MODELING ELK DISTRIBUTION

IN BANDELIER NATIONAL MONUMENT, NEW MEXICO

by

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ABSTRACT

Elk (*Cervus elaphus nelsonii)* are large ungulates that can have significant impacts on ecosystems. Bandelier National Monument, New Mexico, is part of the winter range for the large herd of elk that summer on the nearby Valles Caldera National Preserve. The proportion of the herd that winters on Bandelier appears to have increased after the 1977 La Mesa fire burned through the area, and created favorable forage conditions at elevations that commonly have snow conditions conducive to wintering elk. Potential damage to archeological resources and disruption of ecosystem function from use by elk is of primary concern to area resource managers.

Winter aerial surveys have shown that elk use of the area is not uniform and that some areas are used much more heavily than are others. Our objectives were to assess wintering elk population density, identify seasonal distribution, habitat associations, and movement patterns to be used as inputs for the development of a spatially explicit computer model to predict the amount and potential duration of winter elk use on Bandelier. Elk *(n = 114)* were captured and radio-collared in and around Bandelier, and monitored from January 2000-February 2002 by fixed-wing aircraft, with most intensive data collection in December, January, and February. We estimated winter population numbers and density distribution by mark-resight analysis using a combination of fixed-wing aircraft telemetry surveys and visual helicopter surveys. We found a correlation between snow depth in the area and the number of elk wintering on Bandelier.

We quantified habitat variables in a $300m^2$ grid cell overlay of the study area in a GIS environment, and assigned a Desirability Index ranking system to cells as an index to

the likelihood of winter elk use. We developed a computer program that assigns elk to cells based on decision criteria supported by literature review and observed elk behavior. Initial conditions were assessed by static habitat parameters (elevation, aspect, slope, cover type, etc.) and then modified by the current values of the dynamic parameters (snow depth, amount of standing crop, number of elk present, etc.).

We found good correlation between DI score and mean number of telemetered locations per cell in all 3 winters studied. We corroborated model function through correlation of model output elk-days use to the density of elk recorded by aerial telemetry flights, concurrent helicopter visual surveys, and historic helicopter visual surveys. Model output was well correlated to telemetry data. Correlation of model output to helicopter survey data was reduced by poor sightability of elk from the helicopter, the limited number of survey flights conducted, and limitations of snow depth estimation techniques, but remained consistent under widely disparate winter conditions. Model output was most sensitive to variations in critical snow depth threshold at which elk are excluded from cells.

While model performance declined under low snow conditions, the model was flexible and dynamic and approximated the process intended. It produced results which could be corroborated quantitatively or qualitatively, can be easily analyzed and displayed, reflects current biological understanding of elk and their interaction with their environment, and can be readily modified as the knowledge base increases.

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Elk *(Cervus elaphus nelsonii)* are large herbivores that can have significant impacts on ecosystems. Gaffney (1941) recorded the results of overuse by elk in Montana, including nearly complete suppression of new growth of preferred woody species, increased volume of non-palatable shrubs, damage to conifers (many stripped of foliage below a 2 m high browse line), destruction of grasses, and acceleration of succession rate (leading to replacement of deciduous tree species by conifers). McCullough (1955) also reported a coniferous browse line, poor reproduction of tree species through suppression of seedlings, and displacement of mule deer *(Odocoilius hemionsis)* from traditional ranges in Idaho as a result of increased elk population. Olmstead (1979) found that age structure of aspen stands in north-central Colorado was inversely correlated to fluctuations in elk population levels. Sheppard and Fairweather (1994) also found evidence that elk herbivory contributed to aspen decline in Colorado. Kay (1985) cited evidence of significantly reduced regeneration of aspen *(Populus tremuloides)* in Yellowstone National Park (4%) when compared to areas outside the Park (60%) where use by elk was lower, and similarly, that willows *(Salix spp.)* were also declining at a greater rate than in surrounding areas. Kay and Bartos (2000) documented failure or reduced regeneration of aspen, and major changes in understory composition through reduction of shrubs and tall forbs in areas exposed to ungulate grazing as compared to areas where ungulates were excluded in south-central Utah. Many studies

have shown the ability of elk to influence secondary succession through selective grazing (Skovlin et al. 2002).

But not all studies point to deleterious ungulate impacts on their environment. Extensive research efforts to assess the effects of grazing in Yellowstone National Park, Wyoming, have also found positive or neutral effects of use by elk. Frank and McNaughton (1993) found that above ground productivity of vegetation grazed by native ungulates (elk and bison [*Bison bison]*) was 47% higher than that of ungrazed vegetation. Coughenour (1991) found that there was reduced standing dead material and litter biomass on most sites grazed by elk in winter compared to ungrazed sites, live above-ground grass biomass varied by year (possibly confounded by weather), live forb:grass ratio and root biomass were not significantly affected, and nitrogen content of both live and dead grass was increased. Grassland productivity, species composition, and bunchgrass mortality were not influenced by winter elk herbivory (Singer and Harter 1996), but elk use contributed to suppressed growth of willow stands (Singer et al. 1994). Croft and Ellison (1960) attributed soil erosion, destruction of vegetation, and increased runoff to excessive use by elk in the Teton Wilderness of Wyoming, but Gruell (1973) working in the same area concluded that range conditions were a product of environmental and geographic influences, and that the primary biotic agent contributing to erosion in the area has been high population levels of pocket gophers *(Thomomys talpoides tenellus).* While there continues to be debate about specific elk impacts, there can be no doubt that elk exact some degree of influence on their surroundings.

Modeling

Evidence of the ability of large ungulates to influence ecosystem structure and function underscores the importance of the relationship between ungulates, the vegetative resources they require, and the physical environment through which they move. The proliferation of the use of Geographic Information Systems (GIS) in natural resource management has allowed for detailed consideration of multiple aspects of the physical environment. By storing related attributes in successive data layers, many geographic features, and their relationships to each other can be examined simultaneously. Through this consideration of numerous individual components, GIS applications have afforded unprecedented examination of complex landscapes (Fedra 1993).

A landscape typically consists of clusters of resource patches distributed in a heterogeneous environment (Foreman and Gordon 1986). Movement is one the most fundamental means by which an animal interacts with its environment, so gaining insight into how animals move between resource patches is critical to a better understanding of ecosystem function. It is this spatial interaction that determines the distribution and abundance of organisms (McIntyre 2001).

Modeling is a powerful tool in natural resource management. By allowing for the simulation of different combinations of scenarios, an ecological model can provide a range of possible outcomes for consideration, without the ramifications of an actual manipulation of the resource, and allow insights into the possible effects of management decisions or natural events before they occur (Moen 1973).

While the modeling of spatial patterns has been a part of many forestry and vegetation studies for some time, until recently, considerations of spatial distributions were strictly statistical. Most results were not spatially explicit, meaning they were not connected to absolute location within some *X,Y* coordinate system (Fedra 1993) such as a landscape map. Van Horne (1991) asserts that making models spatially explicit is the key to the modeler's goal of integrating the benefits of simplicity and complexity, and can dramatically reduce error in the modeling process. Fedra (1993) observed that spatially explicit environmental modeling is increasing, but found modeling approaches built directly into GIS rather simple and restrictive. Fedra (1993) found that many modeling efforts reconcile this problem by using GIS to prepare spatially explicit data for model input, and then use GIS to display or analyze model results.

However, a spatially explicit model is not necessarily a realistic model. An ecological model is a simplified representation of some part of the real world (Morrison et. al 1998), but a simplification of a complex system demands the identification of critical elements, the components most vital to the interactions portrayed. Moen (1973) emphasized the need for realistic models built on a sound theoretical base, and functional biological relationships. A successful model must incorporate features of both the animal and the environment in order to represent the range of behaviors considered. In order to realistically represent movement of a free-ranging animal through a heterogeneous landscape, the modeler is faced with the challenge of identifying the features and processes that are important to the animal, and how they influence the distribution of individuals within the constraints of a spatially explicit environment.

Elk Model Parameters

Foraging. The daily activity of free-ranging elk in winter is dominated by foraging (Craighead et al. 1972, Gates 1980, Hanley 1982). As a group, wild ungulates typically devote 40-60% of each day to finding and consuming food (Wickstrom et al. 1984). Forage available to elk in winter is of lower quality than at other times of the year (Cook 1971) and so daily consumption rates required for animal maintenance must compensate for the lower crude protein content, among other energetic and nutritional deficiencies (Nelson and Leege 1982). While there have been many investigations into the daily food intake rates of elk, they have been primarily limited to study of tame animals under controlled conditions, as logistical constraints make measurement of the intake rates of free-ranging animals virtually impossible (Cook 2002). Results of forage consumption trials detailed by Nelson and Leege (1982) range widely, from 1.5 to 3.1% of net body weight and represent studies across age and gender categories. However, elk in those studies are often fed a high quality, ad libitum (HQAL) diet, with crude protein often in the range of 8 to 14%. Winter diets of free-ranging elk (browse and dormant herbaceous forage) are likely to be of considerably lower quality (Nelson and Leege 1982). Lang (1958) found that forage intake was 1.8-2.0% of body weight for elk eating native forage in New Mexico. Nelson and Leege (1982) suggested that for most natural wintering conditions for elk, consumption rate would be about 20 grams per day per kilogram of body weight. These results paralleled the conclusions of Holechek et al. (1995) who summarized a wide range of ruminant forage studies to estimate forage intake. They estimated that an elk intakes 6.4 kg of dry matter per day for a 318 kg elk

(2% of average weight of mature male and female animal). However, this estimate represented a yearlong average across seasons, and Holechek (1988) suggested that 1.5% of body weight was a more reasonable estimate during the dormant period when forage was of lower quality. Cook (2002) proposed a formula to estimate total food intake based on metabolic weight (MW = body weight$^{0.75}$). Their estimate of daily food intake rate for the winter months was 60 g kg^{-1} MW, which translated to 1.44% of body weight. However, this estimate was based on the work of Robbins et al. (1981), who worked with elk confined to a 0.32 acre enclosure which consumed alfalfa hay ad libitum with >17% protein content. The energetic demands of free-ranging elk would likely require forage consumption at higher rates than for penned animals (Thorne et al. 1976), but the cost of increased rumination time for lower quality winter forage available to free-ranging elk in winter may severely limit the total amount of forage consumed (Hanley 1982). Rowland et al. (1983) found mean crude protein of only 3.7 (± 0.35)% for winter forage consumed by elk in Bandelier National Monument, New Mexico (BAND), and 5.1 (± 0.35)% on higher elevation range just north of BAND. Hobbs et al (1980) reported an average crude protein of 5.4 (± 0.31)% in elk winter diets in Colorado. While crude protein content was particularly important for maintaining animal condition during winter (Hobbs et al. 1981) it is not the only factor determining forage quality. There is potential disparity between intake estimates from HQAL diet studies and the likely intake rates of free-ranging elk in winter.

Since herbivores tend to select forages of high nutritional value (Cook 2002), as total amount of vegetation in a given area is reduced, it is reasonable that nutritive quality

of forage per unit area will decline with continued use by elk. Hobbs and Swift (1985) and Thomas et al. (1988) reported that the nutritional quality of herbage was inversely related to its abundance in many ecosystems. Even when the total amount of forage available was not limiting, the nutritional status of individual animals may deteriorate as the nutritive quality of available forage declines with declining quantity. As forage quality declines, the time required for rumination increases, and daily food intake will decline as it is increasingly restricted by food passage rate (Green and Bear 1990). Hence elk cannot endlessly compensate for declining forage quality by eating greater quantities, and in order to optimize foraging time, changes in activity pattern can be expected (Hanley 1982).

Elk are classified as intermediate feeders, with adaptations between the concentrate feeders like white-tailed deer *(Odocoilius virginiana)*, who have narrower muzzles and select for more highly digestible forage, and the roughage feeders like cattle and bison, with larger muzzles and increased capacity for digesting large volumes of food (Cook 2002). While dietary habits of elk are quite plastic and vary widely both spatially and temporally, they are considered to be grazers rather than browsers (Kufield 1973). However, browsing tends to increase in the winter (Boyd 1970, Moran 1973, Hobbs et al. 1981). Hobbs et al. (1981) reported that the proportion of browse consumed during winter months increased and the proportion of grass declined as winter progressed, allowing elk to maintain relatively constant diet quality in the face of large fluctuations in quality of individual forages. Lang (1958) found that browse comprised up to 95% of elk winter diets in New Mexico. Rowland et al. (1983) found that elk are able to maintain

diets with protein and digestibility values higher than mean forage values, which tend to be at their minimum during winter months. While grasses provide a better digestible source of energy, browse contains more protein, allowing elk to vary the chemical composition of their diets by shifting the proportions of grass and browse consumed (Hobbs et al. 1981). This flexibility of foraging behavior as winter progresses not only helps to offset the potential deleterious physiological effects of protein deficiencies, but can also promote increased digestion of the poorer quality grasses by promoting a rumen environment better able to digest grass fiber (Hobbs et al. 1981).

Declining forage quantity can also constrain food intake in large-bodied ungulates like elk. Elk seem to be better suited to foraging in high-biomass herbaceous or mixed communities, and when available forage declines below some critical threshold, energy requirements may not be met (Wickstrom et al. 1984). Wickstrom et al. (1984) found that while absolute availability of forage was not initially an important limit to food intake, when biomass was reduced to some specific critical threshold, food intake would decline dramatically. They reported a similar asymptotic intake response to overall forage biomass in a number of wild and domestic ungulates, with different threshold levels specific to the metabolic needs and foraging strategies of the different species. Collins et al. (1978) observed that when forage density decreased, elk would spend more time walking and searching for more preferred species, and Wickstrom (1984) found elk rate of travel to be greater in areas of lower biomass, all serving to increase the likelihood of the animal moving until a more desirable area could be found.

Seasonal movements. Migratory behavior has long been observed in northern species of artiodactyls like caribou *(Rangifer tarandus)*, moose *(Alces alces)*, and elk (Orr 1970). However, not all elk populations migrate, and not all seasonal movements can be classified as true migrations. Some elk populations move in response to changes in forage or other local conditions and are not considered migratory (McCullough 1969). Such movements resemble migration in that they are generally from higher elevation summering areas to lower elevations in winter, but they differ from true migration in that under the right conditions (some combination of ample forage, water and cover availability) elk will remain in an area year-round, moving to a more suitable area only if conditions change in the course of the season (Adams 1982). Another consideration is that seasonal movement patterns can vary within a population. There is evidence that some segments of a population will migrate while others do not, with no stable distinctions between the groups at other times of the year (Martinka 1969, Boyd 1970, Craighead et al. 1972), and that portions of a population may remain on winter range months after the bulk of the herd has moved off (Knight 1970). Return to summer range is influenced largely by emergence of new vegetation (Knight 1970), or decreasing snow cover, especially on south-facing slopes (Skovlin 1982). Migratory behavior allows support of more individuals than would be allowed by year-long use of a single range, allows greater recovery and accumulation of forage on winter range during non-use summer periods, and allows the potential for range expansion by individuals moving into non-traditional areas, but may also increase exposure to anthropogenic influences, especially increased exposure to hunting mortality (Irwin 2002).

Range fidelity. Individual elk often exhibit fidelity to seasonal ranges (Murie 1951, Brazda 1953, Knight 1970, Craighead et al. 1972, Irwin and Peek 1983, Edge et al. 1985, Van Dyke et al. 1998). Gillingham and Bunnell (1989) found that herbivores are able to remember locations with abundant, suitable food. In feeding and foraging trials they found that black-tailed deer (*Odocoileus hemionus columbianus)* learned to better exploit food distributions with repeated exposure to them. They found that success rates increased significantly with repeated exposure to a familiar distribution of resources. Range fidelity in elk confers a similar benefit through increased knowledge of the seasonal availability of resources (Edge et al. 1985). Such combined herd knowledge of range use may be possible through the cow-calf bond and the common leadership role of older females in the herd. Murie (1951) asserted that elk learned seasonal affinity for specific areas by following their mothers. Franklin and Lieb (1979) found the elk mother-offspring relationship to be a cohesive and relatively stable assemblage that may persist throughout the life of the animals. They found that the period of greatest stability occured during the months from early winter through late spring, and while their study involved a non-migratory herd in a highly stable environment, a similar pattern in a migratory herd would be concomitant with migration and range selection behaviors. Anecdotal support of such patterns of social strúcture from observations of unmarked animals has long persisted (Darling 1937, Altman 1952), and elements of similar group characteristics have been reported in other non-migratory herds in California (McCullough 1971) and in Michigan (Moran 1973).

However, the inherent challenges of quantifying lasting associations between individuals in a free-ranging migratory elk herd are great, and there have been conflicting assessments in the literature. Knight (1970) examined "group constancy" as determined by a coefficient of association. His marking procedure precluded examination of mother-offspring groups specifically, but he found there to be no great attraction or association between individual animals in a migratory elk herd in Montana, while Shoesmith (1980) reported that cows and their calves consistently sought each others company during his investigation of a migratory elk herd in northern Yellowstone National Park. While supporting evidence is as yet inconclusive, a stabile mother-offspring assembly combined with long-term use of a given range would provide a process by which range boundaries could remain virtually unchanged from generation to generation, exceeding the life span of individual elk (Van Dyke et al. 1998). Elk have also been shown to use the same migratory routes year after year through some combination of topography and learning through repeated use (Altman 1952, Brazda 1953, Boyce 1989).

Snow depth. While the influence of snow on wintering ungulate populations can vary by snow depth, density, and hardness, snow depth has been considered the most important attribute affecting ungulate movement and mobility (Parker et al. 1984), and may be the most important factor influencing overall movement patterns and seasonal migration of elk (Adams 1982). Anderson (1954) suggests that initiation of winter migration of elk in Jackson Hole, Wyoming coincided with snow depths of 15 to 25cm. Similarly, Rudd et al (1983) correlated the timing of migration from Yellowstone National Park in response to ~20cm of snow. While such moderate snow accumulations

are unlikely to restrict access to underlying vegetation, Fancy and White (1985) found that snow accumulations of 25-30 cm considerably increase energy expenditures and Parker et al. (1984) showed that relative increase in net energy expenditure as a percentage above the cost of travel without snow increased exponentially as a function of effective snow depth. Snow depths >46 cm have been observed to restrict elk movements in Montana (Beall 1974), Idaho (Leege and Hickey 1977), and Michigan (Moran 1973). Sweeny and Sweeny (1984) found that in Colorado snow depths >40 cm resulted in elk moving to areas with less snow and areas with snow depths >70 cm were rarely used. Models of the influence of snow depth on migration of the Jackson elk herd in Wyoming indicates that snow accumulations in October were inconsequential to the timing of migratory movements, while heavy November snow accumulation results in a high proportion of elk migrating in November, illustrating that the timing of snow accumulations was also important (Boyce 1989).

Elevation. While elevation does not directly impact patterns of use by elk and elk inhabit a broad range of elevational gradients, it does influence habitat use as snow depth, precipitation, and plant distribution and phenology are all directly related to elevation (Skolvin et al. 2002). Use of higher elevation summer ranges may provide access to forage of greater nutritional value than vegetation available at lower elevations (Albon and Langvatn 1992, Morgantini and Hudson 1989).

Slope. Variations in slope also contribute to differential use by influencing microclimate and vegetation (Skolvin 1982). In Idaho Leege et. al (1975) found that summer elk use was slightly higher on 20-40% slopes, while Hershey and Leege (1982)

later found that elk used slopes of <20% in excess of their availability and avoided slopes >60% in the same area. Mackie (1970) and Komberic (1976) both found that the majority of wintering elk use in central Montana occurred on slopes of <18%. Julander and Jefferey (1964) report that summer use by elk was fairly uniform on slopes up to 30% and decreased on steeper slopes in Utah. Elk use was most common on 15-30% slopes on summer range in Montana (Zahn 1974). Slopes used appear to vary seasonally, and considering the studies listed here, and more listed in Skovlin (1982) and Skovlin et al. (2002), it appears that elk tend to make greater use of steeper slopes (~15-40 %) during the summer months, and gentler slopes (0-20%) during winter, and that use decreases sharply between 40-50 %, with slopes >90 % rarely used.

