.

The significant correlation which I observed between mean Percentage 3D Fix Likelihood and the mean Percentage 3D Fix Success showed that the relative fix success per seasonal home range could be well predicted by topography and vegetation. This supported the validity of applying correction factors to biased collar data before interpreting habitat-selection data.

Although seasonal Percentage 3D Fix Likelihood values were significantly correlated with seasonal Percentage 3D Fix Success values, the regression equations did not accurately predict absolute percentages of Percentage 3D Fix Success. Within seasonal home ranges, Percentage 3D Fix Success was consistently less than Percentage 3D Fix Likelihood; on average 25.8% lower. This trend was expected for a number of reasons. First, animal movement might decrease the probability of acquiring a GPS fix (Edenius 1997, Bowman *et al.* 2000), whereas my tests used stationary collars. Other studies have found that location success decreased with lower temperatures (Dussault *et al.* 1999), and when animals were bedded (Moen *et al.* 1996, Bowman *et al.* 2000). Within the Stafford River, GPS fix success could be affected by micro-topographical features such as overhanging rock walls and caves. I often observed mountain goats beneath such features surrounded by dense *krummholtz* or other vegetation. Finally, heavy snowfall within tree canopy could have decreased fix success (Janeau *et al.* 2001).

It is reasonable to expect that collared individuals of the same species within similar habitats should experience relatively similar GPS fix success; my results do not support this. Observed seasonal fix-success percentages varied widely among individuals, and seasonal fix likelihood values similarly varied widely. However, the correspondence between the observed and expected fix success was not significantly different for any of the 3 collars. From this limited sample size, despite the large variation in observed fix success, no collar significantly under-performed in its ability to acquire fix locations relative to expectations. Individual GPS collars with poor ability to receive fixes have been reported anecdotally (C. Kochanny, Advanced Telemetry Systems, personal communication) but researchers should not assume that a low fix success represent malfunctions. Estimation of "proper" collar performance should be based upon GIS estimation of GPS fix likelihood.

I analysed collared-animal data for differential fix success per season, and observed differences relative to prediction rates. Absolute fix success was lower in Winter than in Fall, likely because goats used greater amounts of forest. However, the correspondence between Percentage 3D Fix Likelihood and Percentage Fix Success was higher during Winter compared to Fall. This result is interesting and the opposite might be expected because more snow in the canopy during winter could have decreased the actual fix success. In fact, Dussault *et al.* (1999) observed greater absolute fix success during winter tests relative to summer despite snow in the canopy and suggested that low-humidity atmospheric conditions during winter might be the explanation. This environmental condition is not expected within my coastal study area.

Although I observed greater fix success relative to fix likelihood during winter, this could be indirectly associated with seasonal factors. Predicted fix percentages within Spring and Fall seasonal ranges could be artificially inflated because some marginal tree cover and vegetation present in the study area is likely absent from forest cover mapping. My fix success tests were in clearcut sites without vegetation present above the fixed-collar test locations and thus regression equations could overestimate the likelihood of receiving fixes within non-winter ranges. Further seasonal GPS work would be helpful in improving understanding of GPS-collar fix success.

General collar performance

The mean Percentage Overall Fix Success (45.6% for all collars combined) that I observed for collared coastal goats are lower than those reported for other species within different topographic environments. Moderately-high Percentage Overall Fix Success was found for elk in plateau and mountain environments of New Mexico (69%; Biggs *et al.* 2001), for mountain goats in the mountainous terrain of the British Columbia interior (76%; Poole and Heard 2001), and for moose (*Alces alces*) in rolling hills in Quebec (70.2%; Dussault *et al.* 2001). Lower fix success in my study area was expected to some degree because of the narrow width and high topographical relief of the coastal Stafford River valley.

Comparisons of fix success among studies are difficult to interpret because of the multiple factors involved, including differences in vegetation and topographical relief, collar make and year, and collar fix schedule. For example, different collars are programmed to attempt fixes for various periods of time, and will sometimes be programmed to make multiple fix attempts after initial failures.

