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Design to monitor trend in abundance and presence of American beaver (*Castor canadensis*) at the national forest scale

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Abstract Wildlife conservationists design monitoring programs to assess population dynamics, project future population states, and evaluate the impacts of management actions on populations. Because agency mandates and conservation laws call for monitoring data to elicit management responses, it is imperative to design programs that match the administrative scale for which management decisions are made. We describe a program to monitor population trends in American beaver (*Castor canadensis*) on the US Department of Agriculture, Black Hills National Forest (BHNF) in southwestern South Dakota and northeastern Wyoming, USA. Beaver have been designated as a management indicator species on the BHNF because of their association with riparian and aquatic habitats and its status as a keystone species. We designed our program to monitor the density of beaver food caches (abundance) within sampling units with beaver and the proportion of sampling units with beavers present at the scale of a national forest. We designated watersheds as sampling units in a stratified random sampling design that we developed based on habitat modeling results. Habitat modeling indicated that the most suitable beaver habitat was near perennial water, near aspen (*Populus tremuloides*) and willow (*Salix* spp.), and in low gradient streams at lower elevations. Results from the initial monitoring period in October 2007 allowed us to assess costs and logistical considerations, validate our habitat model, and conduct power analyses to assess whether our sampling design could detect the level of declines in beaver stated in the monitoring objectives. Beaver food caches were located in 20 of 52 sampled watersheds. Monitoring 20 to 25 watersheds with beaver should provide sufficient power to detect 15–40% declines in the beaver food cache index as well as a twofold decline in the odds of beaver being present in watersheds. Indices of abundance, such as the beaver food

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cache index, provide a practical measure of population status to conduct long-term monitoring across broad landscapes such as national forests.

Keywords Management indicator species · Monitoring · Habitat suitability · Beaver · National forest · Sampling design · Power analysis

Introduction

Biologists and land managers implement long-term monitoring programs to understand population dynamics, project future population states, and evaluate the impacts of management (Gibbs 2000). Evidence of population trends in monitoring data are used to trigger management responses, and monitoring is often done to fulfill agency mandates (e.g., federal, territorial, provincial or state management agencies; Witmer 2005) or is called for by law (e.g., Endangered Species Act of 1973; Campbell et al. 2002).

Monitoring programs are designed to match the scale at which monitoring data will influence policy (Urquhart et al. 1998). Monitoring can focus on specific sites to detect trends in a local population, or it can incorporate many sites to make inferences regarding regional population trends (Larsen et al. 2001). For example, long-term monitoring data on the Jackson elk (*Cervus elaphus*) herd in northwest Wyoming, USA is used to set harvest limits and understand the dynamics of that population (Lubow and Smith 2004). In another example, the US Environmental Protection Agency monitors networks of stream sites to assess the ecological condition of stream resources across large regions (Herlihy et al. 2000).

An effective population monitoring program requires population spatial distribution (presence on the landscape), status, and trend to be defined in the monitoring objectives. Monitoring must be logistically feasible yet rigorous enough to detect population changes. This often means balancing the monitoring effort at one site with the number of sites that are monitored. For example, an index of abundance may need to be used instead of a precise estimate of abundance to make a monitoring program more time efficient, which will increase the number of sites that can be sampled and increase statistical power (Dauwalter et al. 2009). Another important component of any monitoring program is the use of a valid sampling design. Programs that monitor many sites to make inferences regarding population trends across a large geographic area (e.g., county, state, management area) must use an unbiased process to select a sample of sites so that strong inferences can be made regarding population status and trends (Thompson et al. 1998).

The USDA, Forest Service is required to monitor management indicator species as part of the National Forest Management Act (Hayward et al. 2001). Management indicator species are “those species whose response to environmental conditions is assumed to index like responses of a larger number of species and whose habitats can therefore be managed to benefit a larger set of species; more broadly, species for which a set of management guidelines has been written” (Vesely et al. 2006:B-2). The Black Hills National Forest (BHNF) in South Dakota and Wyoming, USA (Fig. 1) has selected American beaver (*Castor canadensis*) as a management indicator species (USDA Forest Service 2005) because of its association with riparian and aquatic habitats and its status as a keystone species (SAIC 2005).

We describe the design of a long-term monitoring program for beaver on the BHNF where estimates of forest-wide trends in abundance and presence can be used to guide forest planning. In our design, we designated beaver food caches as sampling elements within watersheds that formed our sampling units. We begin by explaining how the monitoring objectives were defined and then describe the sampling design and field methods used to meet those objectives. We also assess the ability of our monitoring design to achieve sufficient statistical power to detect the magnitude of population trends specified by our objectives. Our protocol sets forth rationale for developing the critical components of a rigorous monitoring program that allows inferences to be made regarding trends in beaver across a large management region. This protocol not only extends past methods that have focused on monitoring beaver in single streams or watersheds (e.g., Robel and Fox

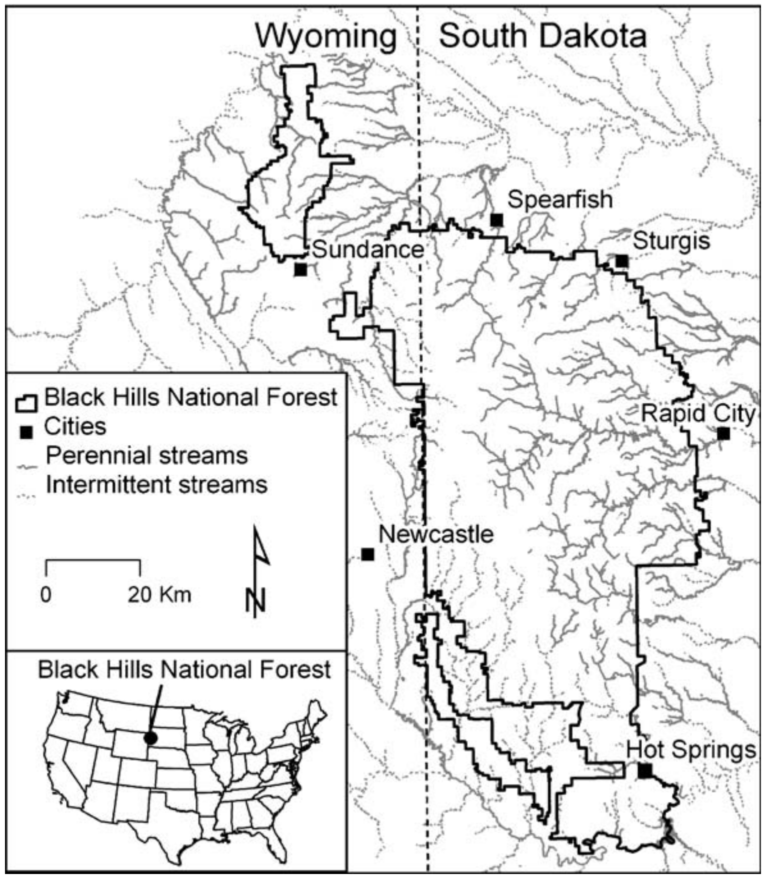

Fig. 1 The Black Hills National Forest in South Dakota and Wyoming, USA

1993) to larger geographic extents but also employs a probabilistic sampling design rather than use a complete census (e.g., Smith 1999), which is not always practical. Our protocol design should assist other land managers in rigorously designing monitoring programs for other wildlife species at large spatial scales.