Aspect. Elk often show preferential use of southern aspects during winter. Skovlin (2002) provides an extensive listing of concurring study results. In addition, Unsworth et al. (1998) found that elk wintering in Idaho preferred areas of south-facing aspect while hardly using areas of east-facing aspect. Irwin and Peek (1983) found that aspect was a primary selection criteria on winter range in Idaho, and that elk selected south to southwest-facing areas. Beall (1974) found similar patterns in western Montana. Weber et. al (1984) reported elk wintering primarily on southern and western slopes in the Jemez Mountains of New Mexico. Leege and Hickey (1977) found that elk in the Pete King Drainage of Idaho made heavy use of southerly aspects during winters of varying snow accumulations, and increased use of east and west aspects during winters with snow depths <45 cm. Seasonal elk use of different aspects is primarily a function of forage availability, variation of thermal conditions, and vegetative cover type. Winter

preference of southern aspects is likely due to increased forage availability allowed by decreased snow depths from combinations of wind, solar radiation, or shade patterns (Skovlin et al. 2002).

Canopy. The importance of vegetative cover for wildlife has long been recognized (Leopold 1933). Elk are often associated with ecotones, or edges where different types of vegetation are juxtaposed, that often provide higher diversity and greater quantity of forage plants used by elk than found in the individual adjacent communities (Skovlin et al. 2002). Reynolds (1966) and Harper (1969) showed that most use by elk occurred within 185m of the edge between cover and forage areas. Leckenby (1984) supported and expanded their conclusions, finding elk use disproportionately greater in cover areas within 185m of cover-forage area edges and in forage areas within 278m of such edges. Thomas et al. (1979) defined cover as either thermal cover, defined as any stand of coniferous trees =12 m tall with >70% average canopy closure, or hiding cover, defined as vegetation capable of hiding 90% of a standing adult elk from the view of a human at a distance ≥61 m. They contended that all levels of canopy closure provided some thermal advantage to elk, with stands of 40-69% canopy closure defined as marginal thermal cover. Forage areas were defined as all openings and forest stands that do not meet hiding or thermal cover requirements. Thomas et al. (1979) used these criteria to define an optimum mix of cover types of 40% cover (20% hiding, 10% thermal, 10% either) to 60 % forage areas in the Blue Mountains of Oregon and Washington. While the importance of thermal cover to elk fitness has been questioned (Geist 1982, Peek et al. 1982, Cook et al. 1998), Lekenby (1984) and Thomas et al.

(1979) did find preferential use of optimal areas, and so the criterion remains valid as a tested habitat attribute (Thomas et al. 1988). Thomas et al (1988) suggested that cover be classified as satisfactory (a stand of coniferous trees >12 m tall with ≥70% canopy closure, marginal (a stand of coniferous trees >3 m tall with ≥ 40% canopy, or forage areas, that do not meet the definitions of satisfactory or marginal cover, without regard to the designations of hiding or thermal cover. Short et al. (1977) found that production of midstory browse and understory herbage was reduced under denser canopies in piñon pine *(Pinus edulis)*-juniper *(Juniperus monosperma)* woodlands in New Mexico and resulted in decreased use by elk. Dense canopy cover blocking transmission of solar energy to understory vegetation results in reduced photosynthetic levels in understory communities (Van Soest 1994). While vegetative biomass in forested areas is typically lower than in grassland areas (Thomas et al 1988), forage within cover stands can be important to elk in winter, as canopy intercept of snow tends to increase access to forage that may be covered by greater snow accumulations in unforested areas (Leckenby 1984, Parker et al. 1984). Beall (1974) found that elk preferred to bed in clumps of dense conifers under virtually all meteorological conditions. Severson and Medina (1983) cite evidence of an inverse relationship between amount of overstory and resulting productivity of understory, and a positive response between understory forage production and cervid use, implying an inverse relationship between cervid use and amount of overstory. Obviously this pattern cannot be applied in the extreme, and it is the balance of the two factors that is important. Reynolds (1964) suggested that tree densities can be

either too high or too low for ideal elk habitat use, implying an optimum potential for elk use at some intermediate canopy densities.

Vegetation type. Elk are highly adaptable animals and their range covers a broad spectrum of vegetation types, from prairie to boreal forest and coastal rainforests to arid sagebrush desert (Peek and Scott 1985). The results of individual studies of elk preference for particular vegetation types vary accordingly. Knight (1970) found strong selection by elk for grasslands during winters in Montana, with observed use as high as 90%, while Irwin and Peek (1983) found no significant selection patterns for elk on winter range in Idaho, with habitat type, successional stage, and canopy cover all used in proportion to availability. Studies of habitat selection by elk reflect the influences of regionally specific vegetation variables, and can often be interpreted in terms of either general forage preference (Krufeld 1973), or the structural components considered above. Vegetation types vary widely regionally, and selection is by definition some function of availability.

Use of burn areas. Native American cultures have probably been aware of the effects of fire to enhance elk habitat for centuries by setting back plant succession to increase the variety and abundance of palatable forage (McCabe 2002). Fire can create a mosaic of forest stands where ecotones produce a preferred combination of forage and cover (Skovlin 1982). Many ungulates show positive response to post fire vegetation (Bendell 1974, Rounds 1981, Hobbs and Spotwart 1984, Hornbeck 1985). Elk winter ranges are often concentrated in areas historically impacted by fires or burned for management purposes (Irwin and Peek 1983, Peck and Peek 1991). Preferential use of

burned areas can continue well beyond the initial increases of early successional herbaceous growth. Winter use by elk captured in 1977-1978 in the Jemez Mountains of New Mexico was centered on areas burned 25 years earlier, but after a winter storm in 1979, winter use shifted to an adjacent, mid-elevation area that had been impacted by a large, canopy fire 2.5 years earlier (White 1981). The latter burn area (from the 1977 La Mesa Fire) was still important wintering habitat for elk in the region 25 years later.

Group Size. Elk group size tends to be larger in winter months (Knight 1970, Mackie 1970, Shoesmith 1979, Franklin and Lieb 1979). During his study of the Sun River elk herd in Montana, Knight (1970) found maximum mean group size occurred in winter [$\bar{x}$ = 6 for bulls, $\bar{x}$ = 48 for cows ($\bar{x}$ = 26 combined)]. Mackie (1970) saw group sizes ranging from 1-66 with maximum mean group size ($\bar{x}$ = 15) in a wintering elk herd in the Missouri River Breaks of Montana. Franklin and Lieb (1979) also reported maximum mean group size during winter in an elk herd in California [$\bar{x}$ = 7 for bulls, $\bar{x}$ = 30 for cows ($\bar{x}$ = 19 combined), and Shoesmith 1978 reported groups of wintering elk in Northern Yellowstone were typically comprised of 20 or fewer individuals.

CHAPTER II

BACKGROUND INFORMATION

Study area

Location, geology and climate. Bandelier National Monument (BAND) is located in north-central New Mexico on the southern portion of the Pajarito Plateau on the east flank of the Jemez Mountains, at the southern edge of the Rocky Mountains, about 35 km west of Santa Fe (Figure 2.1). The Pajarito Plateau is composed of up to 300 m of consolidated ash tuff deposited during volcanic activity around 1.4 to 1.1 million years ago. The resulting ash flows from cataclysmic eruptions buried the surrounding area under vast quantities of ash and debris (Mathien et al. 1993). The subsequent collapse of the volcanic pile resulted in the formation of the giant Valles Caldera, a huge bowl-like depression 19-24 kilometers across with a floor up to 900 m below its rim of surrounding mountain ridges, the Sierra de los Valles. Forested mountain peaks formed by resurgent magma domes punctuate the vast open grassy meadows of the Valles Caldera that lies just to the northwest of BAND. This volcanic debris is the primary parent material for the soils in the region, derived from rhyolite tuff, ash, and other volcanic debris. Subsequent erosion has cut the surface of the plateau into long, narrow, flat-topped mesas separated by abrupt, steep-walled canyons, many 200-250 m deep (Earth Environmental Consultants 1974, Mathien 1993). Steep canyon side-slopes are characterized by extremely rocky, shallow soils less than 51 cm deep, mesa-top soils are moderately deep (51-91 cm), and sandy alluvial soils are found in the canyon bottoms (Foxx 1984).

Bandelier is comprised of 13,629 hectares, with elevations ranging from 1,680m at the Rio Grande River to 3,240m at the summit of Cerro Grande which lies at the edge of the Valles Caldera. The area has a semi-arid continental mountain climate (Foxx 1984), receiving an average annual precipitation of 47.7 cm that varies considerably (+/- 12.2 cm). Precipitation is dependant on elevation, with an annual average of 23 cm along the Rio Grande to as high as 76 cm along the mountain ridge of BAND's upper boundary (Purtymun and Adams 1980). Most of this moisture arrives via late summer convective thundershowers during July and August. July is typically the warmest month with average daily temperature range from 27.2 °C to 12.8 °C. Mean annual precipitation was below average for the extent of this project (Figure 2.2). Winter temperature extremes are usually in January, with daily average temperatures ranging from 4.4 °C to –8.3 °C. The relatively dry, clear atmosphere in the region allows strong solar heating during the day and rapid radiative cooling at night, producing this large daily range in temperature. Annual snowfall averages 148.8 cm but is also quite variable (+/- 71 cm). The area experienced below average snowfall during 2 of the 3 winters documented in this study (1999-2000 and 2001-2002) and above average snowfall during the winter of 2000-2001 (Figure 2.3). Data are from the official Los Alamos meteorological station (elevation 2,250m) from 1971-2000 (Weather Machine 2003, NOAA 2003).

Topography and vegetation. Bandelier is dominated by 3 major canyons and a system of secondary canyons carved by erosion through the soft volcanic rock, generally sloping to the southwest from the plateau's upper elevations down toward the Rio

Grande. A steep escarpment (~2320-2460 m elevation) marks an approximate dividing line between the lower and mid-elevations below, and the upper elevations above. Variations in topography and elevation have yielded diverse vegetative patterns (Wilcox and Breshears 1994). The elevations in BAND correspond to three broad vegetative communities (Conely et al 1979, Foxx and Hoard 1995, Mathien et al. 1993) (Figure 2.4). The lower elevations (~1,680-2,000 m) dominated by piñon-juniper woodlands. This region is typically more arid with widely spaced trees, and a shrub component of wavey-leaf oak *(Quercus undulata)*, Apache plume *(Fallugia paradoxa)* and mountain mahogany *(Cercocarpus montanus)*, with scattered grassland patches of little bluestem *(Andropogon scoparius)*, galleta *(Hilaria jamesii),* and grama grass *(Bouteloua spp.)*. The mid-elevations (~2,000-2,500 m) are transitional areas with a ponderosa pine *(Pinus ponderosa)* overstory and mixed grasslands that include mutton grass *(Poa fendleriana)*, June grass *(Koeleria cristata)*, mountain muhly *(Muhlenbergia montana)*, pine dropseed *(Blepharoneuron tricholepis)* and little bluestem. Understory is comprised primarily of Gambel oak *(Quercus gambelli)*, New Mexico locust *(Robinia neomexicana)*, and mountain mahogany. Mixed conifer forests dominate the upper elevations (~2,500-3,240 m), with an overstory typified by a mix of ponderosa pine, Douglas fir *(Pseudotsuga menziesii)*, white fir *(Abies concolor),* blue spruce *(Picea pungens)* and groves of quaking aspen *(Populus tremuloides)*. Understory components include Gambel oak, rock spirea

(Holodiscus dumosus), waxflower *(Jamesia americana)*, kinnikinnik *(Arctostaphylos uva-ursi)*, and creeping barberry *(Berberis repens)*.

Grasses include slender wheatgrass *(Agropyron trachycaulum)*, Canada bluegrass *(Poa compressa)*, and Parry oatgrass *(Danthonia parryi)*. High-elevation grasslands typically dominated by oatgrass *(Danthonia spp.)*, brome grass *(Bromus spp.)*, and Thurber fescue *(Festuca thurberi)* occupy intermittent breaks in the mixed conifer canopy, usually on south-facing slopes of the upper elevations. Los Ritos de los Frijoles in Frijoles Canyon is the only perennial stream in BAND. This and other canyon streams in the upper elevations can have water nearly year-round and support riparian communities with relatively high productivity, including narrow-leaf cottonwood *(Populus agustifolia)*, boxelder *(Acer negundo)*, and a variety of shrubs and grasses, while streams in the lower canyons are intermittent and representative species from each vegetative community can be found throughout (Foxx 1981).

Human influence and administration. The landscape of the area has been altered significantly by human influences. Since the 1880s, heavy livestock grazing and fire suppression have produced profound changes in the floral and faunal communities (Allen 1989). President Woodrow Wilson established BAND as a National Monument on February 11, 1916, by the authority granted by the Preservation of American Antiquities Act of 1906 to reserve Federal land of significant pre-historic, historic, and scientific interest by proclamation as a national monument. The proclamation was intended not only to preserve the abundant archeological resources of the ancestral Puebloan civilization that flourished there from the 1100s through the 1500s, but was also an

attempt to resolve conflicts between the U.S. Forest Service (USFS) and the National Park Service (NPS) about the future of land use on the Pajarito Plateau (Rothman 1988). Artifacts and architectural remains can be found in over 3,000 archeological sites within the modern boundaries of BAND (Lissoway 1996), making it one of the richest concentrations of prehistoric cultural artifacts in the Southwest (Foxx 1981). The NPS sought to preserve a larger portion of the region as a National Park, while the USFS feared excessive reservation of large areas of timber and pastureland on the plateau (Rothman 1988). Historically, livestock grazing was widespread and largely uncontrolled across the Jemez Mountains (Allen 1989). The new National Monument was to be administered by the USFS, and livestock grazing continued in the area until BAND was transferred to the NPS in 1932. Since that time BAND's mission has been expanded from the preservation of archeological resources to include the protection and preservation of the natural resources and wilderness values (Dilsaver 1994).

BAND is surrounded by a patchwork of land ownership and administration. The Santa Fe National Forest (SFNF) of the USFS borders BAND to the west, northeast, and southwest. The Valles Caldera National Preserve (VCNP) that lies to the northwest is a unit of the USFS and is administered by an appointed Board of Trustees. Before its acquisition by the federal government in June of 2000, the Valles Caldera was privately owned and managed as the Baca Ranch, primarily for the grazing of cattle and timber harvest. The VCNP represents the bulk of the summer range for the largest herd of elk in New Mexico. Los Alamos National Laboratory (LANL) borders BAND to the east, and both state and private lands lie just across the Rio Grande on BAND's southern border.

The area is also home to a number of tribal reservation lands including the Cochiti, San Ildefonso, Santa Clara, and Jemez Pueblos (Figure 2.1). All represent distinct jurisdictional entities, often with differing management objectives.

Fire History. Fire is an integral part of forested ecosystems throughout the Southwest. Allen (1989) documents evidence of fire as a major component of ecosystem process in the Jemez Mountains for the last several thousand years. He also used fire scar chronologies to show that frequent wide-spread, low-intensity surface fires were the dominant fire regime in the Frijoles watershed, which extends from the northern-most point on BAND (the summit of Cerro Grande) to its southern-most boundary where the Rio de los Frijoles joins the Rio Grande, encompassing nearly half of BAND's total area. This pattern changed abruptly in the late 1800's, and coincides with dramatic increases in domestic livestock in the Jemez Mountains. The coming of the railroad into the Upper Rio Grande watershed in 1880 added greatly to the already increasing human and livestock populations, and accelerated the shift from more subsistence-oriented agricultural practices to a commercialized livestock industry. Livestock populations in the region reached an all time high in 1900, and remained unregulated until the passage of the Taylor Grazing Act in 1934 (Smith 1953). Heavy grazing pressure likely induced widespread reduction in the quantity and continuity of herbaceous fuels, inhibiting the spread and intensity of surface fires throughout the region (Allen 1989). Although inadvertent, this de facto fire prevention effectively changed the role of fire throughout the region. This reduction of widespread, low-intensity surface fires led to the build up of woody fuels by the early 1900's, when land management agencies began

institutionalized fire control efforts in earnest (Pyne 1982). The aggressive fire suppression policy of the NPS mirrored that of the USFS of the day, emphasizing rapid suppression of all fires. This remained the guiding directive until a gradual paradigm shift in the 1960s and 1970s brought greater understanding of fire dynamics and recognition of fire as a part of the system rather than a categorical threat to it (Pyne 1982). A variety of fire management strategies, policies regarding natural fires vs. human-caused fires, and prescribed fire programs emerged during this period. By the time the NPS appointed a task force in 1976 to evaluate the various plans and produce a consistent national program (Pyne 1982), the legacy of decades of fire suppression was evident throughout the forested landscape of BAND. Lissoway (1996) cites forest densities often exceeding 800 stems per hectare of even-aged and stagnant mature trees, Forester (1976) recorded fuel loads up to 8.7 metric tons per hectare, and Allen (1989) reports the build up of increasing ladder fuel loads, setting the stage for increasingly large, intense, and destructive fires.

In June 1977, a human-ignited fire started 2 miles west of BAND under exceptionally hot, dry conditions. By the time it was declared contained over 6,250 ha of forested land had burned: 1,086 ha on Santa Fe National Forest (SFNF), 1,024 ha on LANL, and 4,140 ha on BAND, making the La Mesa Fire the largest and most intense fire in the Jemez Mountains in almost 100 years (Lissoway 1994) (Figure 2.5). The La Mesa Fire burned as an intense crown fire through the dense ponderosa pine forests centered on the Frijoles watershed, profoundly altering the structure and composition of the area, leaving large treeless grasslands and relict forest stands in the heart of a zone

otherwise dominated by ponderosa pine forest (Allen 1989). This pattern was repeated in 1996 when an unattended campfire in the SFNF ignited the Dome Fire, another hot, fast-moving crown fire that burned an even larger area, 6,684 ha on BAND and SFNF, again centered on the ponderosa pine grassland community, just west of the La Mesa burn area (Figure 2.6). A series of smaller lightning and human-caused fires soon followed in and around BAND until in May of 2000, a management-ignited burn to reduce fuel loads on BAND escaped its prescription and raged across more than 17,350 ha of BAND, SFNF, LANL, and the San Ildefonso and Santa Clara Pueblos, the largest and most destructive fire in New Mexico history (Figure 2.7). The burn perimeters fit together like pieces of a puzzle across similar habitat types. The resurgence of fire into the forested ecosystems of BAND has had profound impacts on the geology, flora, and fauna of the entire region.

Elk and Bandelier. Rocky Mountain elk are native to northern New Mexico (Bryant and Maser 1982) but archeological and historic information suggests that they were not abundant in the BAND area (Allen 1996) and were extirpated from the region around the turn of the twentieth century (Bryant and Maser 1982). In 1948, the New Mexico Game and Fish Department (NMGF) reintroduced 28 elk to the Clear Creek area of the Jemez Mountains with another 58 animals released in 1964-1965. The population has exhibited rapid growth, although population estimates have been imprecise (Allen 1996). Many factors can bias the results of aerial surveys of elk, including group size, amount of vegetative cover in the survey area, snow conditions, animal behavior, search rate, and observer bias (Samuel et al. 1987). NMGF began applying a sightability model in 1999 to help account for these inherent variations and refine their estimation

procedures. Recently, NMGF permitted increased hunting pressure and population estimates of the Jemez Mountains elk herd have declined from a high of around 7,000 animals in the early 1990s to about 4,500 in 2000 and 2001 (NMGF 2002). Surveys in September 2002 estimated the population to be ~ 5,200 individuals, with 60-80 % of that number likely to be in the Valles Caldera National Preserve (VCNP) (hunt unit 6B), (Kirkpatrick 2002-pers. comm.). This results in the most recent estimate of elk on the VCNP to be between 3,120-4,160 individuals.

Justification

It is appropriate to focus our attention on use by wintering elk, as winter range conditions can be the primary determinant of large ungulate survival and reproduction (Houston 1982, Parker et al. 1984, Wickstrom et al. 1984). The population of the Jemez Mountains elk herd as a whole and the portion of the herd that winters on BAND appears to have increased dramatically after the La Mesa Fire burned densely forested areas of ponderosa pine on BAND, creating about 6,000 ha of new winter range. Aerial seeding of burned areas and post-fire succession provided a diverse mix of grasslands, shrubs, and forests at moderate elevations (from 2000 to 2600 m), creating productive food sources at elevations that commonly have favorable snow conditions for wintering elk (Allen 1996).