Although the proportion of successful fixes was low relative to more recent studies, the number of successful fixes I found is relatively high considering the potential disturbance costs associated with an equivalent number of fixes obtained from aerial telemetry techniques. As well, fixes were obtained under conditions when conventional aerial telemetry is impossible (e.g., at night or during storms). Observation bias is a distinct problem resulting from the fix environment in mountains but it can ultimately be corrected. However, aside from this issue, the performance of GPS appears well suited for studying mountain goat habitat use.

Mountain goat observations

Habitat selection

Results from analyses of 3 mountain goats are insufficient to generalise for forest management; however, the consistency of results among them is interesting. In selecting seasonal ranges, goats overwhelmingly chose forest over non-forested habitat during Winter, and also chose forested habitat during Spring. Within the seasonal home ranges, goats significantly selected forested habitat during Winter. In Fall, each goat used forest significantly less than its availability. During spring a mixture of selection preferences were observed. One male used forest habitat twice the proportion of its availability, while the other male and female used significantly less forest than was available.

Other reports related to mountain goat natal range support varying habitat selectivity by goats during Spring. Groups of adult females and young appear to vary in their use of elevation and habitat in relation to winter ranges. Common areas where multiple females give birth are generally not observed (Foster 1982, Lemke 1999), but females give birth at isolated patches of escape terrain before rejoining others after a few days (McFetridge 1977, Côté and Festa-Bianchet 2001). Adult females with young have been observed during spring near low-elevation winter ranges (D. Jury, Ministry of Environment, Lands and Parks, S. Gordon, Ministry of Sustainable Resource Management, personal communications, this study), while other female groups have been observed closer to summer ranges (Stevens 1983). Animals in these groups can show high site fidelity from year to year (Joslin 1986, Côté and Festa-Bianchet 2001) but it may be that groups and individuals show more behavioural plasticity during spring relative to other seasons. Perhaps differing availability of local escape terrain needed for predator avoidance (Fox and Taber 1981, Foster 1982, Fox 1983) affects goats' spring preferences.

RECOMMENDATIONS FOR GPS WILDLIFE-DATA ANALYSIS

For purposes other than describing home range, in areas of high topographical relief and using only 3D data, GPS wildlife habitat studies must correct data for GPS-observation bias. Differing GPS fix likelihoods can create observation bias of consequence at multiple scales of habitat analysis. Even for studies within narrow ranges of topographical relief, correction may be necessary to obtain unbiased results. This should be especially true for studies in which animals use both forested and non-forested habitats. The consequences of failing to correct data will vary between study areas depending on the variability of topography and vegetation and the relative patch size of habitat types. GPS tests within a study animal's expected habitats should always be made. Studies that attempt to estimate proportional habitat use or selection without addressing and correcting for bias where necessary, risk making false interpretations.

The exclusion of 2D data is certainly not recommended, but if GPS studies do use these data to increase accuracy, observation-bias correction is absolutely critical. This recommendation is likely applicable to all GPS studies, not only those conducted in mountainous environments.

Before determining habitat selection from GPS data, a valid approach would be to apply a filter for desired DOP to location values of all fix classes. The remaining data could then be corrected based on an overall fix regression model. An effective technique to correct for GPS-observation bias could be to combine the process of GPS fix-likelihood estimation for each animal location, as performed here, with a probability detection function. The detection function could then be used within a resource selection function (RSF) model to apply contribution weightings of fix likelihood for all locations.

LITERATURE CITED

Biggs, J. R., K. D. Bennett, and P. R. Fresquez. 2001. Relationship between home range characteristics and the probability of obtaining successful Global Postioning System (GPS) collar positions for elk in New Mexico. West. N. Am. Naturalist 61:213-222.