Methods

Study area

The Black Hills of southwestern South Dakota and northeastern Wyoming originated from a dome-shaped, elliptical uplift of Precambrian igneous and sedimentary basement rocks that are exposed at the core and surrounded by Palaeozoic and Mesozoic sedimentary rock formations that form a concentric ring around the core (Williamson and Carter 2001). The Black Hills uplift occurred ~50 million years ago about the same time as the geological uplift that formed the Rocky Mountains (Knight 1994). Topography ranges from hogback ridges with faulted valleys to karst limestone topography to highly eroded outcrops with wide valleys. The BHNF (latitude 44°0′40″ N, longitude 103°47′35″ W; altitude 900–2,207 m) encompasses much of the Black Hills and was originally established as the Black Hills Forest Reserve in 1897 (USDA Forest Service 2005). Of the 6,300 km^2 within the National Forest boundary (Fig. 1), approximately 1,170 km^2 (19%) is owned by private, state, or other federal agencies. Mean annual precipitation is 47 cm but can be as high as 74 cm in the north, and mean annual air temperature is 6.6°C with cooler temperatures at higher elevations (Knight 1994; Williamson and

Carter 2001). The Belle Fourche River drains the northern portion of the Black Hills, while the Cheyenne River forms the primary drainage for the southern portion (Knight 1994).

Forested vegetation in the Black Hills is a mixture of Rocky Mountain species such as ponderosa pine (*Pinus ponderosa*) and narrow-leaf cottonwood (*Populus angustifolia*) and eastern deciduous forest species such as American elm (*Ulmus americana*), bur oak (*Quercus macrocarpa*), and box elder (*Acer negundo*; Knight 1994). Dominant land uses in the Black Hills are livestock grazing, logging, recreation, and mining. The sedimentary Madison Limestone and Minnelusa formations at high elevations in the west comprise the Limestone Plateau region that is a recharge zone where streams seldom flow except where perched springs occur (Carter et al. 2005). At low elevations, these formations and the Minnekahta formation create the Loss Zone where many streams lose all or most of their surface flow as they flow north and east off the Black Hills (Williamson and Hayes 2000; Carter et al. 2005).

Beaver were historically found in the Black Hills (Novak 1987) and have been selected as a management indicator species by the BHNF because of its "relationship to riparian/aquatic habitat condition, status as a keystone species, available monitoring protocols, and dependence on riparian forest and shrub habitat (SAIC 2005:40)." In addition, beaver are recognized for their close affinity to salicaceous riparian species including aspen (*Populus tremuloides*), cottonwood (*Populus* spp.), and willow (*Salix* spp.); this association with hardwood riparian areas is the basis for their selection as a management indicator species (USDA Forest Service 2007). Beaver historically were the single greatest influence on riparian systems in the BHNF (SAIC 2005). It is further recognized that restoration of aspen forests, where conifers have out-competed them adjacent to riparian areas, will lead to increasing habitat for beaver (USDA Forest Service 2007).

Setting monitoring objectives

Defining monitoring objectives is critical to the success of monitoring programs (Stout 1993). Forest Service biologists collaborated with scientists at the University of Wyoming to select the objectives for monitoring beaver on the BHNF. Objectives were set during planning meetings and based on biologically meaningful trends in beaver populations that could trigger management response or change forest planning.

Monitoring objectives were identified to detect trends in abundance and presence (geographic distribution) of beaver at the scale of the BHNF. The objective for beaver abundance is to detect a 5% average annual decline in abundance over a 9-year period, equating to a 37% absolute decline in abundance after 9 years ($1 - [0.95]^9$; Beck et al. 2008). Because abundance monitoring will occur at 3-year intervals, the 5% annual decline may be detected after only 3 or 6 years, corresponding to 14% or 26% absolute declines, respectively. The objective for beaver presence is to detect a twofold change (increase or decrease) in the odds (odds $= p/[1 - p]$, where $p =$ the proportion of watersheds with caches) in watersheds having beaver food caches after 12 years (Beck et al. 2008). Presence is expressed as a change in the odds of watersheds having food caches present because proportions can only range from 0 to 1 and they often can be expected to change nonlinearly in response to factors such as time. Presence will be monitored at 6-year intervals as opposed to a 3-year interval. This was a compromise between monitoring rigor, monitoring costs, the presence of beaver across the forest, and the consequences to forest management and planning as a result of this change.

The statistical power to detect trends in beaver abundance and presence was set at $1 - \beta = 0.80$ using a statistical type I error rate of $\alpha = 0.2$. Type I errors are often tightly controlled in research and set at 0.05 or lower. However, a type I error rate of 0.20 is reasonable in monitoring to reduce the prevalence of type II errors that are often more important in management contexts (Kendall et al. 1992; Beier and Cunningham 1996; Gibbs et al. 1998). Because type I and type II error rates are inversely related, a higher α increases our power $(1 - \beta)$ to detect real changes in the beaver food cache index. Selection of these statistical error rates also makes it as likely to fail to detect real changes (type II error, $\beta = 0.20$) versus saying change is occurring when in fact it is not (type I error, $\alpha = 0.20$). A decline in beaver abundance of 5% or more annually or a twofold change in beaver presence will trigger the BHNF to evaluate and address potential drivers for the change and make modifications to the forest plan as necessary.