Estimation of winter elk population size in the study area has historically been hampered by inherent difficulties in conducting surveys in heavily forested rugged terrain. Bear et al. (1989) found that probability of sighting elk varied widely across

terrain and vegetation types and usually resulted in greater than 50 % of the animals being missed. Even so, winter aerial counts in BAND between 1990 and 1995 indicate that from 46 to 98% of the total elk population within Unit 6 as estimated by NMGF may include BAND as part of their winter range (Allen 1996). These same aerial surveys showed that elk use of the area was not uniform and that the distribution, duration and number of wintering elk on BAND appeared to vary with winter conditions and/or elk population size (Allen 1996).

While there is much debate about direct cause-and-effect connections between ungulate use and specific results, many impacts on BAND have been attributed to elk use. Increased soil erosion may be attributed to elk on BAND, especially in the shallow soils of the piñon-juniper regions on BAND's lower elevations, where a 1978 soil survey documented unsustainable net soil losses from erosion in many areas (Earth Environmental Consultants 1978). Allen (1989) found evidence of past and current erosion in almost all areas of BAND. Park resource managers were concerned that high elk use of these areas might add to the problem, as did impacts from feral burros in the past (Allen 1996). Over 70% of archeological sites on BAND have been damaged by soil erosion, and in the spring, elk hoof prints can cover the bare ground between the sparse piñon-juniper stems (Allen 1996). Water is a scarce resource in the region, particularly at upper elevations. Water sources on portions of BAND may have been degraded by heavy elk use, evidenced by elk-trampled pond margins, wallows, and high water turbidity (Allen 1996). Impacts of browsing by elk are common. Wintering elk damage banana yucca *(Yucca baccata)* across the piñon-juniper woodlands. Aspen reproduction

has been inhibited in some area of the La Mesa burn, and mature aspen trees are heavily barked in many areas. Browse damage to many shrubs [ocean spray *(Holediscus dumosa)*, New Mexico locust *(Robinia neomexicana)*, various oaks *(Quercus spp)*, and buckbrush *(Ceanothus fendlerii)* can be found in high-use wintering areas (Allen 1996). There is also evidence of the suppression of vegetative development on montane meadows in BAND. Vegetation cover on montane grasslands consisted of early to mid-seral introduced plant species as the result of heavy elk use when sampled in 1993. Incidental exclusion of grazing pressure resulted in a shift in species composition of both grass and forbs (Wolters 1996).

The results of our research will be applied to efforts by BAND and Texas Tech University to assess potential impacts of different intensities of elk use across BAND. Data are needed on elk population density, distribution, habitat use, and movement patterns to provide BAND managers with the basis for informed management decisions.

Objectives

Our objectives were to:

1. Identify seasonal distribution and movement patterns of elk that winter on BAND in relation to major topographic features and land administration boundaries.
2. Provide population and survival estimates of elk wintering on BAND.
3. Develop a spatially explicit computer model to predict the timing, amount and potential duration of elk use on areas within BAND.

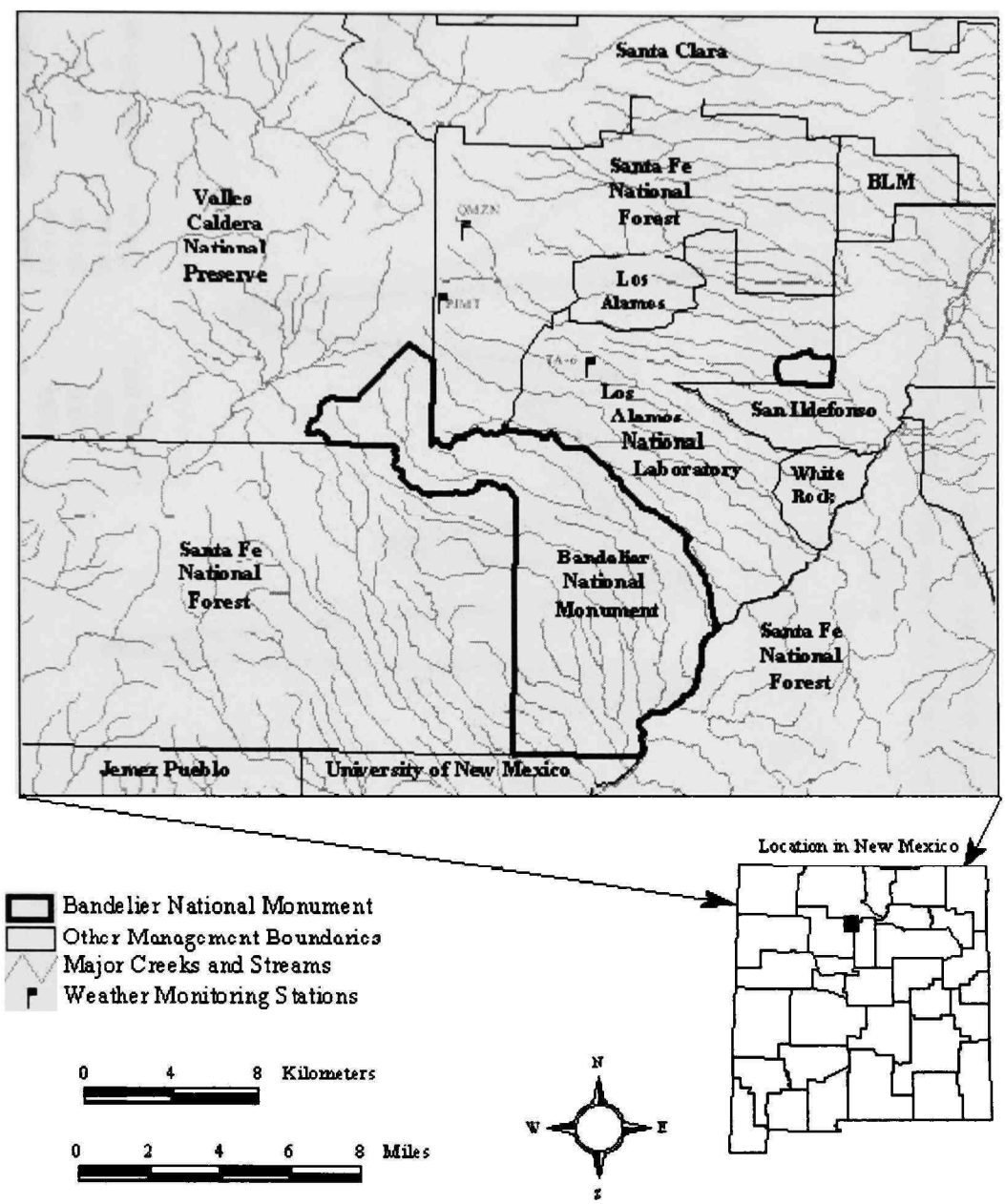

Figure 2.1. Location of Bandelier National Monument and surrounding management units in New Mexico.

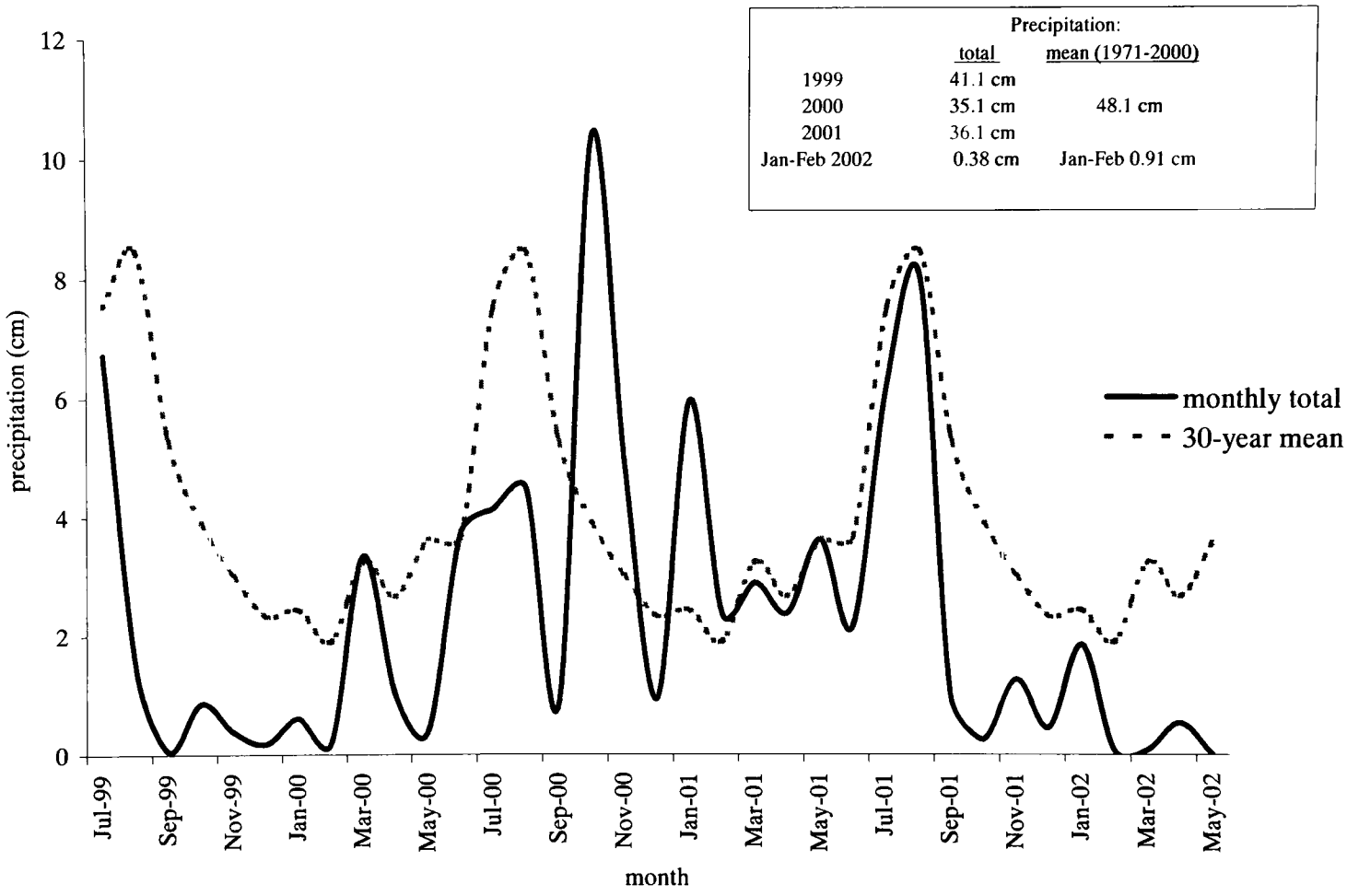

Figure 2.2. Montly precipitation from July 1999-May 2002 in the Bandelier National Monument, New Mexico area compared with average monthly precipitation (1971-2000).

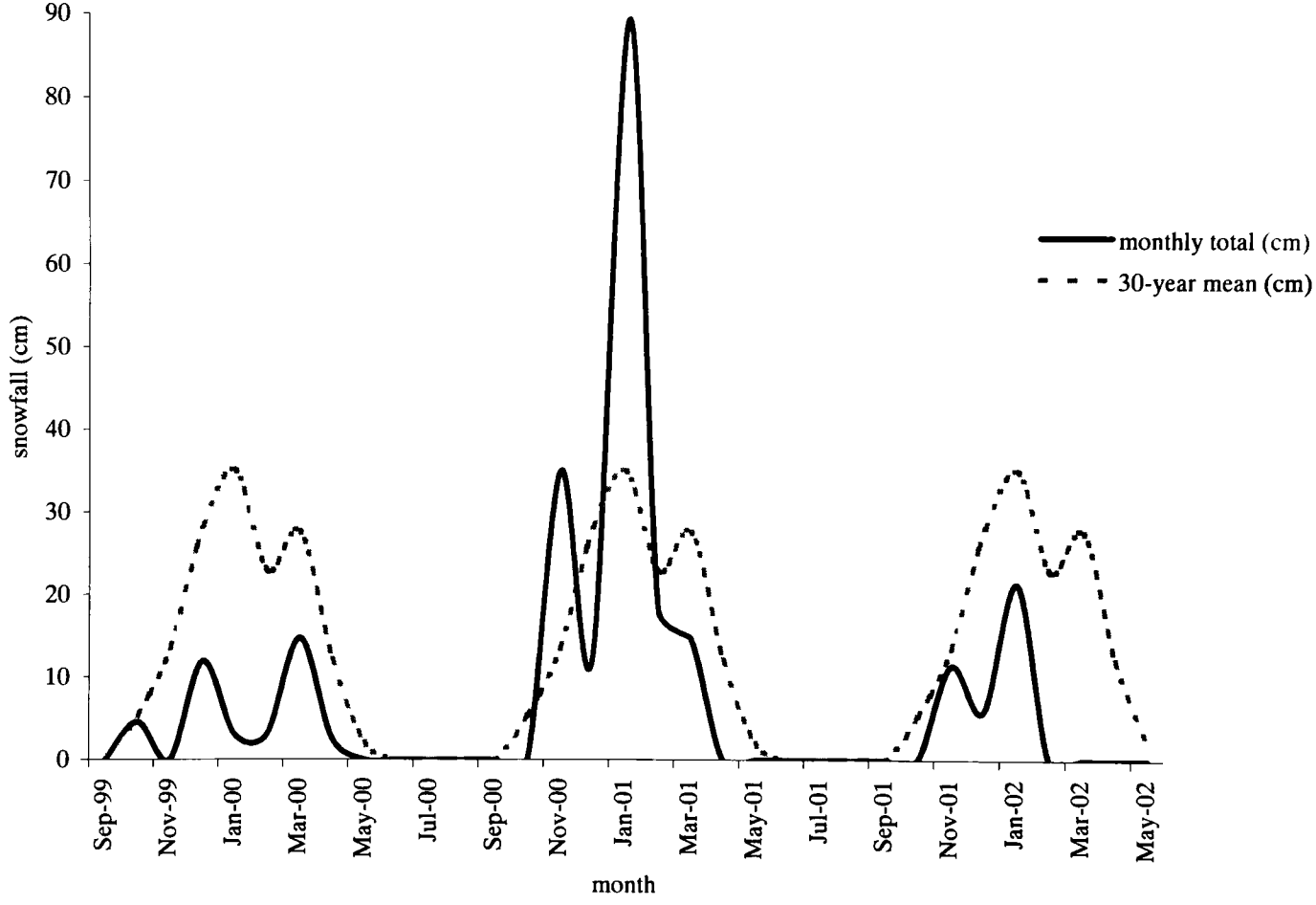

Figure 2.3. Monthly snowfall from September 1999-May 2002 in the Bandelier National Monument area compared with average snowfall (1971-2000)

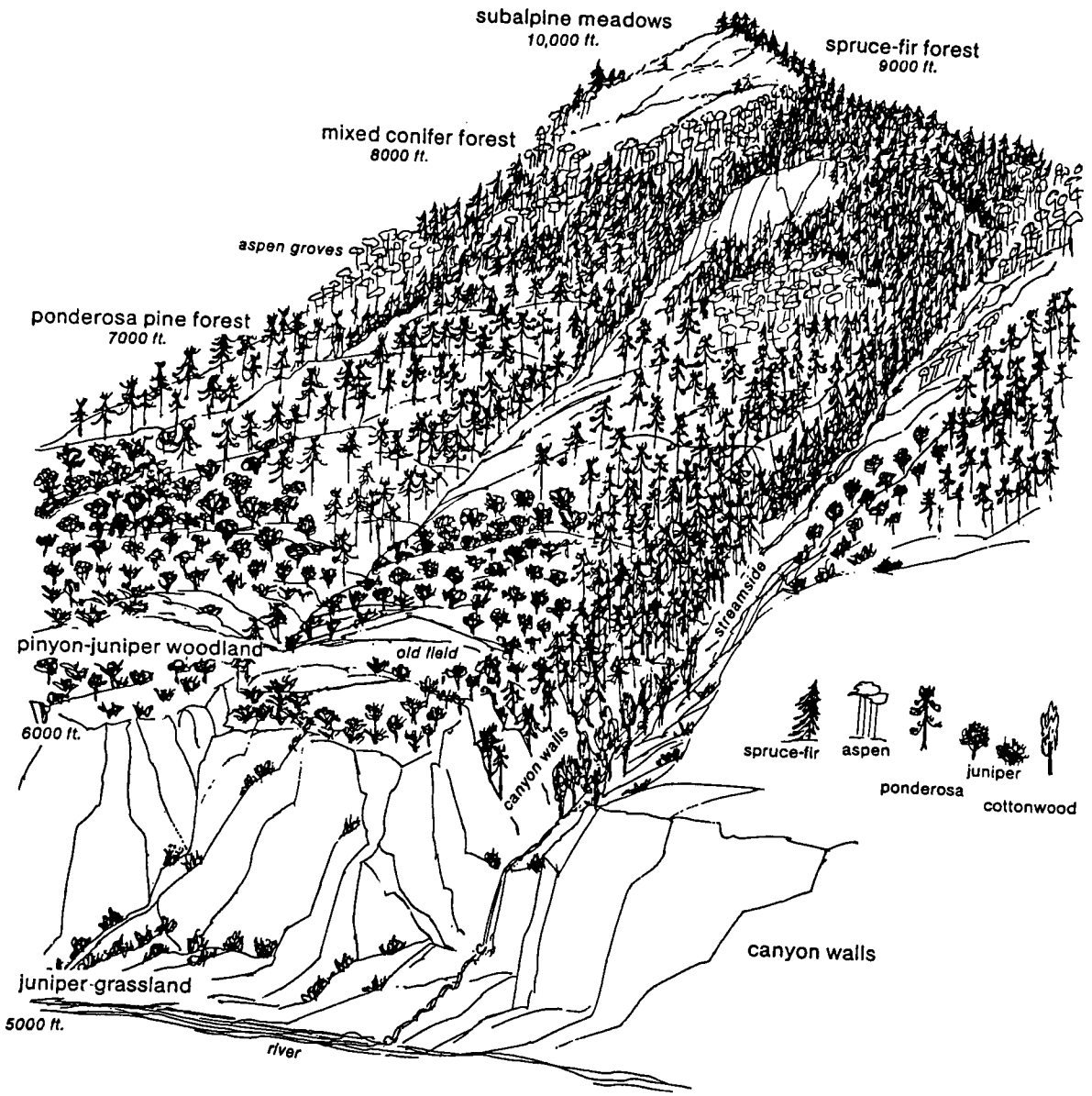

Figure 2.4. Representation of plant communities, habitat-types and their general relationship to the topography in and around Bandelier National Monument, New Mexico. (Reprinted with permission [Foxx and Hoard 1995]).

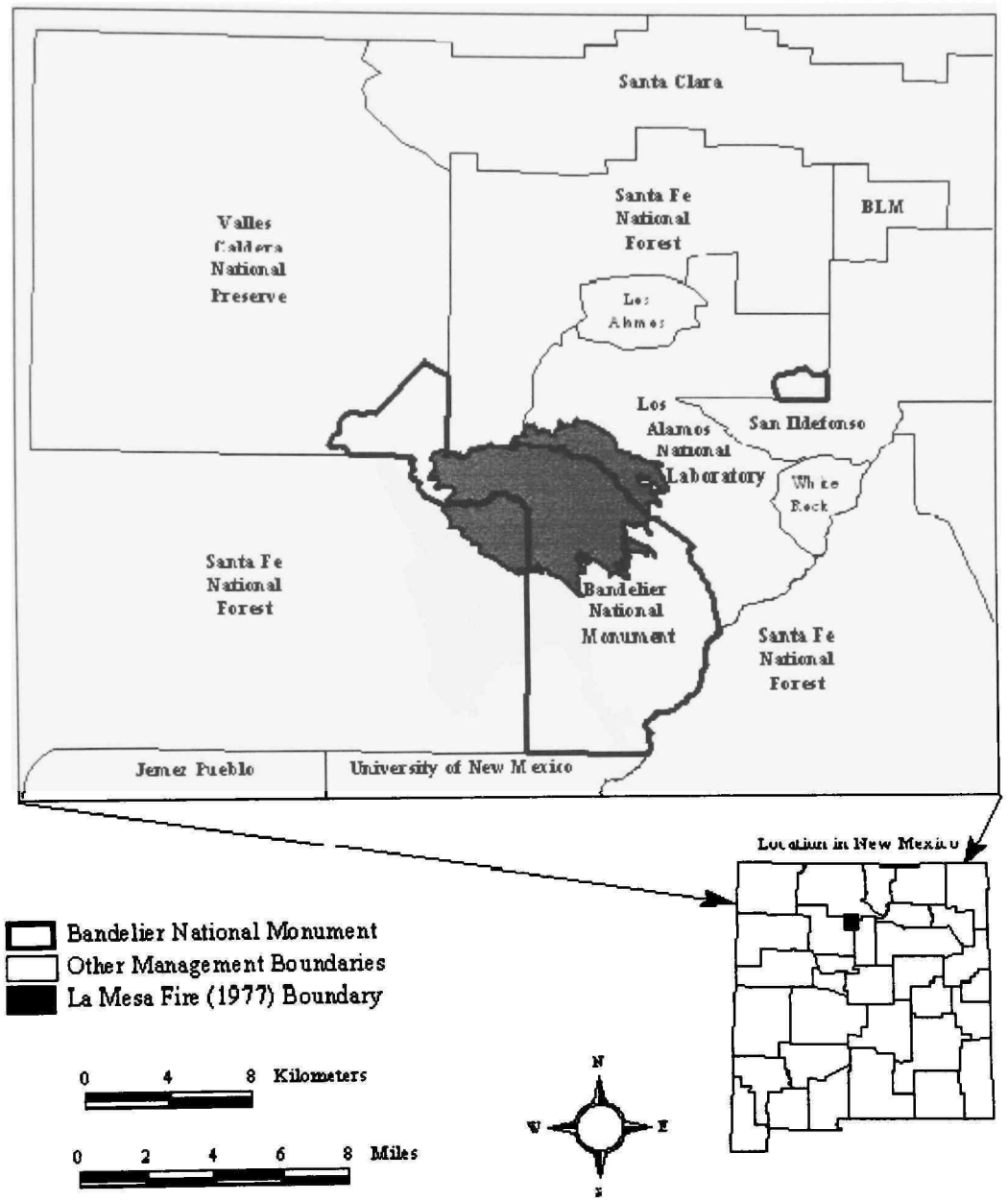

Figure 2.5. Boundary of the 1977 La Mesa fire in and near Bandelier National Monument, New Mexico.