BMGS (British Columbia Base Mapping and Geomatic Services Branch), Ministry of Sustainable Resource Management. 2002. Policies and specificiations for TRIM II. Revision Data Capture. http://home.gdbc.gov.bc.ca/TRIM/TRIM/trm2spcs/trm2spcs.pdf.

Bowman, J. L., C. O. Kochanny, S. Demarais, and B. D. Leopold. 2000. Evaluation of a GPS collar for white-tailed deer. Wildl. Soc. Bull. 28:141-145.

Brandborg, S. M. 1955. Life history and management of the mountain goat in Idaho. Idaho Dep. Fish and Game Wildl. Bull. 2:142.

Brunt, K. Wildlife Biologist, B. C. Ministry of Water, Land and Air Protection, Nanaimo, B. C. Personal communication, June, 2001.

Clark, J. D., J. E. Dunn, and K. G. Smith. 1993. A multivariate model of female black bear habitat use for a geographic information system. J. Wildl. Manage. 57:519-526.

Côté, S. D. 1996. Mountain Goat responses to helicopter disturbance. Wildl. Soc. Bull. 24:681-685.

Côté, S. D., and M. Festa-Bianchet. 2001. Birthdate, mass and survival in mountain goat kids: effects of maternal characteristics and forage quality. Oecologia 127:230-238.

Demarchi, M. W., and F. L. Bunnell. 1995. Forest cover selection and activity of cow moose in summer. Acta Theriologica 40:23-36.

Demarchi, M. W., S. R. Johnson, and G.F. Searing. 2000. Distribution and abundance of mountain goats, *Oreamnos americanus*, in westcentral British Columbia. Can. Field-Nat. 114:301-306.

Demers, M. N. 2000. Fundamentals of Geographic Information Systems, 2nd edition. New Mexico State University and John Wiley & Sons, Inc., New York.

D'Eon, R. G., R. Serrouya, G. Smith, and C. Kochanny. *In press*. GPS radiotelemetry error and bias in mountainous terrain. Wildl. Soc. Bull.

Dussault, C., R. Courtois, J.-P. Ouellet, and J. Huot. 1999. Evaluation of GPS telemetry collar performance for habitat studies in the boreal forest. Wildl. Soc. Bull. 27:965-972.

Dussault, C., R. Courtois, J.-P. Ouellet, and J. Huot. 2001. Influence of satellite geometry and differential correction on GPS location accuracy. Wildl. Soc. Bull. 29:171-179.

Dyer, S. J., J. P. O'Neill, S. M. Wasel, and S. Boutin. 2001. Avoidance of industrial development by woodland caribou. J. Wildl. Manage. 65:531-542.

Edenius, L. 1997. Field test of a GPS location system for moose *Alces alces* under Scandinavian boreal conditions. Wildl. Biol. 3:39-43.

Foster, B. R. 1982. Observability and habitat characteristics of mountain goats (*Oreamnos americanus*, *Blainville*, 1816) in west-central British Columbia. M.Sc. Thesis. UBC, Vancouver, B. C. 134 pp.

Fox, J. L. 1983. Constraints on winter habitat selection by the mountain goat (*Oreamnos americanus*) in Alaska. Ph.D. Dissertation. University of Washington, Seattle. 147 pp.

Fox, J. L., and R. D. Taber. 1981. Site selection by mountain goats wintering in forest habitat. Final Report. Coop. Agreement No. FS-PNW-#153. University of Washington, Seattle.

Gamo, R., R. Scott, M. A.Rumble, F. Lindzey, and M. Stefanich. 2000. GPS radio collar 3D performance as influenced by forest structure and topography. J. H. Eiler, D. J. Alcorn, M. R. Neuman (eds.) *In* 15th International Symposium on Biotelemetry. Wageningen, The Netherlands. 15:464-473.

Geist, V. 1964. On the rutting behavior of the mountain goat. J. Mammal. 45:551-568.

Gordon, S. M. Forest Ecosystem Specialist, B. C. Ministry of Sustainable Resource Management, Powell River, B. C. July, 2002.