Sampling design

Monitoring across a large region requires a sampling design that allows inferences to be made regarding an entire target population (Thompson et al. 1998). Monitoring trends in beaver abundance and presence across the BHNF requires a sampling design that permits forest-wide inferences to be made regarding trends in abundance and presence. Sampling designs have multiple components: target population, sampled population, sampling frame, sampling units, sample, and sampling elements (Thompson et al. 1998). Consequently, we defined these components according to their use in our sampling design (Table 1). The abundance and presence of beaver food caches will be monitored in randomly selected sixth-level Hydrologic Unit Code watersheds. Hydrologic Unit Code watersheds (hereafter watersheds) are hierarchical drainage basin planning units developed by the US Geological Survey to organize water resource information and guide water resource planning (Seaber et al. 1987; Verdin and Verdin 1999). There are 106 watersheds on the BHNF, and these watersheds provide a convenient unit in which beaver abundance and presence can be monitored. We assumed that the abundance (or presence) of food caches in watersheds are spatially independent, that is, the abundance or presence of food caches in one watershed does not influence the abundance or presence in adjacent watersheds. We thought that this assumption was appropriate because sixth-level watersheds are on average approximately 6,000 ha and often only contain one food cache. Caches are enumerated by one observer during aerial surveys, a common method for monitoring beaver populations (Swenson et al. 1983). A sample of 40 watersheds was determined to be a logistically feasible sample size for each monitoring year, and these watersheds were randomly selected for monitoring beaver abundance. An additional 12 water-

Table 1 Definition of design components of a monitoring program and definitions for beaver monitoring on the Black Hills National Forest, South Dakota and Wyoming, USA

Design component	General definition	Beaver monitoring definition
Element	An item on which some type of information is collected	Beaver food cache
Sampling unit	A unique set of one or more elements, but in area sampling a sampling unit may contain zero elements	6th level HUC watershed
Sampling frame	List of sampling units within the geographic area of the target population available for sampling	All 6th level HUC watersheds with suitable beaver habitat
Sampled population	All elements associated with sampling units listed in the sampling frame. Typically coincides with the target population	All 6th level HUC watersheds with suitable habitat
Target population	All elements of interest within some defined area and time period	All 6th level HUC watersheds with suitable habitat in late October or early November following aspen and willow leaf drop
Sample	Selected set of sampling units	Randomly selected 6th level HUC watersheds

sheds (52 total) were randomly selected to monitor beaver presence. The density of beaver food caches on perennial water in each watershed will be monitored as an index of beaver abundance (caches/km), and the presence of a food cache in a watershed will be used to monitor beaver presence.

Beaver monitoring will focus on food caches because estimating the abundance of beaver is difficult due to their behavior and because one to several lodges may be used by each family group. The density of beaver food caches is often considered the preferred observation on sampling units because only one winter food cache is established annually by each family group (Hay 1958; Novak 1987). Food caches are stores of edible foods, such as aspen (*P. tremuloides*) and willow, near lodges that are constructed in fall to provide an accessible food source under ice in winter (Slough 1978). Construction of food caches begins with the first heavy frost and caches are most visible following leaf fall (Novak 1987). The presence of food caches marks the location of family groups (Grasse and Putnam 1955; Hay 1958; Jenkins and Busher 1979). The density of highly visible food caches is an effective index of family group abundance in watersheds, but only in regions where winter ice forms (Robel and Fox 1993).

Field methods

Beaver abundance and presence is monitored in selected watersheds using helicopter surveys (Beck et al. 2008), which have been successfully used to monitor beaver food caches (Payne 1981; Swenson et al. 1983; Smith 1999). Aerial monitoring occurs in late October and early November. By this time, caches have already been constructed and they are most visible because of leaf fall. This period is also prior to winter ice formation when cache visibility decreases (Olson and Hubert 1994). When monitoring beaver abundance, one observer in a helicopter enumerates food caches along the entire length of perennial streams, rivers, and standing waters in each watershed. Typically, only one pass is made by the helicopter directly above each stream, except when a second pass is required to ensure complete coverage of the stream network and reservoirs. When monitoring beaver presence, helicopter surveys using one observer begin at one end of the watershed and continue only until a food cache is located. Surveys will be conducted every 3 years for abundance monitoring and every 6 years for presence monitoring. Abundance and presence monitoring will occur concurrently every 6 years.

Stratification and habitat suitability modeling

Reliable monitoring programs provide precise estimates of population status and trends. One way to increase the precision of abundance, presence, and trend estimates is through stratification of the sampling frame (Thompson 1992; Thompson et al. 1998). Stratification places similar sampling units together, and then a sample of sampling units is drawn from each stratum for monitoring. Identifying a small number of strata (two or three) provides the most effective way to increase precision of abundance and presence estimates (Thompson 1992).

We stratified the sampling frame for beaver monitoring into two strata by modeling beaver habitat suitability on the BHNF. All data used to evaluate habitat suitability were obtained from geospatial data (30-m resolution) provided by BHNF personnel. Habitat suitability was modeled by comparing areas used by beaver to random areas. A helicopter survey from 14 to 16 September 2004 was used to locate 74 active beaver lodges on the BHNF (Burns 2004). Through literature review, we identified elevation (m), percentage slope (gradient), elevation deviation (m), distance (m) to perennial water source (perennial), and distance to aspen and/or willow as habitat characteristics important to beaver (Table 2).

We compared habitat characteristics between 74 active beaver dam locations to 400 randomly selected locations across the BHNF using logistic regression to model beaver habitat selection (PROC LOGISTIC; SAS 2003). Our logistic regression model provided a fit to habitat predictor variables where the dependent data were 1 for used units and 0 for randomly available units (Boyce and McDonald 1999). Prior to modeling, we assessed multicollinearity between variables with a Pearson's correlation matrix (PROC

Table 2 Literature review of variables used to model American beaver habitat suitability

Reference	Location	Beaver habitat suitability
Retzer et al. (1956)	Colorado	Excellent habitat was characterized by valley grades of ≤6%; valley width of >46 m; and, rock types of glacial till, schist, or granite. Unsuitable habitat had a valley grade of >15%, and a valley width that was not much wider than the stream itself.
Slough and Sadleir (1977)	British Columbia	Beaver occupancy along lakes and streams was related to food availability (aspen along lakes and cottonwood along streams).
Beier and Barrett (1987)	Eastern California and western Nevada	Increasing stream width and depth and decreasing stream gradient were most influential on beaver habitat use. Food availability added little explanatory power.
Howard and Larson (1985)	Massachusetts	Watershed size (ha) above the colony site, stream width (m) below the final dam, stream gradient, soil drainage class, percent hardwood vegetation within 100 m of the site center, percentage hardwood vegetation within 200 m of the site center, and percentage abandoned fields within 100 m of the site center all affected beaver colony site longevity
McComb et al. (1990)	Eastern Oregon	Stream reaches with beaver dams were shallower and had a lower gradient than unoccupied reaches. Beaver did not build dams at sites with a rocky substrate. Bank slopes at occupied reaches were not as steep as those at unoccupied reaches. Occupied streams had greater tree canopy cover, especially of thin-leaf alder
Suzuki and McComb (1998)	Western Oregon	Beaver built dams in areas with wide valley floors, low gradient streams, high graminoid cover, low red alder cover, and low shrub cover.
Fryxell (2001)	Ontario, Canada	Beaver abundance was related to food availability.