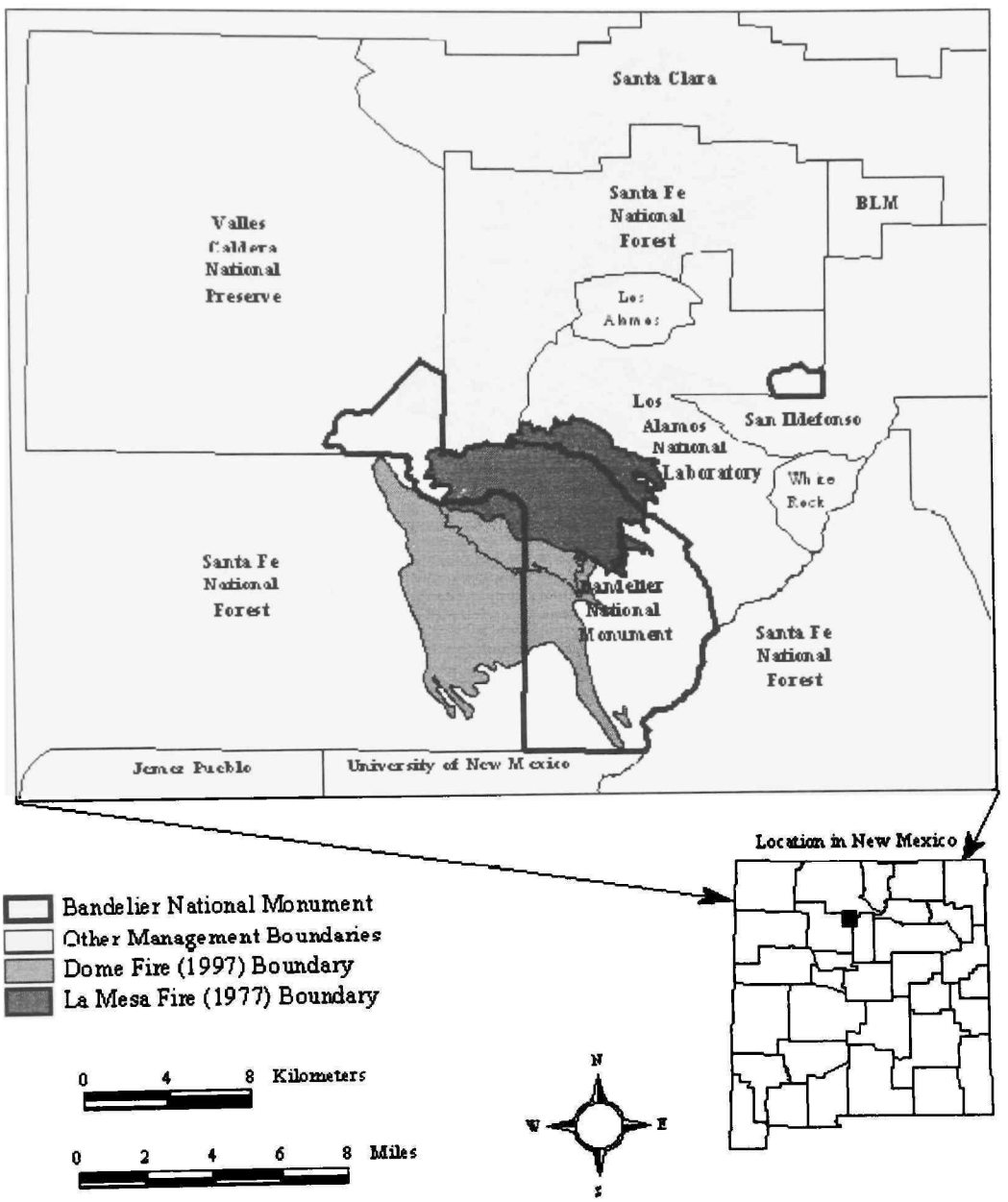

Figure 2.6. Boundaries of the 1977 La Mesa fire and the 1996 Dome fire in and near Bandelier National Monument, New Mexico.

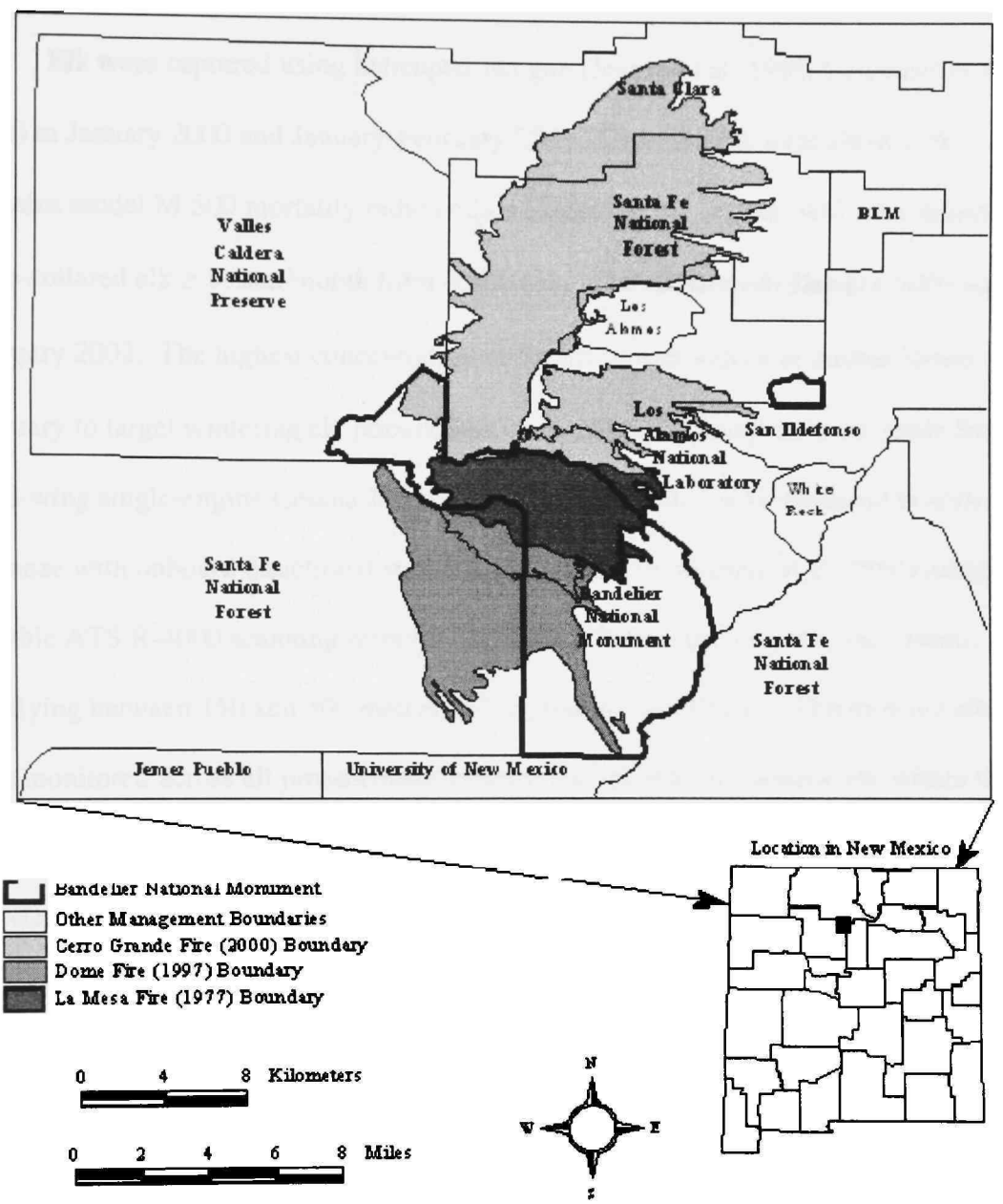

Figure 2.7. Boundaries of the 1977 La Mesa fire, the 1997 Dome fire, and the 2000 Cerro Grande fire in and near Bandelier National Monument, New Mexico.

CHAPTER III

MATERIALS AND METHODS

Telemetry

Elk were captured using helicopter net gun (Jessup et al. 1988, Carpenter et al. 1996) in January 2000 and January-February 2001. Captured elk were fitted with Telonics model M-500 mortality radio collars (Telonics, Inc., Mesa, AZ). We relocated radio-collared elk ≥ 1 time/month from fixed-wing aircraft between January 2000 and February 2002. The highest concentration of flights (≥ 4/month) was during January and February to target wintering elk populations on BAND. All locations were made from a fixed-wing single-engine Cessna 175 aircraft equipped with 2 strut-mounted H-style antennae with onboard directional switching capability (Krausman et al. 1984) using a portable ATS R-4000 scanning receiver (Advanced Telemetry Systems, Inc., Isanti, MN) and flying between 150 and 300 meters above ground level (AGL). Telemetered elk were monitored across all jurisdictional boundaries. In order to monitor elk within the restricted airspace of Los Alamos National Laboratory (LANL) immediately northeast of BAND, locations were made from above the restricted airspace ceiling of 3,810 meters, approximately 1,525 meters AGL. All locations were made between 0700 and 1545 hours.

Elk location data were recorded during fixed-wing observations using an on-board Global Positioning System (GPS) unit. We logged Universal Transverse Mercator (UTM) coordinates as waypoints and recorded these to hard copy for transfer to maps and

GIS coverages. Location data were plotted as minimum convex polygons (MCP) in ArcView® (Environmental Systems Research Institute, Redlands, CA). Elk mortalities were located on the ground as soon as possible after mortality signal was detected during a fixed-wing flight and the suspected cause of death was recorded.

We defined winter and non-winter seasons based the relative intensity of survey flights, with telemetry efforts concentrated in the winter months. Winter 1999 extended from January 1, 2000-February 29, 2000. Winter 2000 was from December 1, 2000-February 28, 2001. Winter 2001 was from December 1, 2001-February 28, 2002. Non-winter periods were those during 2000 and 2001 that were not defined as winter periods.

We estimated elk populations on BAND using helicopter surveys in conjunction with locations of known elk gathered from fixed-wing surveys. We delineated 5 survey units on BAND and 1 in the adjacent portions of the Santa Fe National Forest (SFNF) upper St. Peter's Dome region (Dome) (Figure 3.1). BAND personnel conducted helicopter survey flights immediately after selected fixed-wing telemetry during winter monitoring periods. The helicopter flew ~30 m AGL and 2 observers recorded location and number of elk seen, noting whether each counted elk had a radio-collar or not. Helicopter surveys were able to determine whether elk seen had radio collars but were unable to identify individual radio-collared elk. This limited us to assessing the number of elk missed in the helicopter surveys by unit rather than by characteristics of habitats used by individual radio-collard elk. We assumed that radio collared elk located by fixed-wing telemetry in the morning did not move to another survey unit before completion of the subsequent helicopter survey. We further assumed that elk with and

without radio collars had equal chances of being observed and that an elk observed with a radio-collar was recorded as such when seen by the helicopter survey.

For each survey period, we recorded the total number of radio collars within the entire survey area and calculated the proportion of radio-collared elk known to be in each unit. We then determined the total number of elk seen and number of radio-collared elk detected by helicopter observers per unit. We calculated elk populations in surveyed units on BAND with Lincoln-Peterson estimates using the Seber (1982) un-biased estimator and confidence intervals based on the Poisson distribution. Krebs (1989) and Seber (1982) recommend using Poisson confidence intervals when the proportion of marked animals (marks recaptured/marks in the population) is < 0.10 and the number of recaptures is <50. We divided the total number of animals observed per unit by the proportion of known radio-collared animals in that unit. We calculated total elk population by summing estimates for each unit.

To estimate total elk on BAND, including elk in units that were not surveyed, we used the distribution of known radio-collared elk and the proportion of marked elk to counted elk in surveyed units to estimate elk in each unit. These estimates assumed that elk sightability was similar in all units and that search effort per unit remained constant over the survey periods. We assumed that proportions of marked and unmarked elk observed when no helicopter survey was conducted would have been equal to that in the surveyed units. We calculated Kaplan-Meier survival rates (Pollack et al. 1988) for the telemetered population over the length of the study period (January 2000-February 2002).

We compared snowfall across winters using data recorded at the LANL TA-6 weather station near the study area (elevation 2,263 m; 380907 east, 3969182 north) and examined snow depth as recorded at the LANL Pajarito Mountain weather station (elevation 3,158 m; 374100 east, 3972050 north) for correlation to distribution of telemetered elk.

Model parameters

Overlay of study area grid. Using the GIS environment we overlaid the study area with a mapped rectangular grid system with each cell treated as an individual unit for comparison. We set grid cell size at 300 m^2 (9ha) based on the resolution of the telemetered locations. Resolution of telemetered locations was determined by comparing telemetered locations gathered from fixed-wing aircraft to coordinates of test collars and mortalities determined using GPS on the ground (Carrel et al. 1997). Rounds (1982) assessed ungulate distribution using grid cells following the recommendation of Taylor (1977) that geographic grids be based on the area of the region to be considered divided by number of points (estimated population observed). BAND is comprised of 13,629 ha and Allen's (1996) previous maximum population estimate of elk wintering on BAND was 1,500 individuals. The result (9.086 ha) very closely conforms to our designation of 9 ha grid cells. Grid overlay extent was 58 x 68 cells to represent the area with greatest available data required for model processing. Attributes from GIS data layers for elevation, slope, aspect, vegetative class, canopy cover, and fire history, were then clipped to the grid and quantified on the basis of percent composition per cell. We

plotted telemetered locations on to existing ArcView GIS coverages and coverages either modified or created to help identify potential patterns in habitat use. Coverages used and their sources are provided in Appendix B.

Standing crop. We estimated standing crop of vegetation using measures of horizontal visual obstruction (VO) (Robel et al. 1970) at random points stratified by different vegetative habitat types (Figure 3.2). Habitat type classifications are modifications of the description classes used in the "Veg81_a" GIS coverage on file at BAND (Table 3.1). Original source was an interpretation of 1981 color aerial photos (Allen 1989). Horizontal visual obstruction was used as an indication of herbaceous yield by correlating the amount of visual obstruction with the amount of vegetative biomass occurring in a given area (Robel et al. 1970, Benkobi et al. 2000, Ganguli et al. 2000, Vermeire and Gillen 2001). We took measurements by observing a 2.5 x 100 cm wooden dowel painted in alternating red and white decimeter bands with thin, black bands at 2.5 cm increments. We observed the measurement pole from 4 meters away at a height of 1 meter. We maintained a consistent observation point by sighting from a 1x 100-meter dowel attached to the measurement pole by a 4-meter cord and recorded the height of the lowest mark visible. If any portion of a mark was seen from the observation point it was considered visible. All measurements were taken after the end of the growing season and before the start of the next growing season. Sampling was curtailed if snowfall was deemed significant enough to alter herbage configuration or if we observed major elk movements into the area, roughly from September through early November. We used the combined model developed by Vermire et al. 2002

$$183\ (\bar{x}\ \text{VO cm}) + 358 = \text{kg ha}^{-1} \qquad (3.1)$$

to relate visual obstruction measures to standing crop in our study area as they found that it could be successfully used on sites with multiple or interspersed range types. We estimated total standing crop per grid cell by combining estimated standing crop per vegetation type based on the percent occurrence by area of each vegetation type per cell. Herbage standing crop and similar measures of biomass cannot account for all of the potential variation in herbivore forage. However, elk are highly opportunistic feeders and winter diets are primarily a function of forage availability (Jenkins and Wright 1988), and such biomass estimates are readily reproducible, frequently reported in the literature, and describe the food resource as adequately as any other single measure (Wickstrom et al. 1984).

Condition of cells. We assessed conditions of cells on the study area by the static habitat parameters (elevation, slope, aspect, vegetative class, canopy cover class, historic use, and fire history) and assigned a desirability index score (DI) based on the following criteria. Dynamic parameters (number of elk on range, snow depth and standing crop) were not included in DI score but were separate inputs so that they could be readily modified to reflect changing input conditions. Elk use in cells were ascribed by filling cells with highest DI score first under the Ideal Free Distribution (Fretwell and Lucas 1970) where elk fill the best first then next best, etc. assuming complete knowledge of the quality of the choices and that individuals can move freely between resource sites. While in reality these assumptions are likely never fully achieved, we have seen that ungulates can increase their knowledge of the seasonal availability of resources through range

fidelity (Edge et al. 1985) and repeated exposure to a familiar distribution of resources (Gillingham and Bunnell 1989). And while there may always be the potential for interference of movement between resources (e.g., geographic, energetic, or anthropomorphic constraints), elk are an adaptable and highly mobile species. Beall (1974) found that elk in his study area traveled an average distance of 5.6 km per day, ranging from 0 km to 13.4 km. Considering those distances as a diameter, the average daily distance traveled of 5.6 km would include a daily potential use area of 24.6 km^2, an area equivalent to nearly 20% of BAND's total area. The extreme of 13.4 km would include an area greater than the entire total area of BAND, making the assumption of idealized access to resources more reasonable.

As nutrient intake rates (considered here as a function of decreasing standing crop) within a cell decline to some critical threshold (response level), elk were expected to try to increase their rate of return by movement to another cell. The model approximates this process. When presence of elk in a cell reduced the original estimated standing crop to a definable response level, the DI was reduced. The elk habitat effectiveness index of Thomas et al. (1988) similarly estimated a precipitous drop in forage quality when percent of original forage remaining had been reduced beyond a critical threshold. The tendency for elk to move in search of more preferred species as forage density decreases (Collins et al. 1978, Wickstrom 1984) would result in the animal moving to a cell with a higher DI value. When presence of elk in a cell reduced the original estimated standing crop by 20%, the DI was reduced by 20% to approximate elk response to diminishing forage quality and quantity as intake rates decline with continued

use. Elk remained in the cell until the resulting reduced DI score fell below that of another cell. At each model time step, elk were reallocated to cells of higher value if they existed.

We have seen that elk are typically gregarious during winter months and so we assigned elk to the cell with highest DI score, until a maximum number of elk per cell is reached. We used average group size (excluding lone individuals) for elk counted by helicopter surveys during this study period (19.6 elk per group) and the range of observed group sizes previously cited to assign a maximum of 20 elk per cell, with any remainder of <20 animals assigned to the cell with the next highest DI value.