Gordon, S. M., and D. M. Reynolds. 2000. Mountain goat winter range habitat identification, helicopter disturbance and management in the Sunshine Coast. Working report for B. C. Ministry of Environment, Lands and Parks, Lower Mainland Region.

Gyulay, A. Technical support, Lotek Wireless communications, Personal communication, June 5, 2002.

Haller, R., F. Filli, and S. Imfeld. 2001. Evaluation of GPS-technology for tracking mountain ungulates: VHF-transmitters or GPS-collars? A. M. Sibbald, I. J. Gordon (eds.) *In* Proceedings of the conference "Tracking animals with GPS". The Macaulay Institute, Aberdeen. pp. 61-66.

Hebert, D. M., and W. G. Turnbull. 1977. A description of southern interior and coastal mountain goat ecotypes in British Columbia *In* Proc. First Internl. Mountain Goat Symp. 1:126-146.

Hooge, P. N., W. M. Eichenlaub, and E. K. Solomon. 2002. Using GIS to analyze animal movements in the marine environment. http://www.absc.usgs.gov/glba/gistools/Anim_Mov_UseMe.pdf.

Hulbert, I. A. R. 2001. GPS and its use in telemetry: the next five years A. M. Sibbald, I. J. Gordon (eds.) *In* Proceedings of the conference "Tracking animals with GPS". The Macaulay Institute, Aberdeen. pp. 51-60.

Janeau, G., C. Adrados, J. Joachim, and D. Pépin. 2001. GPS performance in a temperate forest environment. A. M. Sibbald, I. J. Gordon (eds.) *In* Proceedings of the conference "Tracking animals with GPS". The Macaulay Institute, Aberdeen. pp. 69-72.

Johnson, D. H. 1979. The comparison of usage and availability measurements for evaluating resource preference. Ecology 61:65-71.

Joslin, G. L. 1986. Mountain goat population changes in relation to energy exploration along Montana's Rocky mountain front *In* Bienn. Symp. North. Wild Sheep and Goat Counc. 5:253-271.

Jury, D. Senior Wildlife Biologist, B. C. Ministry of Environment, Lands and Parks, Southern Interior Region. Personal communication, 2001.

Kochanny, C. Technical support, Advanced Telemetry Systems, Personal communication, June 5, 2002.

Krajina, V. J. 1976. Biogeoclimatic zones of British Columbia. University of British Columbia.

Lawler, A. 2000. Scientists gain access to sharper GPS signal. Science 288:783.

Lemke, S. L. 1999. Cayoosh Range mountain goat study results and recommendations. Report for B. C. MELP and Ainsworth Lumber Company Limited.

Lemmon, P. E. 1956. A spherical densiometer for estimating forest overstory density. Forest Science 2:314-320.

Lotek, Wireless Inc. 2001. Small animal GPS location system. User's manual. GPS 2000 Series. 43 pp.

Moen, R., J. Pastor, and Y. Cohen. 1997. Accuracy of GPS telemetry collar locations with differential correction. J. Wildl. Manage. 61:530-539.

Moen, R., J. Pastor, Y. Cohen, and C. C. Schwartz. 1996. Effects of moose movement and habitat use on GPS collar performance. J. Wildl. Manage. 60:659-668.

Moen, R. Research Associate, Center for Water and the Environment, University of Minnesota. Personal communication, October 15, 2001.

Moy, A. GIS Programming Specialist, Centre for Conservation Research, University of British Columbia, Personal communication, June 13, 2002.

Neter, J., M. H. Jutner, C. J. Nachtsheim, and W. Wasserman. 1996. Applied Linear Statistical Models. WCB/McGraw-Hill, Boston, Massachusetts.

Neu, C., C. Byers, and J. Peek. 1974. A technique for analysis of utilization-availability data. J. Wildl. Manage. 38:541-545.

Norquay, A. 1999. Assigning error values to 2 dimension, differentially corrected GPS positions collected from animal borne receivers. Report for British Columbia Ministry of the Environment, Kamloops, BC. 7 pp.