CORR; SAS 2003) and removed elevation deviation because it was highly correlated ($r = 0.80$) with slope. We developed seven single and multivariable candidate models with the remaining four variables and assessed the plausibility of each candidate model using Akaike's information criterion (AIC_c; Burnham and Anderson 2002). We considered the model with the lowest AIC_c to be the best supported, and models within 2 ΔAIC_c were also considered plausible models. We used Akaike weights (w_i) to assess the weight of evidence for each model (Burnham and Anderson 2002). We used fivefold cross-validation to evaluate goodness-of-fit of the most plausible model (Boyce et al. 2002).

We used habitat suitability predicted across the BHNF to construct and stratify the sampling frame of watersheds. The best-supported logistic regression model was used in conjunction with spatially explicit GIS data on important habitat to predict habitat suitability for each 30-m grid cell across the BHNF. Next, the predicted probabilities were placed into quartiles, and then the proportion of a watershed in each quartile was used to determine watershed suitability. Non-habitat was defined as watersheds with at least 95% of its area in quartile 1; these watersheds were excluded from the sampling frame. The abundance and presence of beaver in non-habitat areas are more likely a function of random occurrence in specialized habitats (e.g., stock ponds, springs) rather than a reflection of forest management practices. Including these watersheds in our sampling frame may artificially influence our inferences because trends in these food caches are not indicative of forest management practices. The remaining watersheds were divided into two strata using index values: index $= 0 \times Q1 + 1 \times Q2 + 5 \times Q3 + 10 \times Q4$, where Q_i is the proportion of watershed in quartile i. Half of the watersheds with the highest index values were placed into the high-quality stratum and the remaining half placed into the moderate-quality stratum.

Prospective power analyses

Statistical power analyses are useful in determining sample sizes needed to detect trend within the bounds of monitoring objectives. We conducted prospective power analyses to assess the ability of our sampling design to detect declines in the beaver food cache index and in the odds of watersheds having beaver present on the BHNF. Our objectives for monitoring set the probability of type I and type II statistical errors equal at 0.20 and the target level of power to detect these changes at 0.80. We used data from the 2007 monitoring season to estimate variance in the food cache index and assess statistical power.

We computed power to detect change in the food cache index by using a *t* test approximation technique to detect declines between two time periods (Gerow 2007). Power is influenced by type I (α; falsely detecting change) and type II (β; failing to detect real change) statistical error rates, the magnitude of change to be detected, sample size (n), variance, and the amount of correlation between the two samples. We computed power based on sample sizes from five to 25 for declines ranging from 5% to 40% in the beaver food cache index between two time periods. Because food cache locations in sampling units over time are assumed to be fairly constant (Novak 1987), our power calculations also required an estimate of the correlation in the number of beaver caches within individual watersheds between two time periods (Gerow 2007). Because we did not have an estimate of correlation, we computed power with conservative ($r = 0.60$), moderate ($r = 0.75$), and high ($r = 0.90$) correlations.

A fundamental issue with our power analysis was the fact that no caches were observed in 25 of 40 watersheds sampled for abundance monitoring in 2007. Zeroes inflate variances and monitoring for declines in abundance where beaver do not occur masks the ability to detect declines where they do occur. Consequently, we focused our power analysis to detect declines in the cache index in watersheds with known beaver populations. This resulted in us focusing our power analysis on the 15 watersheds (11 in high-quality stratum and four in moderate-quality stratum) with beaver. We also adjusted our total finite population size (N) to account for the proportion of watersheds ($15/40 = 0.375$) with beaver present; the sampling frame to which inferences are drawn was reduced from the 73 watersheds with suitable beaver habitat to 28 that are estimated to have beaver present ($0.375 \times 73 = 27.4$).

Although monitoring is based on a stratified sampling design, the 2007 monitoring data showed no difference in food cache index means or variances between strata. Consequently, we computed power as if monitoring was conducted under a simple random sampling design (mean = 0.0688 caches/km, SD = 0.0579). A simple random design should yield slightly conservative estimates of power when compared to a stratified design that does not notably increase precision. Our estimate of variance used in power calculations also incorporated a finite population correction since 37.5% of the sampling frame was sampled and assumed that variances were proportional to the mean.

Power to detect a decline in the odds of a watershed having beaver present was calculated using the hypergeometric distribution. This was done by determining the probability that all watersheds where beaver were lost were in the unsampled portion of the sampling frame. For example, assume beaver were lost from four watersheds. Since 28 of 73 watersheds were estimated to have beaver present (20 in sampled watersheds and eight in unsampled watersheds), the probability that all four watersheds occurred in the unsampled portion of the sampling frame is computed as: $(8 \times 7 \times 6 \times 5)/(28 \times 27 \times 26 \times 25) = 0.0006$, equivalent to a power of $1 - 0.0006 = 0.9994$. Although the hypergeometeric distribution is based on sampling without replacement, the incorporation of the finite population correction for the binomial proportion during trend analysis will accommodate the finitude of the sampling population and result in accurate estimates of power. However, an important assumption of computing power in this way is that any watersheds losing beaver in the sampled watersheds are detected with 100% certainty (i.e., power = 1.00). Since cache detection probabilities are often ~0.90, this assumption results in slightly optimistic power estimates. We computed power to detect a decline of up to 12 watersheds with beaver—equivalent to a 21% decline or 0.45 change in odds—for sample sizes of five to 25 watersheds.

Results

Sampling design

Beaver monitoring on the BHNF is based on a stratified random sampling design. Although there are 106 watersheds on the BHNF, 33 watersheds were classified as non-habitat during habitat suitability modeling (see "Stratification and habitat suitability modeling"); therefore, the sampling frame consisted of $N = 73$ watersheds (Table 3). A sample of 40 watersheds was selected for abundance monitoring that was initiated in fall 2007; 23 of 37 watersheds were randomly selected from the high-quality stratum and 17 of 36 were selected from the moderate-quality stratum (Table 3). Between both strata, 54.8% (40 of 73) of watersheds in the sampling frame (40 of 73) were sampled for abundance monitoring. Twelve additional watersheds were selected for monitoring beaver presence, resulting in 52 of 73 watersheds in the sampling frame (71.2%) being selected for presence monitoring (Table 3). The sample of 52 watersheds includes 59.5% of the total area within the BHNF boundary. Non-habitat included 25.9% of total area, and the 21 watersheds with beaver habitat that were not sampled encompassed 14.6% of the total area (Table 3).