Desirability Index (DI). We assigned cell desirability as an index (DI) of the combination of conditions in a cell that we assumed would increase the probability that it would be used by elk. We based these assumptions on winter telemetry survey data from winter 2000-2001 when elk use on BAND was highest, and the literature reviewed above. We considered that increased percent occurrence of a desired feature in a cell would increase its likelihood of use. We set favored conditions as percent of cell area comprised of: south-facing aspect (exposure of 136-225°), east-facing aspect (exposure of 46-135°), slope 0-20 % incline, canopy closure of 0-9% and 30-59%, grassland vegetation class, and ponderosa pine vegetation class. In order to incorporate previous patterns of winter elk distribution observed by BAND personnel, we added one point to the previously derived percent composition component of the DI score if a cell was located within areas previously found to be subject to frequent use by wintering elk (i.e., the La Mesa Fire impact area, and historic use areas [essentially between Frijoles and

Alamo Canyons]) (Figure 3.3). Sivinski (1979) included elevations in BAND of > ~2,440 m as part of elk summer range and that elevation was important to habitat selection by elk in BAND, likely correlated to high densities of grasses and forbs, providing many preferred food items for elk. Our telemetry data indicated use of areas on BAND > 2,600 m virtually year-round. In order to simulate increased likelihood of use of the upper elevations of BAND in the absence of restrictive snow accumulations, we also added DI points to cells with favorable conditions above 2600m mean elevation, including percent of cell area comprised of: south and east-facing aspect, canopy closure of 20-29% and 70-79%, and mixed conifer-ponderosa pine forest vegetation class. We also added an increasing gradient of points to cells of increasing mean elevation class, and to cells >2600 m in the Cerro Grande burn area to simulate use patterns of telemetered elk observed during winters with below average snow accumulations (see Table 3.2 for example).

Changes to cell conditions. Bull: cow: calf ratio estimate of the Unit 6 elk herd was 42:100:24 as of September 2002 (NMGF 2002). Considering this sex-ratio and typical elk weights from Cook (2002) and Hudson et al. (2002) we assumed the following: mature bulls weighed 450 kg representing 25% of the population, mature cow weighed 310 kg representing 60% of the population, and calf weight at first winter of 80 kg representing 15% of the population. We used the product to represent typical elk weight in the Jemez Mountains herd as 311 kg. This approximates the Holecheck et al. (1995) estimate of average animal weight (318 kg) and as such, seemed a reasonable estimate of typical elk weight.

With such a broad range of forage intake estimates found in the literature, we set the estimated forage consumption level at 1.75% of net body weight. This estimate altered the model of Cook (2002) to reconcile the increased energy demands of free-ranging elk (as compared to the confined animals upon which the Cook [2002] estimate was based), with intake limits due to increased rumination time required for lower quality winter forage. It also represented a compromise between the recommendation of Holechek et al. (1988) of 1.5% net body weight, and that of Nelson and Leege (1981) of 2.0% net body weight, since both estimates targeted free-ranging elk under the nutritional constraints of senescent winter vegetation. Our estimate also approximated the observation of Lang (1958) of 1.8-2.0% of body weight consumed by elk on native forage in New Mexico.

Given these assumptions, we accepted average animal weight of 311 kg consuming 5.4 kg of forage per day for integration into the model. As such, the model reduced the standing crop estimated per cell by 5.4 kg per day times the number of elk in each cell. This projection was well within the projected daily forage intake of 4.5-6.8 kg estimated by Skovlin (1982).

Snow depth. We have seen that snow depth influences elk movements, and so any effort to model elk movements must estimate snow accumulations across the study area. We recorded snow depth at 12 monitoring stations (Figure 3.4) from November 2000-February 2001 by attaching a yardstick to the back of fence posts at different elevations in BAND. Snow stations were located far enough from the road to insure that they would not be affected by snow plows and we recorded snow depth at 15 cm from the post to

minimize the influence of drifting and/or conductive melting due to the metal posts. We also monitored snow depths recorded at 2 nearby weather stations maintained by LANL, at Pajarito Mountain (PJMT), and Technical Area 6 (TA-6), where snow depth was measured with an ultrasonic device that measures the time required for an acoustic pulse to travel down to the snow surface and back up to the instrument. From these data we generated a model to predict snow depth at different elevations across BAND based on the snow depth recorded at PJMT

$$[\text{PJMT snow}] + ([\text{PJMT elevation}] - [\text{BAND elevation}]) * (-0.024627) = [\text{BAND snow}]. \quad (3.2)$$

Corroboration. The terms model verification and validation are often discussed in the literature. However, Oreskes et al. (1994) asserted that verification is used to mean the establishment of truth, and validation refers to the establishment of legitimacy. Therefore, neither is possible in the modeling context since the natural processes that we are trying to emulate are perpetually open systems, thus absolute verification, in the sense of asserting the 'truth' of a model is impossible (Scott et al. 2000). Oreskes et al. (1994) suggested the alternative terminology of model corroboration, where evidence corroborates a model when it does not contradict it.

We corroborated our model through comparison of the number of model output elk-days use per cell with density of telemetered locations per cell during winter 2000 and winter 2001, assuming that cells with higher density of telemetered elk locations were subject to greater use, and therefore would likely result in higher number of elk-days use. Since the calibration of model parameters included winter 2000 telemetry data

as well as literature review, we also sought model corroboration through comparison to elk distributions observed during winter 2001helicopter survey flights on BAND, as the results of these helicopter surveys represented the best available independent data set of elk distribution on BAND during this period.

We classified model output elk-days use per cell into 3 density classes using ArcView Spatial Analyst extension and examined results for correlation with similarly derived density classes of telemetered elk locations, and elk observations per cell as recorded during helicopter surveys. To avoid potential bias in the delineation of density classes, we accepted the divisions assigned by the program, where totals were divided into 3 equal groups. Helicopter surveys were most intensive in winter 2000 ($n = 5$) and winter 2001 ($n = 4$). These data provided a general (albeit incomplete) representation of elk distribution on BAND during winter 2000 and winter 2001. The distribution of winter elk derived from previous helicopter survey results (1990-1995) provided an even more limited 'snapshot' of elk distribution on a particular day because only 1 survey flight per winter was conducted,

The model uses snow depth recorded at PJMT to project snow depth on the rest of the study area. However, snow depth was not recorded at PJMT during 1990-1995. To predict snow depth in those years we used data from the NOAA SNOTEL Quemazon (QMZN) station located 3.5km north of PJMT (375186e, 3975389n) (Figure 3.2) at a similar elevation (2,896m) where accumulated precipitation was monitored by a pressure-sensing snow pillow that recorded snow water equivalence (QMZNswe). While not a true measure of snow depth, these data were correlated ($r^2 = 0.63$) to the snow depth data

from PJMT used in our model during winter 2000 when snow accumulations were > the 30-year average. Correlation decreased dramatically when comparing QMZNswe data in winters with below average snow accumulations (winter 1999 $r^2 = 0.07$, winter 2001 $r^2 = 0.17$). Given the nature of the QMZNswe data these discrepancies were to be expected (especially in low snow winters when very little water arrives as precipitation in a form that can be recorded by the snow pillow). Overall, these data represented the best available data set with which to predict snow depth at PJMT in winters 1990-1995. We developed a simple linear regression equation using QMZN and PJMT data recorded November 2000-March 2001 ($r^2 = 0.63$) to predict PJMT snow depth as an input for corroboration of our model with 1990-1995 elk helicopter survey data.

$$[\text{PJMT snow}] = ([\text{QMZNswe}] * 1.508115) + 15.37 \quad (3.3)$$

Sensitivity. Sensitivity analysis is an evaluation of the relationship between information flowing in and out of a model (Saltelli 2000). To evaluate the relative sensitivity of model parameters and input conditions we used 0.25, 0.5, 1.0, 2.0, 4.0 times the original input variable values as inputs to our model. We correlated elk-days use per cell output with these altered variables to elk-days use per cell output from original variables. High correlation indicates little change in output values, whereas low values ($r^2 < 0.60$) indicated greater effects of changes in parameter values. Model parameters evaluated were: snow depth at which elk were excluded from a cell, maximum elk allowed per cell, critical threshold of crop reduction required to reduce DI, the amount DI score was reduced when crop reduction threshold was reached, daily forage intake per elk (kg/day), the amount of standing crop per cell, and the number of elk on the range.

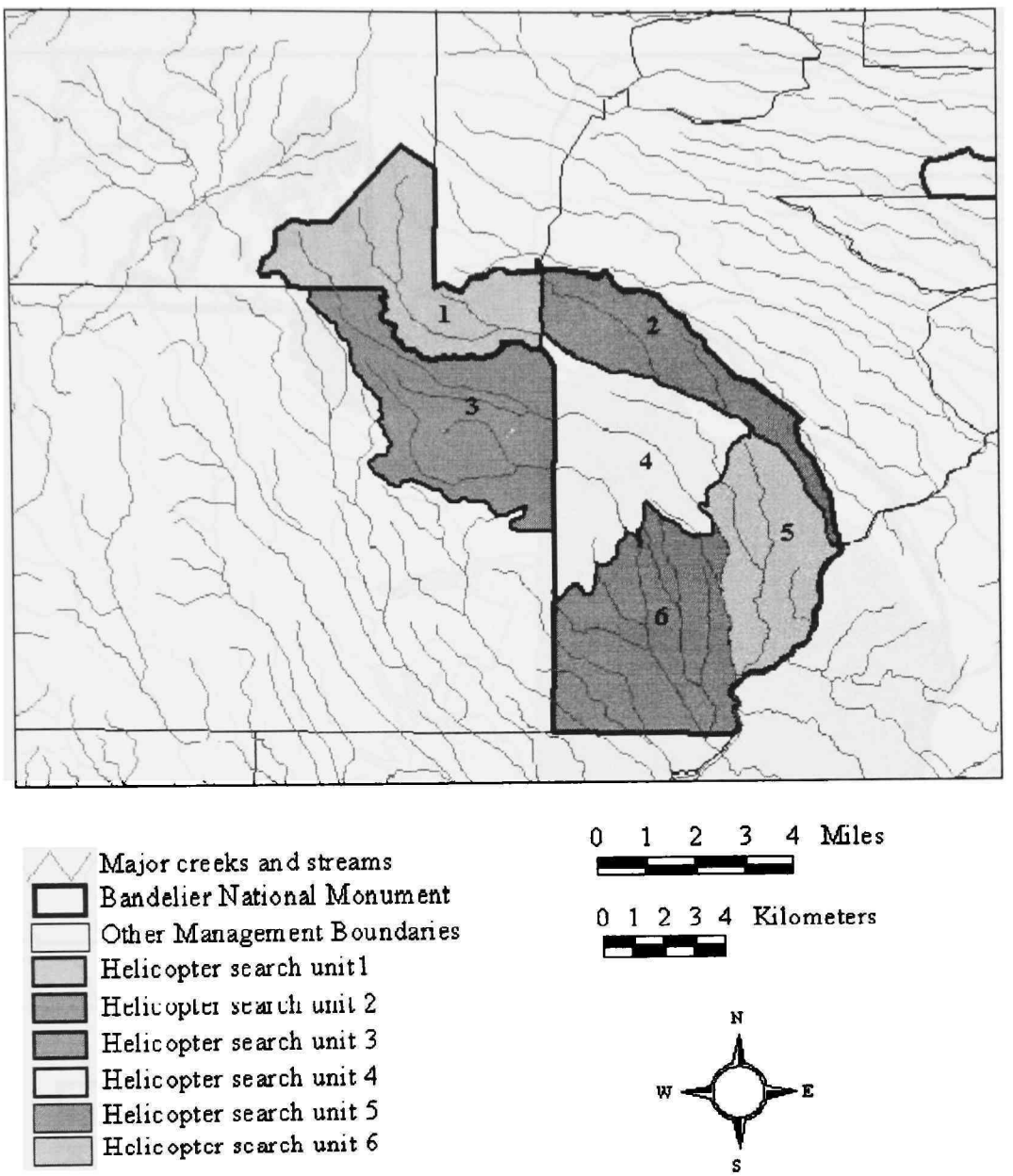

Figure 3.1. Helicopter search units in Bandelier National Monument (Units 1, 2, 4-6) and Santa Fe National Forest upper St. Peter's Dome Region (Unit 3), New Mexico.

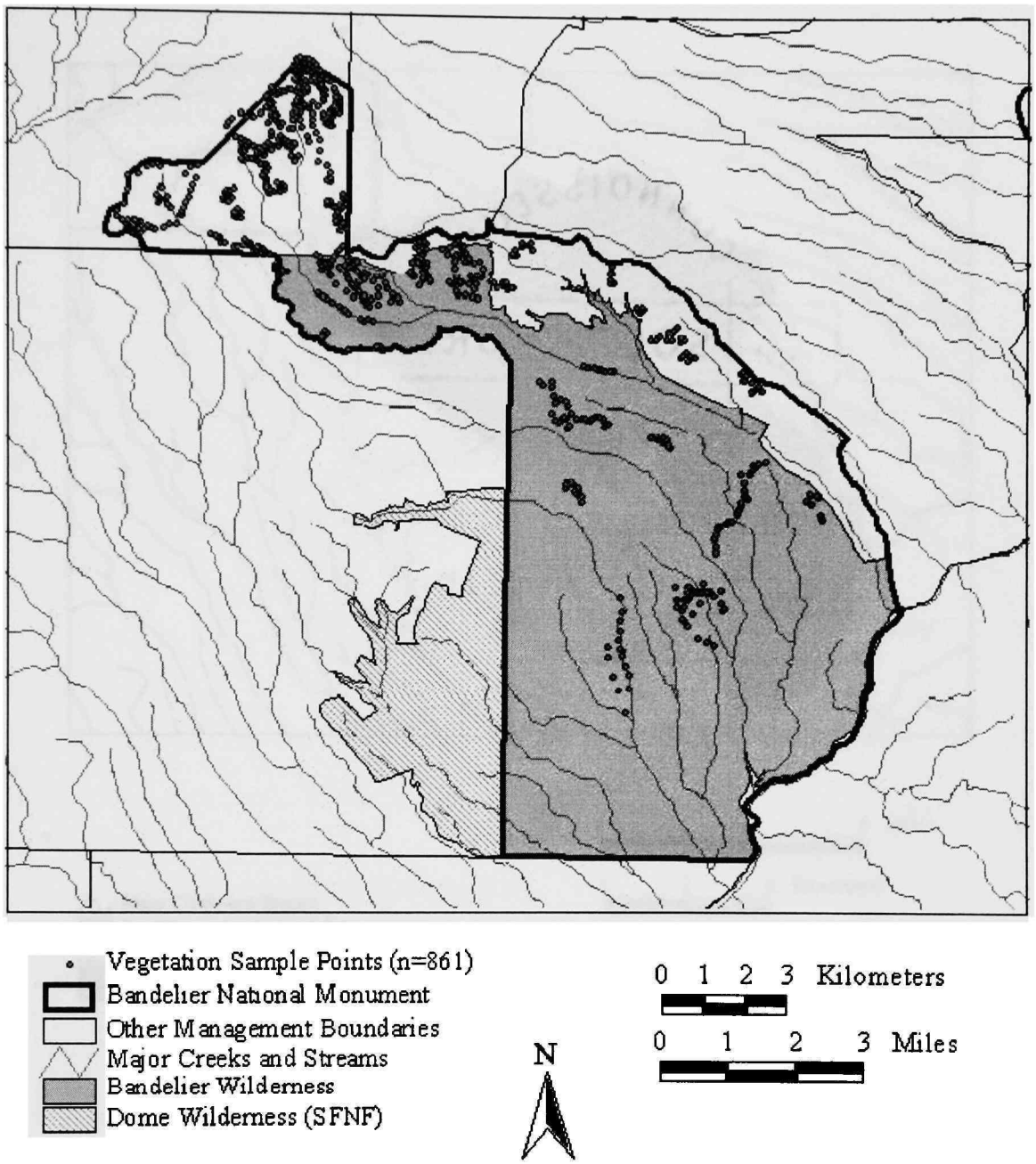

Figure 3.2. Sampling points for measure of vegetative horizontal visual obstruction as index of standing herbaceous crop on Bandelier National Monument, New Mexico, September-November 2000 and 2001.

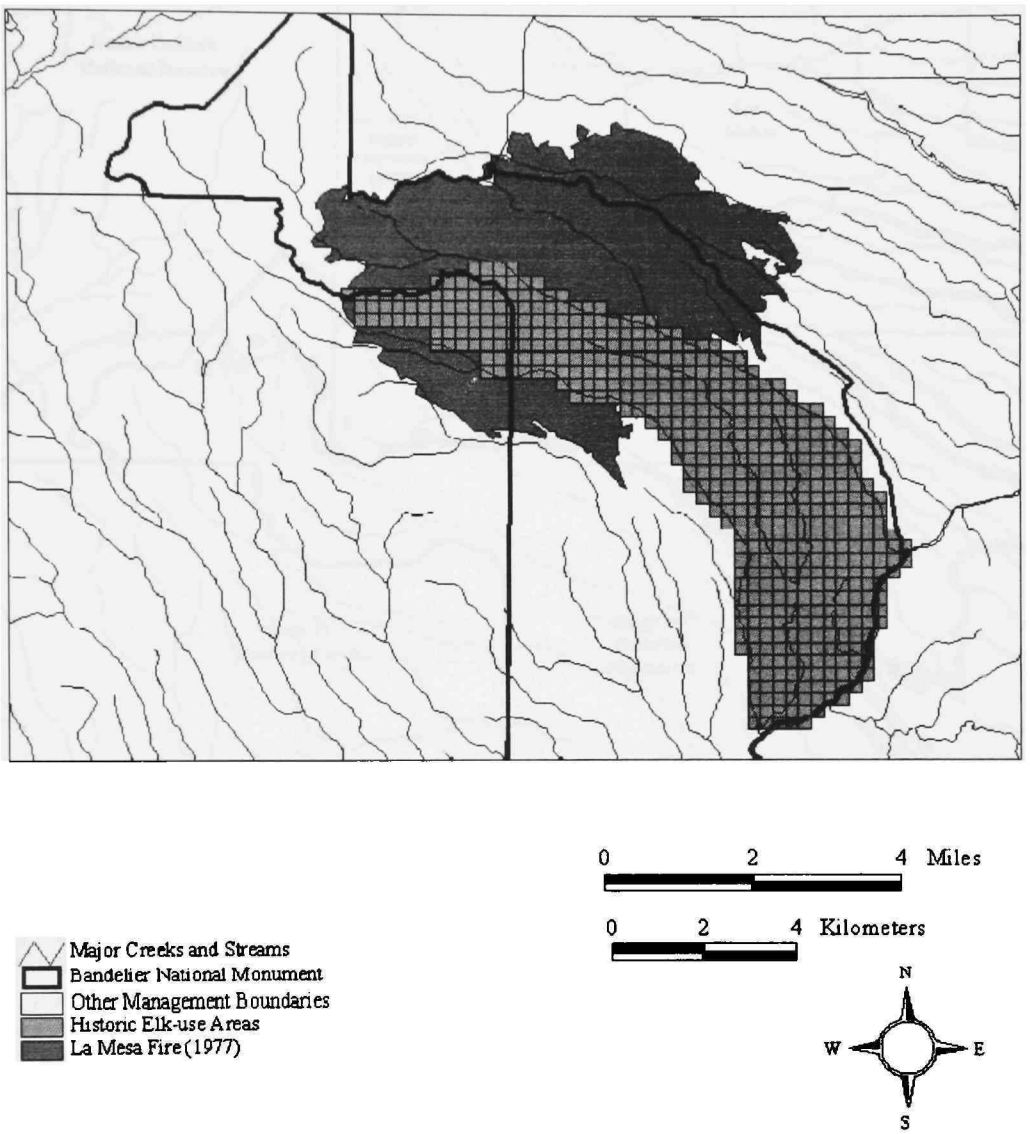

Figure 3.3. Areas previously found to be subject to frequent use by wintering elk (i.e., the La Mesa Fire impact area, and other historic elk-use areas between Frijoles and Alamo Canyons in and near Bandelier National Monument, New Mexico.