Poole, K. G., and D. C. Heard. 2001. Seasonal habitat use and movements of mountain goats in east-central British Columbia. B. C. Ministry of Water, Land & Air Protection, Prince George. 27 pp.

Ratti, J. T., and E. O. Garton. 1996. Research and experimental design, 5th edition. The Wildlife Society, Bethesda, Md.

Rempel, R. S., and A. R. Rodgers. 1997. Effects of differential correction on accuracy of a GPS animal location system. J. Wildl. Manage. 61:525-530.

Rempel, R. S., A. R. Rodgers, and K. F. Abraham. 1995. Performance of a GPS animal location system under boreal forest canopy. J. Wildl. Manage. 59:543-551.

Rodgers, A. R. 2001. Tracking animals with GPS: the first 10 years A. M. Sibbald, I. J. Gordon (eds.) *In* Proceedings of the conference "Tracking animals with GPS". The Macaulay Institute, Aberdeen. pp. 1-10.

Rodgers, A. R., R. S. Rempel, and K. F. Abraham. 1996. A GPS-based telemetry system. Wildl. Soc. Bull. 24:559-566.

Rumble, M. A., and F. Lindzey. 1997. Effects of forest vegetation and topography on global positioning system collars for elk. Resource Technology Institute 4:492-501.

Sall, J., A. Lehman, and L. Creighton. 2001. JMP Start Statistics - A guide to statistics and data analysis using JMP and JMP IN software. 2nd edition. SAS Institute Inc.

Samuel, M. D., and K. P. Kenow. 1992. Evaluating habitat selection with radio-telemetry triangulation error. J. Wildl. Manage. 56:725-734.

Schoen, J. W., M. D. Kirchhoff, and O. C. Wallmo. 1980. Winter habitat use by mountain goats. Vol. 3 Project Progress Report. Alaska Dept. of Fish and Game, Juneau. 13 pp.

Schwab, F. E., and M. D. Pitt. 1991. Moose selection of canopy cover types related to operative temperature, forage, and snow depth. Can. J. Zool. 69:3071-3077.

Smith, C. A. 1994. Evaluation of a multivariate model of Mountain Goat winter habitat selection. *In* Bienn. Symp. North. Wild Sheep and Goat Counc. pp. 159-165.

Springborn, E. G., and D. S. Maehr. 2001. Diurnal and nocturnal habitat use by reintroduced elk in eastern Kentucky, United States. A. M. Sibbald, I. J. Gordon (eds.) *In* Proceedings of the conference "Tracking animals with GPS". The Macaulay Institute, Aberdeen. p. 19.

Stevens, V. 1983. The dynamics of dispersal in an introduced mountain goat population. Ph.D. Dissertation. University of Washington, Seattle. 203 pp.

Watts, S. B. (ed.) 1983. Forestry handbook for British Columbia, 4th edition. The Forestry Undergraduate Society: D.W. Friesen and Sons Ltd., Cloverdale, B. C.

Wells, D. E. (ed.) 1986. Guide to GPS positioning. Canadian GPS Associates, Fredericton, New Brunswick.

White, G. C., and R. A. Garrott. 1986. Effects of biotelemetry triangulation error on detecting habitat selection. J. Wildl. Manage. 50:509-513.

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

Zar, J. H. 1996. Biostatistical analysis, 3rd edition. Prentice Hall, Upper Saddle River, NJ.

APPENDIX

GIS Avenue scripts

Number	Name	Author	Modified
ESRI Avenue Script[a] #1	ImageWarp 2.0	Kenneth R. McVay	March 16, 1999
ESRI Avenue Script #2	Grid2pt	Jeff Ardron	October 27, 2000
ESRI Avenue Script #3	View.ShiftFeatures	ESRI	October 1, 1998

Note[a]: ESRI Avenue is ArcView software's object-oriented scripting language.