Table 3 Number of sampling units by stratum and area (km^2) encompassed by sampling units within each stratum selected for beaver abundance and presence monitoring on the Black Hills National Forest, South Dakota and Wyoming, USA

Stratum	Objective	Sampling units	km^2 (%)
Sample			
Moderate	Abundance	17	1,184.6 (19.0)
	Presence	2	222.9 (3.6)
High	Abundance	23	1,792.9 (28.7)
	Presence	10	510.4 (8.2)
Not sampled			
Moderate		17	877.0 (14.1)
High		4	31.2 (0.5)
Non-habitat		33	1,612.9 (25.9)
Total		106	6,231.9[a]

Sampling units are sixth-level hydrologic unit code watersheds

[a]This area does not equal the total area within the boundary of the Black Hills National Forest (6,300 km^2) due to the exclusion of small fragmented parcels of Forest Service lands primarily west of the main Bearlodge District in Wyoming that were excluded from the sampling frame

Field methods

The initial period of beaver monitoring on the BHNF occurred from 22 to 26 October 2007. Surveys were performed while flying a Bell 206B3 helicopter 80.5–96.6 km/h at an altitude of 152 m above ground outside and 305 m inside the Black Elk Wilderness (S. R. Hirtzel, Black Hills National Forest, personnel communication). Surveys were conducted on 40 watersheds for abundance monitoring and an additional 12 watersheds for presence monitoring at a cost of US $31,693. Helicopter and pilot rental cost $24,875 for 32.6 h of flight time. Forest Service biologist (United States Grade series 11) time cost $7,000. Within the sampled watersheds, 1,294 km of stream and 14 reservoirs (<1 to 345 ha) were surveyed during 23.7 h of flight time. A total of 2,856 km were flown across the BHNF during watershed surveys, shuttle time between watersheds, and refueling at local airports. The cost of monitoring averaged $609 per watershed or $24.50 per perennial stream km (27 min per watershed or 1.1 min per perennial stream kilometer). All perennial streams were flown in both abundance and presence watersheds during the 2007 survey because additional money was available for monitoring.

Stratification and habitat suitability modeling

Habitat suitability modeling for stratification showed that active beaver locations were related to specific landscape characteristics. The global model was the best-supported logistic regression model identifying suitable beaver habitat on the BHNF, which included percent slope, distance to perennial water, distance to aspen and/or willow, and elevation ($\log[L] = -137.42$, $K = 5$, $\text{AIC}_c = 284.96$, $w_i = 1.000$). No other model was competitive with the best-supported model ($\Delta\text{AIC}_c \geq 19.557$), and cross-validation indicated that the

Table 4 Mean (±1 SE) habitat characteristics at 74 active beaver dam and 400 random location pixels, Black Hills National Forest, South Dakota and Wyoming, 2004

Habitat characteristic[a]	Beaver	Random	*t*	*df*	*P*
Distance (m) to riparian	558 ± 68	3,296 ± 313	−3.76	472	<0.001
Distance (m) to perennial water	452 ± 105	2,062 ± 107	−6.38	472	<0.001
Elevation (m)	1,536 ± 20	1,618 ± 12	−2.74	472	0.006
Elevation deviation (m)	13.7 ± 0.6	13.3 ± 0.4	0.45	472	0.655
Gradient (%)	18.1 ± 1.4	19.9 ± 0.7	−1.10	107	0.272

Independent sample *t* tests evaluated differences between beaver and random locations

[a]Habitat characteristics are percentage slope (gradient), distance (m) to nearest aspen and/or willow (riparian), distance (m) to nearest perennial stream or water body (perennial), and elevation (m) at each beaver or random pixel (elevation)