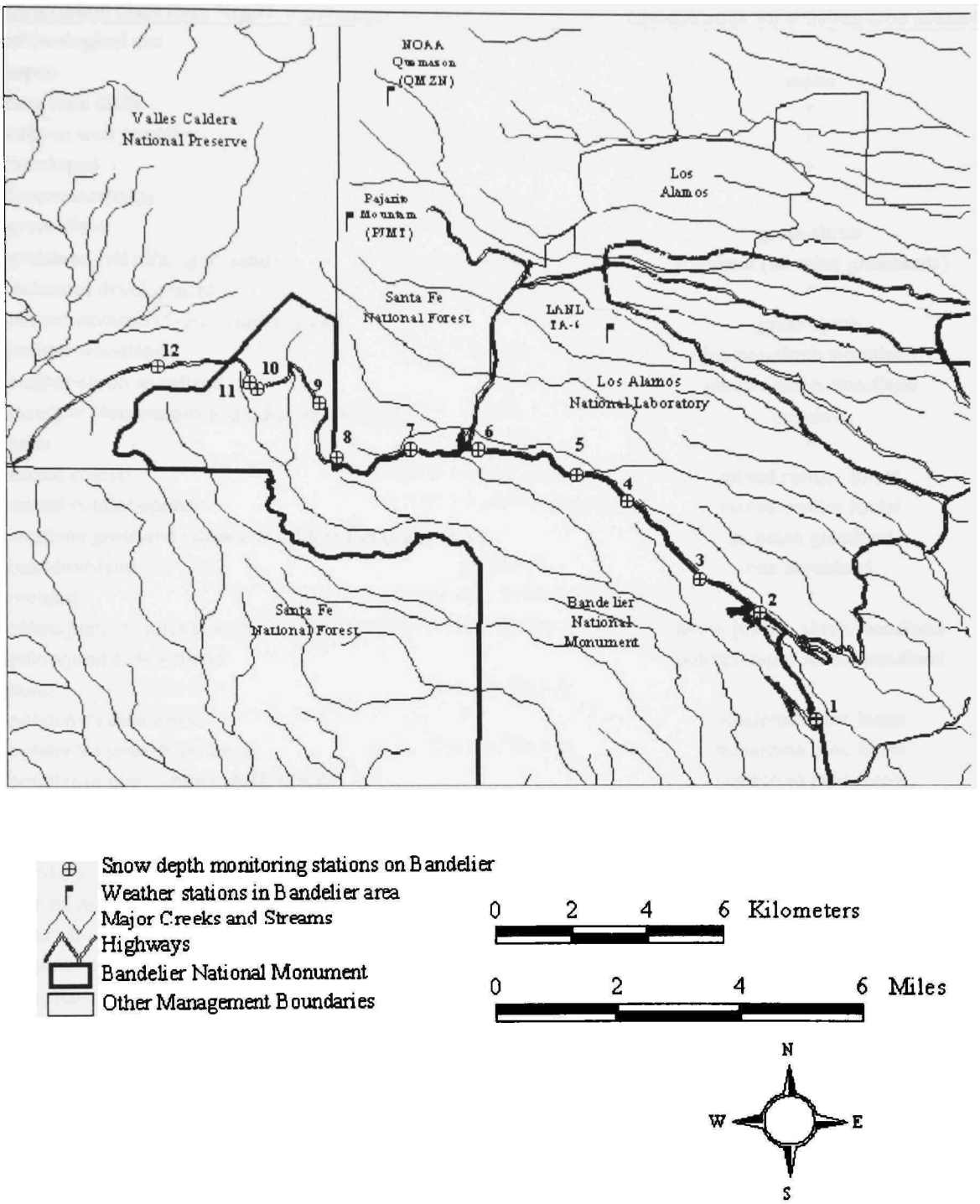

Figure 3.4. Location of snow depth monitoring stations and permanent weather stations in and near Bandelier National Monument, New Mexico.

Table 3.1. Description class assigned to vegetative communities in Bandelier National Monument, New Mexico from Veg81_a (from Allen 1989) GIS coverage as classified for standing crop estimates in each community.

Description class from Veg81_a coverage:	Classification for standing crop estimate:
archeological site	*
aspen	aspen
bare rock cliffs	*
canyon wall complex	*
developed	*
felsenmeer/talus	*
grass-shrub	grass-shrub
grassland (all other grasslands)	grassland (all other grasslands)
industrial development	*
juniper savanah (5-9% juniper cover)	grass-shrub
juniper woodland	juniper-shrub woodland
juniper-shrub woodland	juniper-shrub woodland
meadow (depressions and other moist sites)	meadow
mine	*
mixed conifer	mixed conifer forest
mixed conifer-spruce	mixed conifer forest
montane grassland (slopes of caldera rim peaks only)	montane grassland
oak shrubland	oak shrubland
orchard	*
piñon/juniper shrub woodland	piñon/juniper shrub/woodland
piñon/juniper woodland	piñon/juniper shrub/woodland
pond	*
ponderosa pine forest	ponderosa pine forest
ponderosa pine shrub forest	ponderosa pine forest
ponderosa pine-juniper shrub forest	ponderosa pine forest
ponderosa pine-mixed conifer forest	ponderosa pine-mixed conifer forest
ponderosa pine-piñon/juniper forest	ponderosa pine-piñon/juniper forest
ponderosa pine-mixed conifer shrub forest	ponderosa pine forest
previoiusly drowned by Cochiti resevoir	*
riparian-evergreen	riparian
riparian-evergreen (mixed conifer)	riparian
riparian-evergreen (ponderosa pine)	riparian
riparian-mixed evergreen/deciduous	riparian
sand	*
shrubland	oak shrubland
stream	*
White Rock Canyon spring/seep woodland	*

*not classified

Table 3.2. Example of Desirability Index (DI) calculations for 300 m^2 grid cell overlay of study area in and near Bandelier National Monument, New Mexico.

		Cell #	
		2673	230
Category	Desirable cell attribute	(score = % composition by area)	
aspect	south	0.800	0.999
	east	0.194	0
	south > 2,600 m elevation	0	0.999
	east > 2,600 m elevation	0	0
slope	0-20%	0.990	0.139
canopy closure	0-9%	0.654	0.106
	30-59%	0.346	0.254
	20-29% > 2,600 m elevation	0	0.639
	70-79% > 2,600 m elevation	0	0
vegetation class	grassland	0.665	0
	ponderosa pine forest - all types	0.336	0.889
	mixed conifer-ponderosa pine forest > 2,600 m	0	0.889
		additions to % composition score	
La Mesa burn area?	Yes = 1; No = 0	1.0	0
historic use?	Yes = 1; No = 0	1.0	0
mean elevation	> 2,900 m = 2.0	0	2.0
	> 2,800 m = 1.5	0	1.5
	> 2,700 m = 1.0	0	1.0
	> 2,600 m = 0.5	0	0.5
Cerro Grande burn area?	Yes = 4; No = 0	0	4.0
	Desirability Index (DI) =	5.985	13.914

CHAPTER IV

RESULTS

Telemetry

Elk captures. Most elk were captured in the ponderosa pine-grassland habitat types between 2,050 and 2,400 m elevations on BAND and similar habitat types between 2,400 and 2,500 m elevations on SFNF (Figure 4.1). We captured elk on BAND (n=37) and the contiguous portions of the SFNF Dome region (n=5) using a helicopter net gun from January 6-11, 2000. Initial telemetered population (n=42) consisted of 10 males (24%) and 32 females (76%), a sex ratio of 1 male to 3.2 females. Elk (n=72) were added to the telemetered population during 2 similar capture efforts January 10-12, 2001 (n=5 male, n=28 female) and February 3-5, 2001 (n=7 male and n=32 female). Elk captured in January 2001 were found on BAND (n=22) and on Mesa del Rito in the SFNF upper Dome (n=11). All elk captured in February 2001 (n=39) were found on BAND. Most elk were captured in the La Mesa fire area. The wider geographic distribution of capture locations in winter 2000 is evidence that fewer elk were on BAND than in winter 2001, as capture crews had to search longer and cover more area to find elk.

Elk mortality. Capture related mortality was 7.1% in 2000, as 3 elk died in the course of capture operations. One bull died while entangled in a capture net. Rectal temperature of ~106 °F suggested overexertion. Another bull suffered a broken neck in a fall down a ravine after the capture net became entangled in vegetation. One cow was in

a group of animals being positioned by the helicopter and died of undetermined causes though it was never handled. No elk died during the January 2001 capture, while 2 died (5.1% mortality) in falls as a result of February 2001 capture operations. Overall capture-related mortality during all capture periods was 4.4%. A total of 23 of the 114 elk that we radio-collared were lost due to mortality or other causes by the end of this study (Feb 28, 2002). Mortalities of collared elk occurred on SFNF (north of VCNP [n=3], Dome region [n=2], American Springs region [n=7]), on BAND (n=4), on LANL (n=6), and on VCNP (n=1) (Figure A.1, Table A.1). One female was found dead 18 days after capture in 2001, this mortality was attributed to capture-related stress. Another female was never located after the Cerro Grande fire (May 2000). We attributed 3 mortalities (2 male, 1 female) to age-related factors (all 3 elk were estimated to be > 9 years old and showed no indications of other causes of mortality). Predation by mountain lions *(Felis concolour)* was the probable cause of 5 mortalities, while 8 were shot (6 legal harvests, 2 poached), and 5 mortalities were of undetermined causes (not recovered in time to assess mortality factors).

Overall Kaplan-Meier survival rate (Pollack et al., 1988) for the telemetered population was 0.62 ± 0.04 between January 2000 and February 2002 (Table A.2). Greatest mortality occurred during October 2000 when 7 collared animals were harvested in the American Springs region (SFNF).

Elk Locations. We conducted 9-10 flights in each January-February of 2000, 2001, and 2002 when elk use on BAND was highest. We conducted 3 flights during March-April and 3-4 flights during October-November in both 2000 and 2001 to gauge

timing and elk movement patterns between summer and winter range. We averaged 1-2 flights per month during the rest of 2000 and 2001, except for May-June 2000 due to airspace restrictions from the Cerro Grande fire and subsequent rehabilitation efforts.

Winter 1999 (January-February 2000). We collected 375 locations between 0755 and 1550 hrs during fixed-wing telemetry flights ($n=9$) in January and February 2000. There were 2 mortalities during this monitoring period. Elk ($n=42$) were monitored during this period (10 male and 32 female [sex ratio *1:3.2*]). Snowfall was well below average during winter 1999 (Figure 2.3). Overall MCP range of the telemetered population was estimated as 435.00 km^2 (including capture locations) (Figure A.2). The majority (60%) of locations occurred on VCNP (Figure 4.2, Table A.3.1). Half (32 of 60) of locations on BAND were capture sites (Figure A.2). These locations typically marked the lowest elevation of range use recorded this monitoring period.

Non-winter 2000 (March-November 2000). Forty elk were still being monitored at the beginning of this period (9 male and 31 female [sex ratio *1:3.4*]). We conducted 10 fixed-wing telemetry flights during this monitoring period. No flights were conducted in May or June due to airspace restrictions related to the Cerro Grande fire and subsequent rehabilitation efforts. There were 10 mortalities and 1 elk, never relocated after the Cerro Grande fire, was removed from the population (censored from survival estimates) during this monitoring period. We collected 359 locations between 0730 and 1610 hrs. The majority of locations (43%) occurred on the VCNP during this period and reached as high as 73% of the telemetered population in August 2000 (Figure 4.2).

Winter 2000 (December 2000-February 2001). Twenty-nine elk were still being monitored at the beginning of this period (6 male and 23 female [sex ratio *1:3.8*]). Additional elk captures during January and February 2001 added 72 elk to the telemetered population. Snowfall was well above average during the winter 2000 (Figure 2.3). We conducted 13 telemetry flights, collecting 979 locations between 0700-1506 hrs. Overall MCP range of the telemetered population was estimated as 376.86 km^2 (Figure A.3). There were 2 mortalities during this monitoring period. BAND was the wintering area most commonly (64%) used by radio-collared elk (Figure 4.2, Table A.3.1).

Non-winter 2001 (March 2001-November 2001). Ninety-nine elk were still being monitored at the beginning of this period (18 male and 81 female [sex ratio *1:4.5*]), 27 from the 2000 capture and 72 from 2001 captures. We conducted 12 telemetry flights, collecting 1,138 locations between 0745 and 1545 hrs. There were 6 mortalities during this monitoring period. Most locations (72.5%) occurred on the VCNP. While we found no telemetered elk on the VCNP at the beginning of the monitoring period (March 19, 2001), percent of locations there increased to ≥70% by April 23, 2001 and stayed high through the remainder of the monitoring period, with as many as 92 % of telemetered locations on the VCNP (May 25, 2001) (Figure 4.2).

Winter 2001 (December 2001- February 2002). Ninety-three elk were still being monitored at the beginning of this period (16 male and 77 female [sex ratio *1:4.8*]), 27 from the 2000 capture and 66 from 2001 captures. Snowfall was well below average during the winter 2001 (Figure 2.3). We conducted 11 telemetry flights during this

monitoring period, collecting 951 locations between 0715 and 1545 hrs. Overall MCP range of the telemetered population was estimated as 888.08 km^2 (Figure A.4). There were 2 mortalities during this monitoring period. The majority of locations (46%) occurred on the VCNP (Figure 4.2, Table A.3.1). Winter use of the American Springs area of SFNF increased (Table A.3.1). Elk captured in 2000 were located in and near BAND more frequently than elk captured in 2001 (Table A.4).

Elk population estimates. BAND personnel conducted helicopter survey flights immediately after selected fixed-wing winter telemetry flights. They recorded number of elk and number of collared elk seen (Table A.5) and approximate location of elk seen on each flight (Figures A.5-A.15). Helicopter surveys were conducted in units where elk concentrations were thought to be greatest. Population estimates for units surveyed = 1 time are given in Table 4.1. Proportion of radio-collared elk observed by helicopter (number of collars seen divided by the known radio-collared elk that unit) did not differ among units 1 through 4 ($P=0.089$) (Table 4.2). Only 1 helicopter survey was ever conducted in units 5 and 6 and no collared elk were seen on that survey. Population estimates for elk in all survey units (including those not flown by helicopter survey) are given in Table 4.3. We estimated number of elk by equating the ratio of radio-collars known to be in that unit with the ratio of estimated total elk to known radio-collared elk in surveyed units. No population estimates are given for winter 1999 due to low number of collars re-sighted by helicopter surveys.

Movement patterns. Elk herd home ranges (Figures A.2-A.4) illustrated different patterns of winter use. Distribution of locations across administrative units varied

between years (Figure 4.2). Percent of total telemetered locations on BAND was inversely correlated to percent of total locations on the VCNP ($r^2 = 0.84$). The correlation between percent of total telemetered locations on LANL to percent of total locations on the VCNP was not nearly so strong ($r^2 = 0.29$). After initial capture in January 2000, elk dispersed back onto traditional summer range on the VCNP and the upper elevations of BAND. During September-October 2000 many elk moved from VCNP to American Springs SFNF and on to BAND by November, suggesting American Springs SFNF as a likely migratory route for elk. During winter 2000, 39-77% of telemetered elk were on BAND. In March-April 2001, 66-92% of telemetered elk moved off BAND onto the VCNP through November 2001. Elk movements leading up to winter 2001 were similar to the pre-winter pattern in 2000, with many elk leaving VCNP in September-October and moving to American Springs SFNF. However, more elk remained on American Springs SFNF during winter 2001, and fewer moved to lower elevations on BAND or LANL. Elk that wintered on BAND moved to summer range on VCNP and SFNF. Elk wintering on LANL remained primarily on LANL or lower elevations of American Springs SFNF during non-winter months. Most elk moved to lower elevations on BAND during winter 2000 when snowfall exceeded the 30-year average but remained at higher elevations on VCNP and SFNF during winter 1999 and 2001 when snowfall was below average.

The percentage of telemetered elk locations per administrative unit between January 2000 and February 2002 (Figure 4.2) indicated differences in distribution of telemetered animals among seasons. Telemetered elk summered primarily on the VCNP

and the upper-most elevations of BAND. Use of the American Springs SFNF increased in autumn (~October and November) presumably as elk moved between summer and winter ranges. High elk-use areas in winter 1999 coincided with high elk-use areas in winter 2001 (both winters with < average snowfall), with the notable exception of American Springs SFNF during winter 2001, which was burned in the Cerro Grande fire of May 2000. During winter 2000, areas of high elk-use were located on lower elevations on BAND and LANL.

We observed differences in range use by elk captured in 2000 and those captured in 2001. During winter 2001, elk collared in 2001were found on the VCNP more often (56%) than were elk collared in 2000 (12%). Conversely, there was greater use of BAND and adjacent SFNF (Dome and American Springs) by elk captured in 2000 (69%) than by those captured in 2001 (35%). Only 0.1% of elk captured in 2001 were found on LANL during winter 2001, compared to 12.2% of elk captured in 2000.

Analysis of telemetry data. To identify preferred cell conditions we used the SAS (SAS Institute Inc. 1999) system and multiple linear regression analysis (PROC REG) to analyze relationships among number of telemetered locations per cell and cell habitat variables. Variables identified by regression analysis produced a maximum correlation (r^2) of 0.29 with number of locations per cell (Table A.6). We also used the STATISTICA (StatSoft Inc. 1995) system and stepwise discriminant function analysis to determine which variables might discriminate between cells used by telemetered elk (cells with telemetered locations) and cells not used across and between winters. Greatest percentage of cases correctly classified as used vs. unused by variables identified was

28.5% (Table A.7). We also examined cells for discrimination between relatively high-use and low-use cells (= 4 locations per cell vs. 1 location per cell) (Table A.8).

Model

Model process. Simple statistical analysis of cell occupancy did not provide adequate correlation to actual elk use, therefore we chose relevant variables and created a ranking system (DI) based on our interpretations of telemetered elk use patterns and the elk literature. Ranking cells according to the DI score (as in Table 3.2) resulted in a range of values per cell from 0.41-13.92. We found consistent correlations between DI scores and mean number of elk per cell in all 3 winters (Figure 4.4) (winter 1999 r^2 = *0.60*, winter 2000 r^2 = *0.45*, and winter 2001 r^2 = *0.92*). In winter 2000 when snow accumulations were well above average, elk were excluded from high elevation cells with DI score = 6.0 by snow depth, reducing overall correlation between DI score and number of elk per cell, especially with higher elevation cells (with high DI values) where greater snow accumulations occurred. However, in cells with DI score < 6, mean number of elk per cell was well correlated to DI score (r^2 = *0.92*) much as in the other 2 winters. Others have found that snow depth is the most important factor in influencing the movement and distribution of elk during winter (Parker et al. 1984, Adams 1982). Our study supported this conclusion. Comparison of telemetry data and snow depth data indicated that percent of total telemetered locations on BAND was correlated to snow depth recorded at PJMT during the course of this study (r^2 = *0.71*) (Figure 4.4). Conversely, locations on the VCNP were inversely correlated (r^2 = *0.69*), while locations on LANL were poorly correlated (r^2 = *0.17*) to snow depth at the PJMT station.

We developed a simple linear regression (Figure 4.5) based on snow depths measured on BAND and the PJMT station to predict snow depth at any elevation on BAND from known snow depths at PJMT (eq. 3.2). Data from the LANL weather stations (Figure 4.6) and snow gauges on BAND (Figure 4.7) indicated that elevations above the escarpment (>~2,460m elevation) had greater snow accumulations than areas below the escarpment. To reflect this difference we multiplied all projected snow depths in cells with mean elevation <2,460 m by 0.52, based on the difference between the 2 greatest depths recorded at TA-6 during winter 2000 and winter 2001 and the depth at PJMT on those same days (Figure 4.6 insert). Correlation of the resultant predicted snow depths to known snow depths averaged $\bar{x}$ = *0.58* (range 0.91-0.43) (Table A.9). To approximate elk response to the combination of conditions we have discussed our model assesses conditions at each time-step (= 1 day). Initial state of each cell was determined at time-step zero by 3 factors: snow depth, DI score, and standing crop. Snow depth was set in each cell, from either a constant snow depth of interest set by the user, or from a text file of daily snow depths from actual data from the PJMT weather station, (or a data set of any varying conditions set by the user). Snow depth was then predicted across the study area by the model (eq. 3.2). Initial DI score was determined (as in Table 3.1) by summing the percent composition score per cell for desired attributes (aspect, slope, canopy closure, vegetation class, and elevation class), the additive scores for cells located within historic use areas, La Mesa or Cerro Grande burn areas, and the elevational score. Initial standing crop value per cell was an initial text file input by the user (standing crop value per cell = standing crop estimate for each vegetation type [kg ha^{-1}] {Table 4.4}

times the percent composition per cell, multiplied by 9 = cell crop estimate [kg per 9 ha grid cell]). Table 4.4 standing crop estimates were based on data collected during growing years with below average precipitation may represent relatively low productivity years (Figure 2.2). Therefore, these baseline data may underestimate standing crop that could be available to elk in both years.