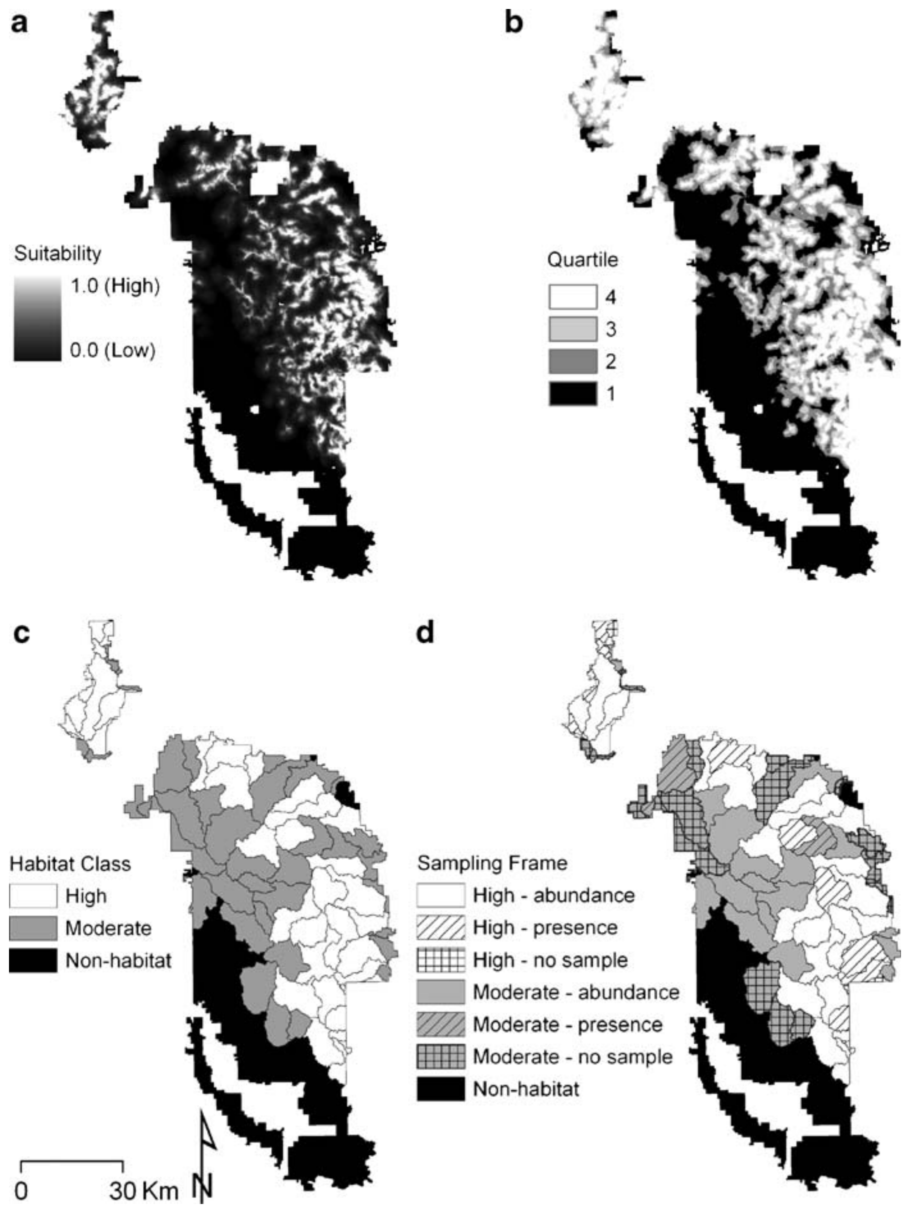

Fig. 2 Beaver habitat suitability on the Black Hills National Forest was used to develop the sampling design for monitoring. Suitability probabilities predicted across the Forest (**a**) were summarized into quartiles (**b**). Watersheds with >95% of area in quartile 1 were classified as non-habitat, and the remaining watersheds were stratified into high and moderate habitat classes based on the proportion of each watershed that was in each quartile (**c**). Watersheds were randomly selected in the high and moderate strata for abundance and presence monitoring (**d**)

best model was a strong predictor of beaver habitat suitability on the BHNF ($r_s = 0.96$, $P < 0.001$, $n = 10$). Parameter estimates (±1 SE) indicated that suitable beaver habitat was near perennial water (−0.001 ± 0.000), near riparian vegetation (−0.011 ± 0.000), and in low gradient streams (−0.028 ± 0.012) at lower elevations (−0.004 ± 0.001). The magnitude of distances from random locations and active beaver lodges to aspen/willow and perennial water was striking; random locations were 5.9 times further from aspen/willow and 4.6 times further from perennial water than active beaver lodges (Table 4).

The best-supported logistic regression model was used to predict habitat suitability for each 30-m grid cell across the BHNF. Spatially explicit prediction of suitability revealed that the northern portion of the BHNF contained more suitable beaver habitat than did the southwest (Fig. 2a). The distribution of predicted probabilities was placed into quartiles (Q1 = 0.00 to 0.025; Q2 = 0.025 to 0.094; Q3 = 0.094 to 0.245; Q4 = 0.245 to 1.00; Fig. 2b); 33 of 106 (31.1%) watersheds on the BHNF were dominated (>95%) by the first quartile and were classified as non-habitat (Fig. 2c). Of the 73 remaining watersheds, the 37 watersheds with the highest index values were placed into the high-quality stratum and the 36 with the lowest values were placed into the moderate-quality stratum to comprise the sampling frame (Fig. 2d).

Densities of beaver food caches were similar between high-quality and moderate-quality watersheds (Fig. 3). The mean density (±1 SE) in 23 high-quality watersheds was 0.030 (±0.007) caches per kilometer. The mean density in 17 moderate-quality watersheds was 0.021 (±0.008) caches per kilometer. For all watersheds, variances did not differ between strata (variance ratio test; $F = 1.47$; $df = 22, 26$; $P = 0.431$), and there was no significant difference in food cache densities between strata (one-tailed t test; $t = 1.197$; $df = 38$; $P = 0.119$). In watersheds where beaver were present, mean densities were 0.062 (±0.009; $n = 11$) caches per kilometer in the high-quality watersheds and 0.088 (±0.019; $n = 4$) caches per kilometer in the moderate-quality watersheds. Twelve additional watersheds were sampled for beaver food cache presence, and beaver food caches were present in 20 of all 52 watersheds sampled (proportion = 0.38; 1 SE = 0.02). In all, food caches were observed in 15 of 33 high-quality watersheds and five of 19 moderate-quality watersheds. There was no difference between strata in the proportion of watersheds with beaver food caches ($X^2 = 1.87$; $df = 1$; $P = 0.172$).

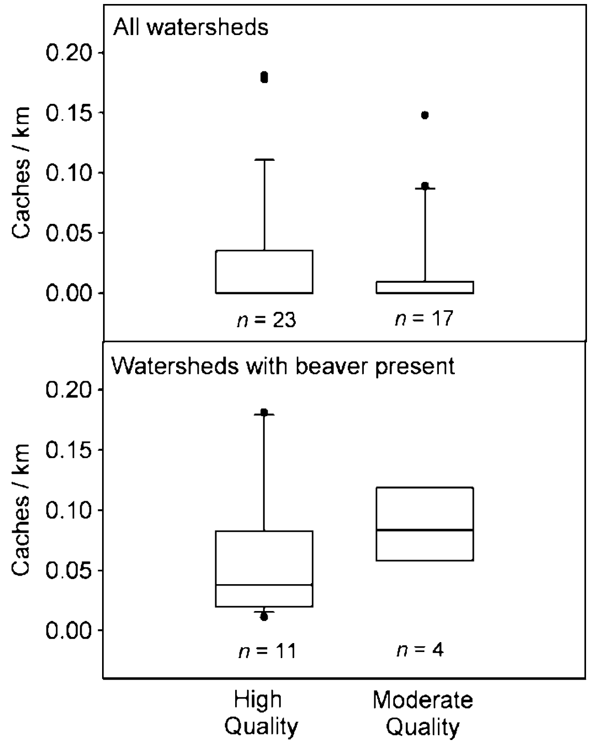

Fig. 3 Box plots of food cache index values in high- and moderate-quality strata for all watersheds sampled in October 2007 and for only watersheds sampled with beaver present. *Lines* are the median, *box margins* are 25th and 75th percentiles, *whiskers* are 10th and 90th percentiles, and *dots* are outliers

Prospective power analyses

Based on the 2007 monitoring data, we can achieve our objective of 0.80 power to detect a 37% decline in the beaver food cache index after 9 years when at least 10 watersheds are sampled, and the correlation of beaver food caches between time periods is conservative or moderate (Fig. 4).