Model users must specify the number of elk to be distributed on the study area and the number of days they will be on the range. At time-step one (each time-step equals one day), elk will be distributed to the cell with the highest DI score, up to a maximum of 20 elk per cell. Elk will then be assigned to the cell with the next highest DI value up to the maximum of 20 elk per cell, and so on until all elk are distributed.

If snow depth in cells was greater than 21 cm, the DI value was drastically reduced to effectively close the cell to elk use until all other cells were reduced to a lower value. When snow depth in the cell fell below 21 cm, DI score was restored to its previous value. For each time-step (each day up to the number of days on range specified by the user), the standing crop would be reduced by 5.41 kg for each elk in a cell (maximum reduction per day = 20 elk * 5.41kg/elk/day = 108.2 kg). When standing crop in a cell has been reduced by 20% of its original value, the DI value was then also reduced by 20%. Elk were reassigned to the highest-ranking cells at each time-step. Reductions in standing crop were cumulative for each day that elk were in a cell, up to the specified number of days that elk are on the range. Cell state was reassessed at the beginning of each time-step. Results of the model process are written to a text file that indicates cell conditions at end of the model run (the time interval specified by the user)

including number of elk present, standing crop remaining, DI score, snow depth in cells, and cumulative elk-days use (the total number of elk in each cell over the course of the model run times the number of days each cell contained = 1 elk). This text file can be easily imported into any statistical analysis package or GIS environment for display of any output condition.

Corroboration. As an initial evaluation of model performance we predicted elk use on BAND during study period times of most intensive data collection and compared results to observed elk distribution patterns during the same time period. We ran the model with actual PJMT snow depth data for 90 days (December 01-February 28) in each of winter 2000 and winter 2001. The number of elk on BAND fluctuates over the course of a winter (Table 4.3). Therefore, to include all of the potential wintering elk population we chose the maximum of the upper 95% confidence intervals for the population estimates of elk on the study area during each winter survey period (2883 elk for winter 2000, 1497 elk for winter 2001) (Table 4.3). We plotted density (calculated with ArcView spatial analyst extension) based on elk-days use per km^2 as generated by the model (winter 2000 Figure 4.9, winter 2001 Figure 4.10) and compared results to density (calculated by the same method) of actual telemetered locations per km^2 for the same time period (winter 2000 Figure 4.11, winter 2001 Figure 4.12). Density of model output elk-days use per cell was correlated to density of telemetered locations per cell for both winter 2000 ($r^2 = 0.67$) and winter 2001 ($r^2 = 0.68$).

Helicopter survey flights were conducted independently of elk telemetry locations to estimate elk numbers on BAND in winter 2000 and winter 2001. Density of

telemetered locations was correlated to the total density of elk per cell counted by helicopter surveys in each winter (winter 2000 $r^2 = 0.51$, winter 2001 $r^2 = 0.44$). Visual aerial surveys can be biased by a number of factors (Caughley 1974, Pollack and Kendal 1987, Samuel et al. 1987). Only ~50% of collared elk known to be in units surveyed (Table 4.2) were seen during helicopter counts. This proportion was similar to that reported by Bear et al. (1989) and likely explains some of the discrepancies in density distributions between helicopter survey and telemetered data (winter 2000 Figure 4.13, winter 2001 Figure 4.14). Additionally, winter 2001 telemetry data showed high elk-use in the American Springs region of SFNF in areas impacted by Cerro Grande fire. These were areas that were not included in our designated search units, and so were not searched during helicopter surveys. Presence of elk there reflected in the density of telemetered locations and modeled by elk-days use is not represented by the helicopter survey data.

Density of elk-days use from model output and density of helicopter observations were also correlated (winter 2000 $r^2 = 0.35$, winter 2001 $r^2 = 0.35$). While the correlation of modeled density to helicopter survey density was not as strong as to telemetered density, it remained consistent across years under very different winter conditions. Helicopter survey data may not correlate well with modeled elk-days use because helicopter counts are simply a 1-day snapshot of elk presence on surveyed areas, and not equivalent to elk use over the entire winter period. Additionally, many elk present in the study area (~50%) were not seen during helicopter surveys (Table 4.2).

Helicopter surveys were also conducted on BAND during winters 1990-1995 (historic observed distribution). We assessed density distribution for these data as we did with winters 2000 and 2001 (current observed distribution). We compared historical density distribution with the model's predicted elk use distribution. However, there are fundamental differences between the historic and the current data sets. The density of current observed distribution of elk was based on the cumulative total of elk counted during all helicopter survey flights per winter (winter 2000 $n=5$, winter 2001 $n=4$), while historic observed distributions were based on a single helicopter survey flight each winter. The modeled current distribution data were generated using known snow depths on PJMT, while modeled historic distribution data depend on projected PJMT snow depth as derived from QMZNswe (eq. 3.3). In addition, search effort was not consistent between years.

Snow accumulations varied between historic survey years in the BAND area as recorded at the NOAA Los Alamos weather station. Winters 1990 and 1994 had below average accumulations while 1991-1993 and 1995 accumulations were above average. In addition snow conditions in winter 1993 were unique among years considered here in that snow events alternated with rainstorms to create dense, icy, snowpack conditions that restricted elk use of traditional wintering areas (Allen 1996).

We determined the number of elk for model input based on the number of elk counted during helicopter survey flights 1990-1995. We assumed that proportion of elk not counted during these historic observation flights would have been the same as in winter 2000 and winter 2001 ($\bar{x}$ = 55% of collared elk known to be in units searched

were not seen [Table 4.2]), and so we increased the total number of elk counted during each flight by 55% to estimate number of elk present each year. We then increased that number by another 55% since the maximum upper 95% confidence interval from the winter 2000 data used in the original model run was 55% higher than the estimated number of elk present. Number of days used for model input = number of days from December 01 the preceding year up to the date of the helicopter survey flight (e.g., winter 1990 flight was conducted on January 31, 1990, so model input days for winter 1990 = 62).

Model input snow depth was the result of Eq. 3.3 based on daily QMZNswe data from December 01 the preceding year up to the date of the survey flight. Allen (1996) reported all data and related information from helicopter survey flights 1990-1995. The northwestern portion of BAND was not covered in these surveys so was excluded from correlation analyses.

Winter 1990 (November 1989-February 1990). Number of elk counted on January 31, 1990, was 504. These data did not show the gradient of density distribution (an increasing number of cells per class as density decreases) that we saw in years with >1 helicopter survey flight (Figure 4.15). Higher density cells were centered on 3 groups of 100 animals. Mean snowfall (4.8cm) for this period was below average ($\bar{x} = 9.47cm$). Number of elk used for model input was 1,211. Model input days was 62. Correlation to model output density of elk use days was $r^2 = 0.14$ (Figure 4.16).

Winter 1991 (November 1991-February 1991). Number of elk counted on January 28, 1991, was 907. Observed elk distribution was more diffuse than in 1990

(Figure 4.17). Mean snowfall (11.68cm) for this period was above average ($\bar{x}$ = *9.47cm*). Number of elk used for model input was 2,180. Model input days was 59. Correlation to model output density of elk use days was r^2 = *0.22* (Figure 4.18).

Winter 1992 (November 1992-February 1993). Number of elk counted on February 11, 1992, was 867. There was a gradient of observed elk distribution (Figure 4.19). Mean snowfall (14.58cm) for this period was above average ($\bar{x}$ = *9.47cm*). Number of elk used for model input was 2,083. Model input days was 73. Correlation to model output density of elk use days was r^2 = *0.36* (Figure 4.20).

Winter 1993 (November 1993-February 1994). Number of elk counted on February 01, 1993, was 499. There was a gradient of observed elk distribution but many elk were seen in the lower elevations on BAND, likely an artifact of the icy snow conditions (Figure 4.21). Mean snowfall (21.08cm) for this period was above average ($\bar{x}$ = *9.47cm*). Number of elk used for model input was 1,198. Model input days was 64. Correlation to model output density of elk use days was r^2 = *0.06* (Figure 4.22).

Winter 1994 (November 1994-February 1995). Number of elk counted on February 17, 1994, was 939. There was a gradient of observed elk distribution (Figure 4.23). Mean snowfall (7.06cm) for this period was below average ($\bar{x}$ = *9.47cm*), and there was little snow cover reported at the time of the flight. Number of elk used for model input was 2,255. Model input days was 79. Correlation to model output density of elk use days was r^2 = *0.13* (Figure 4.24).

Winter 1995 (November 1995-February 1996). Number of elk counted on February 07, 1995, was 548. There was no gradient of observed elk distribution, with density centered on 1 observation of 250 elk (Figure 4.25). Mean snowfall (13.03cm) for this period was above average ($\bar{x}$ = *9.47cm),* but there was little snow cover reported at the time of the flight. Number of elk used for model input was 1,316. Model input days was 70. Correlation to model output density of elk use days was r^2 = *0.16* (Figure 4.26).

Sensitivity analysis. To evaluate the relative sensitivity of model parameters and input conditions we used values of 0.25, 0.50, 2.0, and 4.0 times the initial model development variable parameters. We then correlated elk-days use per cell output between these parameters and the original parameter values (Table 4.5). The model showed greatest sensitivity to changes in snow depth at which elk were excluded from cells. Correlation decreased dramatically as snow depth was increased or decreased, eventually dropping to zero as snow depth increased from 21cm to 84cm. Maximum elk allowed per cell proved to be remarkably insensitive to input changes. A reduction from 20 to 5 elk finally produced a major change in correlation, but even with a 4-fold increase from 20 to 80 elk allowed per cell, correlation to original output changed very little. Variations in total standing crop estimates, daily forage intake, and the threshold at which reduction of original crop reduces DI) generally increased with increased deviation from original values, but were relatively stable overall. Daily forage intake showed greater sensitivity as values were decreased than when increased. Correlation to original values decreased with extreme reduction in the amount that DI is reduced when the crop reduction threshold is reached but remained stable at all other values.

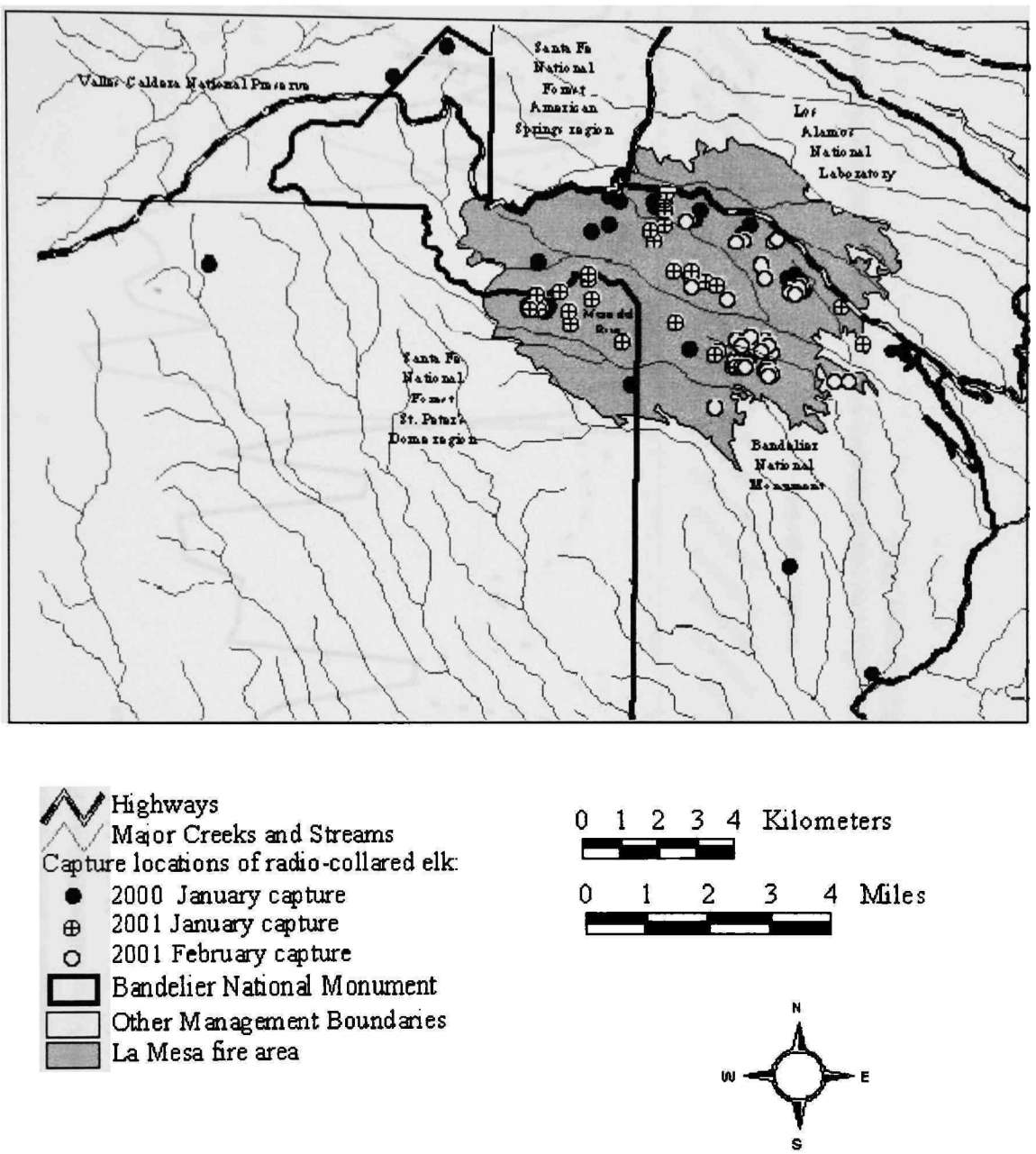

Figure 4.1. Capture locations of elk radio-collared in and near Bandelier National Monument, New Mexico, in January 2000 and January-February 2001.

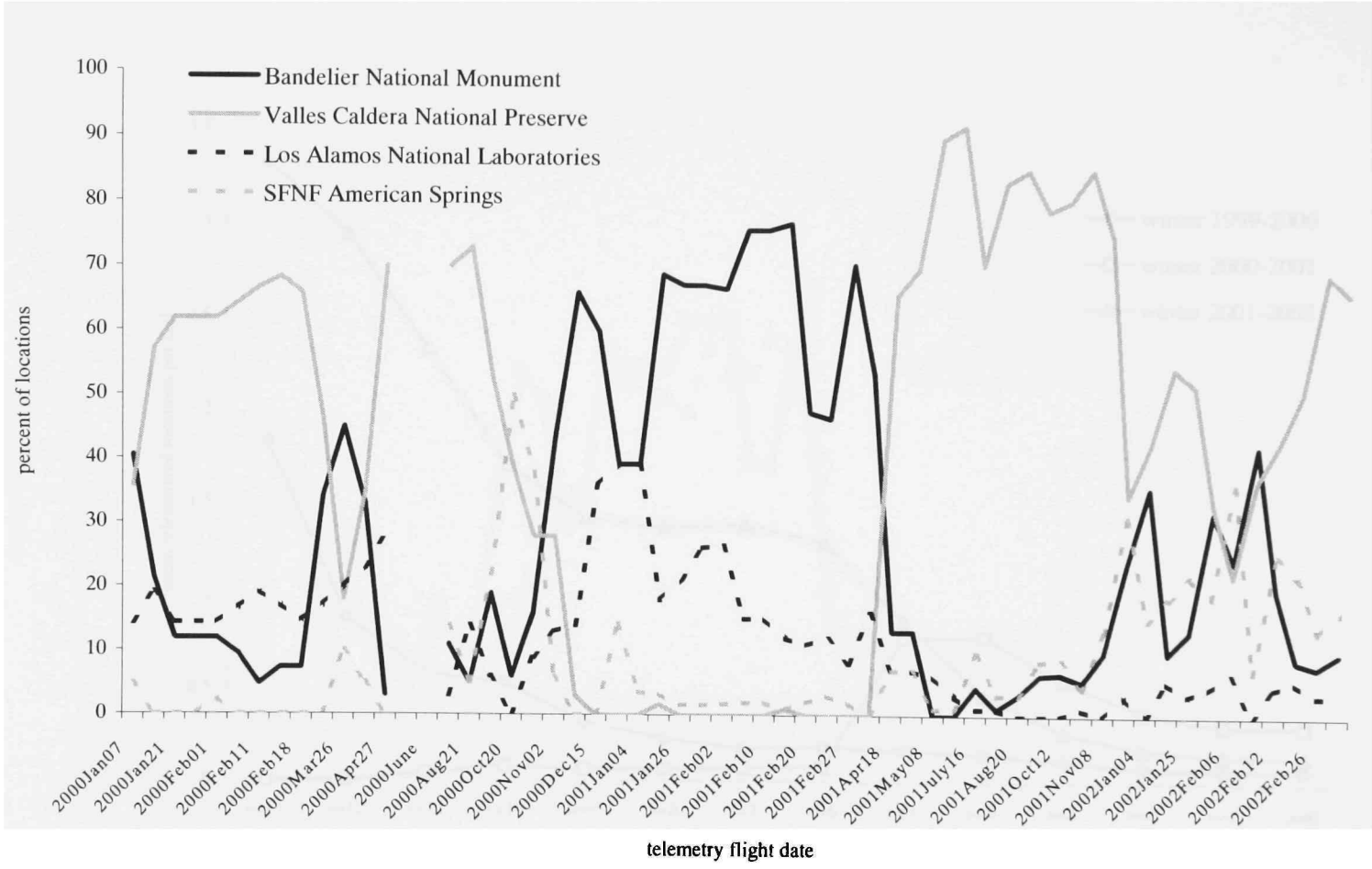

Figure 4.2. Percent of telemetered elk locations by administrative unit in and near Bandelier National Monument, New Mexico, January 2000-February 2002.

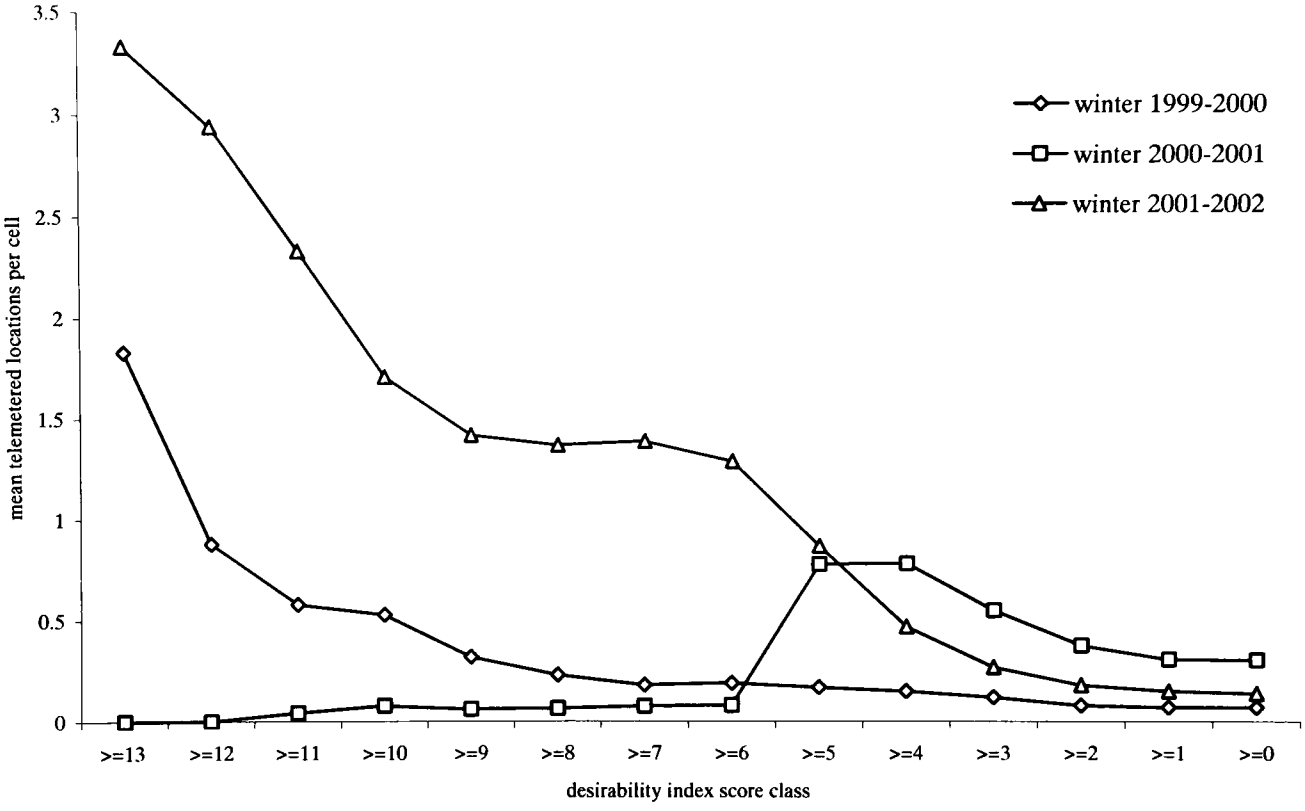

Figure 4.3. Mean telemetered locations of elk per 300 m^2 grid cells verus desirability index (DI) class during 3 winters in and near Bandelier National Monument, New Mexico, and correlation (r^2) of mean telemetered locations per cell to DI class.