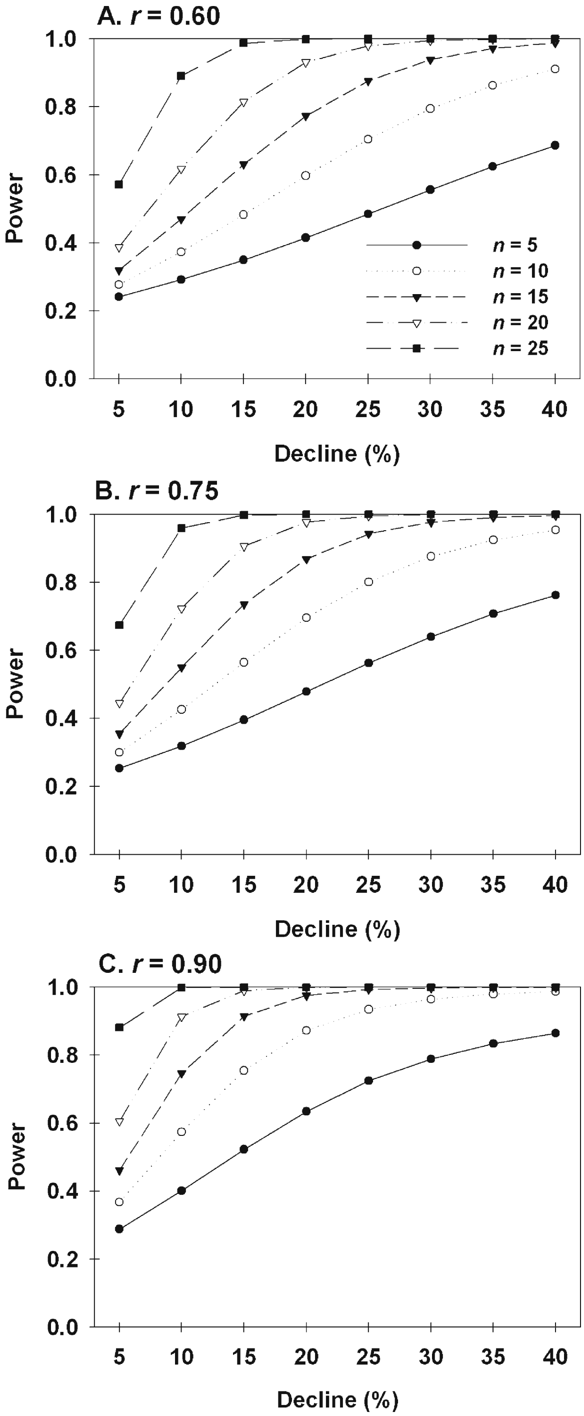

Fig. 4 Prospective statistical power to detect 5–40% declines in the food cache index between two time periods. Power was estimated for sample sizes (n) ranging from five to 25 at **a** conservative ($r = 0.6$); **b** moderate ($r = 0.75$); and **c** high ($r = 0.9$) levels of correlation in year-to-year locations of beaver food caches between two time periods. A 37% decline after 9 years is equivalent to a 5% average annual decline, which is the target level of change identified in the monitoring objectives

Sufficient power to detect the smallest decline (5%) in the beaver food cache index between two time periods is only possible when monitoring 25 sampling units, and the correlation of beaver food caches between time periods is high (power = 0.88; Fig. 4c). We found sufficient power (power ≥ 0.81) to detect 15–40% declines in the beaver food cache index when sample sizes were 20 or 25 at conservative, moderate, and high correlations in beaver food cache locations between time periods (Fig. 4a–c).

Our current sampling design also allows the target decline in the odds of watersheds having beaver present (change in odds = 0.50) to be detected with near certainty (power ≈ 1.00; Fig. 5). As expected, power increased as both sample size and the change in odds increased. Only very small sample sizes of five to ten watersheds would prohibit detecting changes in the odds of watersheds having beaver present at our target level of power (≥0.80).

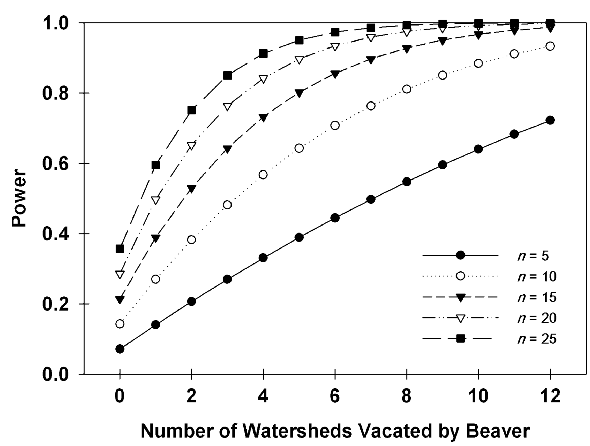

Fig. 5 Prospective statistical power to detect the loss of beaver from watersheds between two time periods. Power was estimated for sample sizes (n) ranging from five to 25. Beaver vacating 11 watersheds is equivalent to a twofold decrease in the odds of a watershed having beaver present, which is the target level of change identified in the monitoring objectives

Discussion

We developed a sampling protocol for American beaver that is logistically feasible and allows for detection of biologically important trends in populations. This was accomplished by setting the objectives for monitoring and constructing a sampling design that was sufficient to meet those objectives. The efficiency of the sampling design allows population trends to be detected because precise estimates of population status and trend parameters can be obtained. Precise estimates of beaver population status and trend can effectively trigger management responses and changes to forest planning. The BHNF is managed for multiple uses, and, consequently, management responses to declines in beaver are not predetermined but are based on post-decline evaluations of management. Post-decline evaluation may also implicate exogenous factors in beaver declines, such as climate change that is predicted to alter Black Hills hydrology (Fontaine et al. 2001).

Anderson (2001, 2003) deemed indices of abundance, as opposed to unbiased estimates of abundance, to be ineffective in detecting changes in the relative abundance of wildlife populations. However, Engeman (2003) countered that indices have great utility in monitoring wildlife populations and the larger issue between abundance estimates and indices of abundance lies in sound study designs that yield rigorous data and analyses that meet study objectives regardless of the techniques used to collect population data. Many agencies use indices for population monitoring (Marsh and Trenham 2008), and they are useful given that certain assumptions are met (Caughley and Sinclair 1994; Hayward et al. 2002). Detection probabilities need to be equal across time, habitat types, and observers for indices to be reliable measures of relative population abundance (Anderson 2001, 2003). Beaver food caches on the BHNF should be detectable with high probability because they are constructed in open water and are highly visible during aerial surveys. Detection probability of caches was 0.89 in forested habitats in southeastern and central Wyoming, USA using a helicopter survey (Osmundson and Buskirk 1993), and detection probability of caches during helicopter surveys was 0.89 on two prairie rivers in southeastern Montana, USA (Swenson et al. 1983). Payne (1981) found helicopters to be more efficient than fixed-wing aircraft at detecting beaver lodges and caches in the boreal forest of Newfoundland, Canada (detection probability; helicopter = 0.89, fixed-wing = 0.61). Future research is needed to estimate cache detection probabilities on the BHNF and verify that they are high. Estimates of detection probabilities could also be used to adjust cache counts made during previous and future surveys to obtain unbiased estimates of cache densities.

We used the abundance of food caches as a surrogate for beaver abundance. Doing so assumes that new caches added or caches lost represents a constant addition or loss of beaver colonies over 3 to 9 years across all populations. The number of beavers per cache is variable and has been reported to be as high as eight (Easter-Pilcher 1990; Osmundson and Buskirk 1993). In Montana, USA, beaver abundance increased with cache size (Easter-Pilcher 1990). In two areas in Wyoming, USA, smaller caches were more likely to be abandoned by beaver, but there was no relation between beaver abundance and cache size (Osmundson and Buskirk 1993). No study has evaluated the relation between beaver abundance and cache size in the Black Hills and further study is needed. However, if beaver abundance is related to cache size and smaller caches are more likely to be abandoned and lost, then the observed decline in cache abundance will be greater than the actual decline in beaver abundance across the landscape.

Using caches as a surrogate to determine changes in beaver abundance and presence is more logistically feasible than estimating abundance on the ground. In 2007, all perennial water in 52 watersheds was surveyed over 33 h. Robel and Fox (1993) found that aerial surveys were approximately ten times faster than ground surveys for beaver in Kansas, USA. Counting beaver at a single cache location and lodge can take 2–4 h after caches are located and can be less than 100% efficient (Easter-Pilcher 1990; Osmundson and Buskirk 1993). Trapping typically takes a minimum of 2 days per colony (Fryxell 2001; Arjo et al. 2007), and precisely estimating abundance using a mark-recapture estimator can take longer. Although expensive, counting food caches using a helicopter survey allowed for the most thorough sampling of each watershed and a large fraction of watersheds on the forest. However, aerial surveys of food caches are only effective in colder climates where beaver use caches, such as in the Black Hills. Robel and Fox (1993) found that aerial surveys of beaver colonies were less efficient than ground surveys in Kansas, USA rivers because most beaver colonies did not construct caches.

Although no differences in food cache densities were observed between moderate- and high-quality watersheds, retaining the stratified monitoring framework is still useful. Monitoring trends in food caches between different strata allows comparison of trends between strata. For example, food cache abundance may increase over time in the high-quality stratum but remain constant in the moderate-quality stratum. Stratification may also improve trend detection capability by increasing precision of forest-wide estimates of abundance and presence in future surveys. Thus, the stratified sampling design will be retained during future monitoring efforts.

We used a sampling design that allows strong inferences to be made regarding trends in beaver abundance and presence within suitable habitat across a large landscape. Monitoring populations across large regions requires a valid sampling design. Our random selection of watersheds allows unbiased estimates of the food cache index across the forest. This is in contrast to convenience sampling where monitoring easily accessible watersheds results in biased estimates of population status and trends. There are also several sampling designs available for regional environmental monitoring (McDonald 2003). Some designs specify revisits to the same sites annually, whereas more complex designs call for visiting some sites only once and others multiple times over the duration of the monitoring period. Different designs have varying levels of statistical power to detect change, but revisiting the same sampling units each monitoring period, sensu beaver monitoring on the BHNF, has the highest statistical power to detect population trends (Urquhart and Kincaid 1999). And randomly selecting watersheds will result in unbiased estimates of the status and trends of beaver population.

Defining watersheds as the sampling unit for monitoring effectively increased the precision of annual estimates for the food cache index and proportion of watersheds with beaver present. The finite nature of watersheds and the ability to survey large watersheds through aerial surveys allows for sampling a large fraction of the sampling frame, that is, 54.8% of the sampling frame was sampled for abundance monitoring and 71.2% of the sampling frame was sampled for presence monitoring. Because of the finite nature of watersheds, the increase in precision was gained by incorporating the finite population correction to variance estimates (Thompson 1992). This reduction in variance due to the correction increased the precision of the food cache index and estimates of beaver presence in watersheds. Precise estimates of change in abundance increases the ability to meet the monitoring objectives of detecting change in beaver abundance and presence over time with good power and triggering appropriate management responses.

We based our power analysis only on watersheds where beaver caches were present in 2007 because monitoring for declines in abundance where beaver are not present reduces the ability to detect trends in watersheds where they are present. This reduced the original sample size from 40 to 15 watersheds and the size of the sample frame from 73 to 28. Consequently, the inference extended to the sampling frame regarding trend in the food cache index changes to only watersheds with beaver caches present. However, it is not known exactly which watersheds are included in the sampling frame. Despite the analytical change, the sample of watersheds originally selected for abundance monitoring will continue to be monitored for abundance. This will allow changes in abundance to be monitored in the future if these watersheds become occupied by beaver. The details of the trend analysis will be determined after the 9-year period specified in the objectives. This complicating issue is one reason why many agencies have not determined specifically how monitoring data will be analyzed prior to data collection (Marsh and Trenham 2008). Regardless, the sampling frame for presence monitoring will remain unchanged.

Although the size of beaver family groups can change from year to year while caches persist (Swenson et al. 1983), aerial surveys of beaver food caches provide an efficient and precise technique to detect trends in beaver populations over longer time periods that are commonly specified by monitoring programs. Many monitoring programs are designed to detect population changes within 10 years (Marsh and Trenham 2008). Precise estimates of the food cache index and beaver presence allow monotonic changes to be detected at the level and within the time period specified by the monitoring objectives, and the current sample sizes result in statistical power to detect changes that meets monitoring objectives ($1 - \beta > 0.80$). It is important that a sufficient number of watersheds continue to be sampled to maintain high statistical power to detect population changes. Because helicopter surveys are expensive, continuing to sample all watersheds selected for monitoring in the future requires that adequate funding be acquired for future monitoring. It cost US $36,000 to sample 52 watersheds in 2007, and the cost of monitoring will increase in the future. A lack of funding to monitor with sufficient statistical power will fail to trigger appropriate management responses and is a major criticism of managed forests (Lindenmayer 1999).

Conclusions

Effective monitoring is needed for sound natural resource management. However, management focused on large geographic areas requires inferences to be made regarding the status and trends of resources across the management region. Monitoring programs with valid sampling designs allow such inferences to be made. This protocol for monitoring beaver will allow forest-wide inferences to be made regarding the status and trends of beaver abundance and presence at the level stated by the monitoring objectives. A strong ability to detect beaver population trends will allow forest managers to effectively alter current management practices if forest-wide trends in this keystone species are eminent and populations need to be conserved.

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