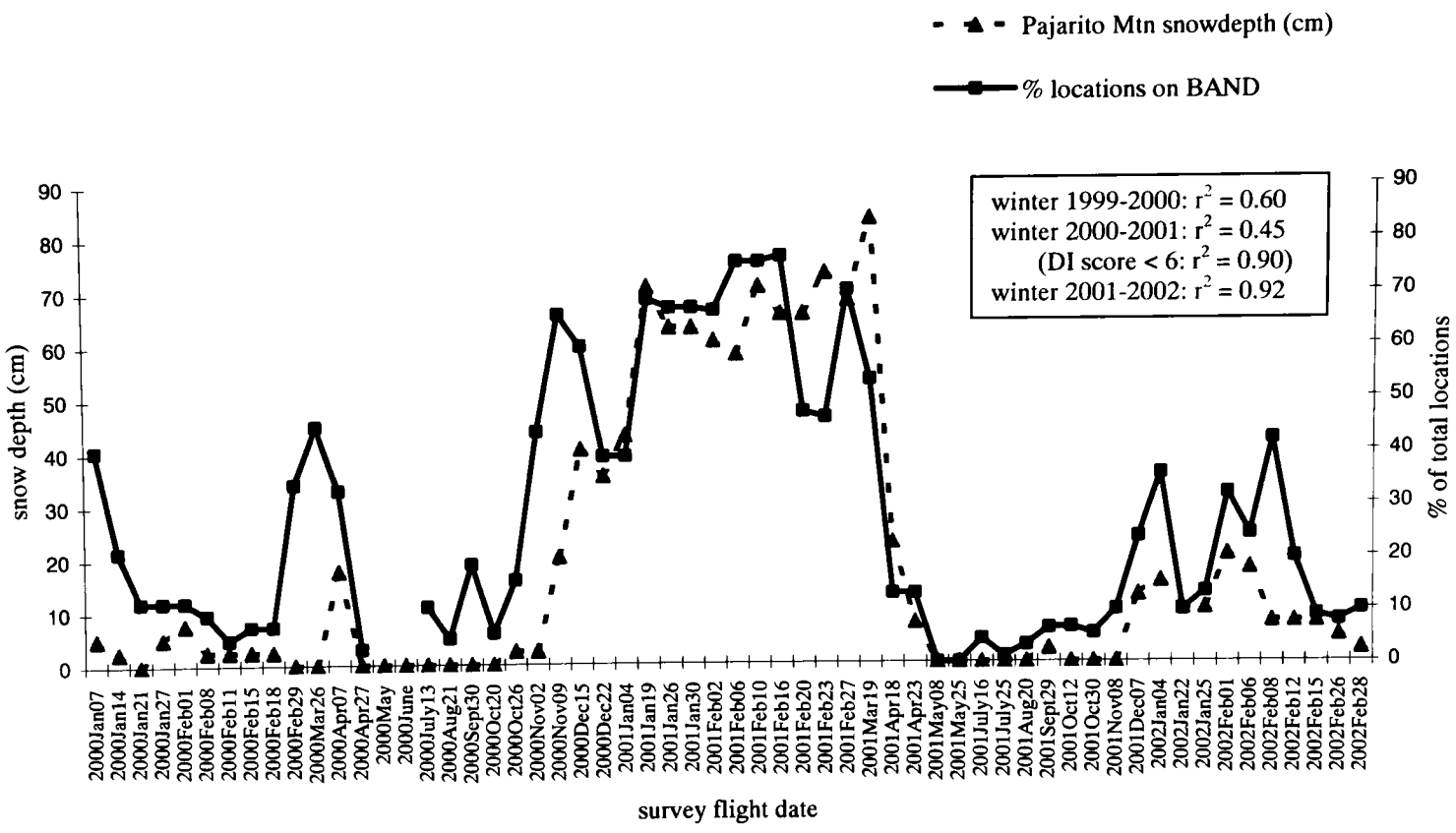

Figure 4.4. Percent of total telemetered locations on Bandelier National Monument, New Mexico, and snow depth (cm) at LANL Pajarito Mountain weather station on survey flight dates January 2000-February 2002 (r^2=*0.71*).

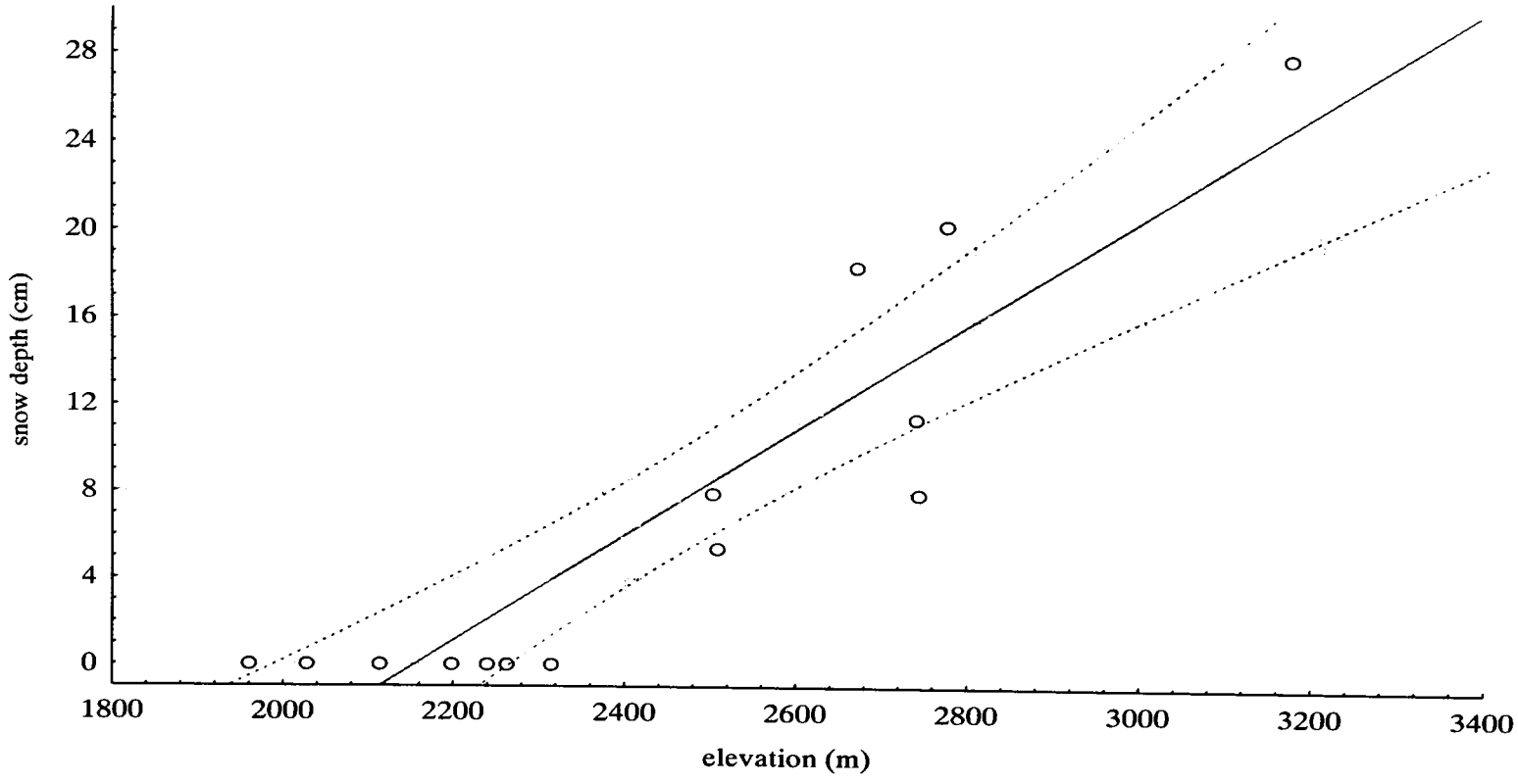

Figure 4.5. The regression line (with 95% confidence interval) of the snow depth data set most highly correlated to elevation of the snow monitoring stations ($r^2 = 0.82$) used to generate the model predicting snow depth at different elevations based on the snow depth recorded at Pajarito Mountain weather station near Bandelier National Monument, New Mexico.

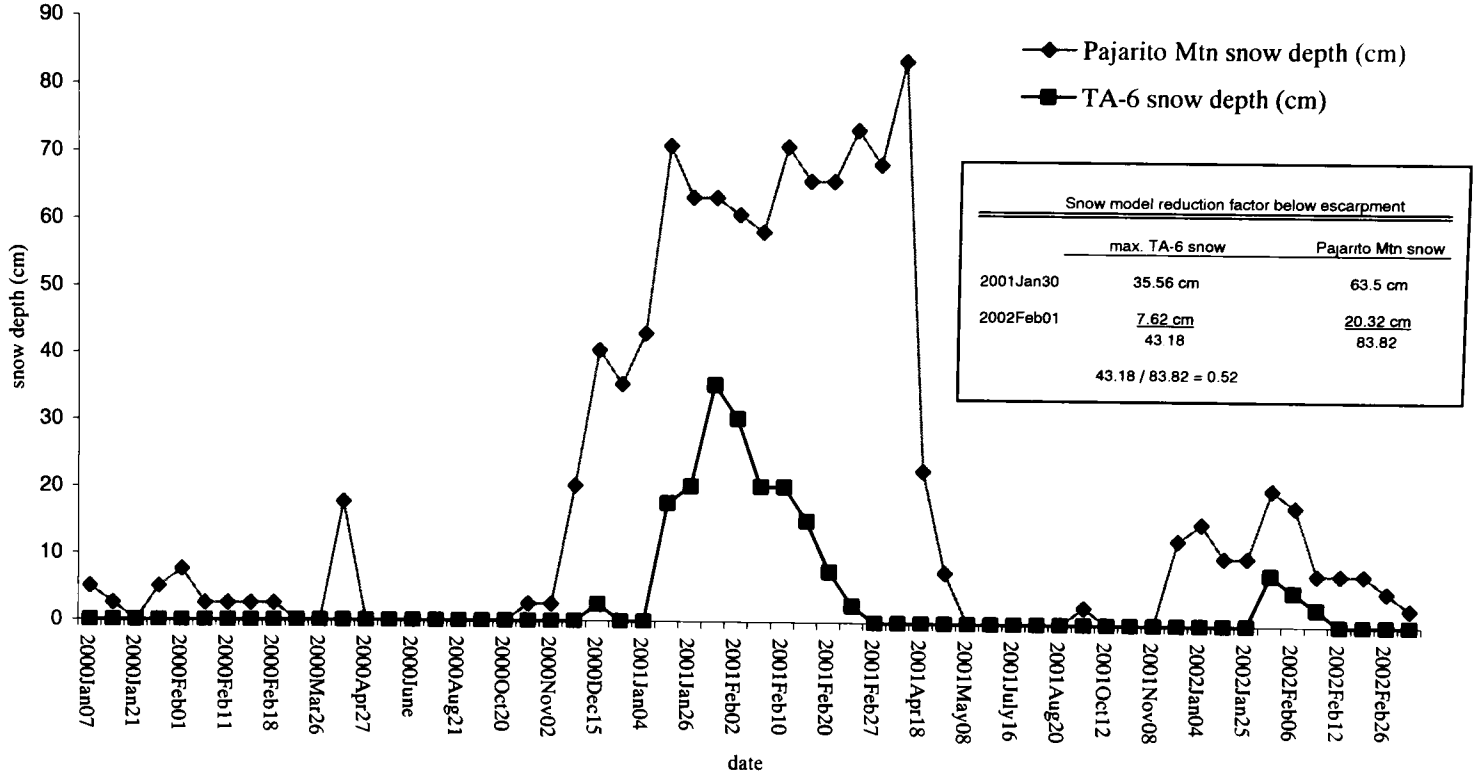

Figure 4.6. Snow depth measured above [Pajarito Mountain (3,158 m)] and below [TA-6 (2,263 m)] the escarpment January 2000-February 2002 and reduction factor used to project snow depth below escarpment in and near Bandelier National Monument, New Mexico.

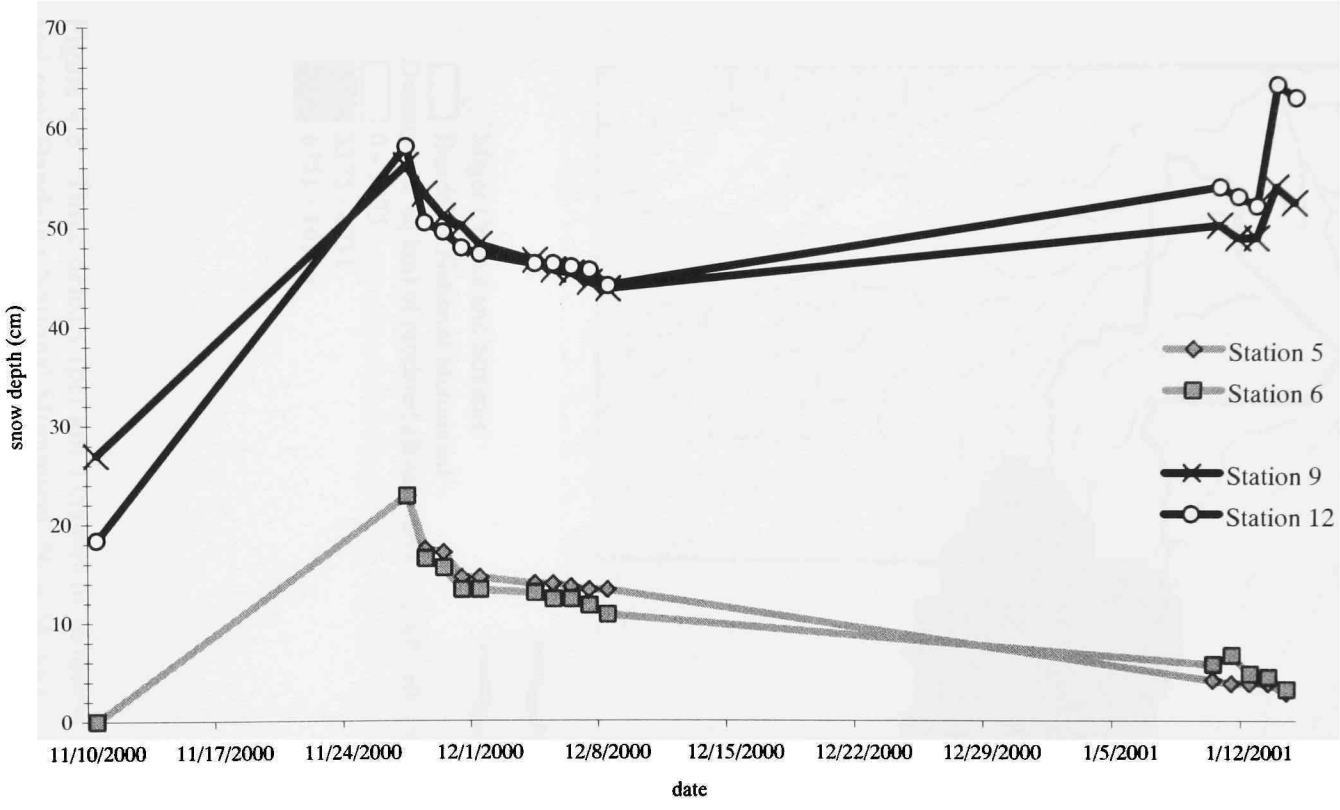

Figure 4.7. Snow depth as measured above (station 9 [2,768 m] and 12 [2,665 m]) and below (Station 5 [2,240 m] and 6 [2,315 m]) the escarpment during November and December 2000 and January 2001 in Bandelier National Monument, New Mexico.

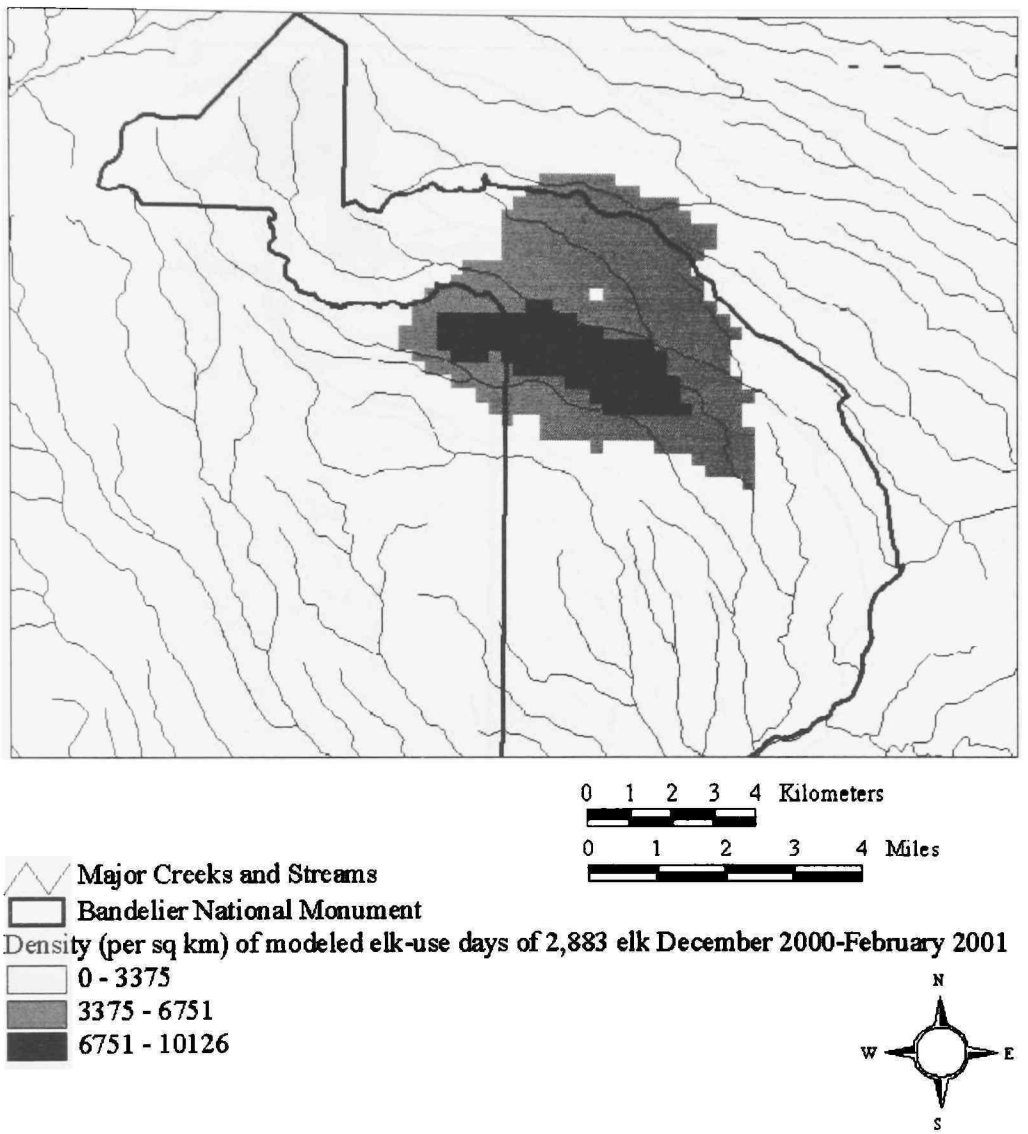

Figure 4.8. Three density (per km^2) classes of modeled elk-use days of 2,883 elk in and near Bandelier National Monument, New Mexico, December 2000-February 2001.

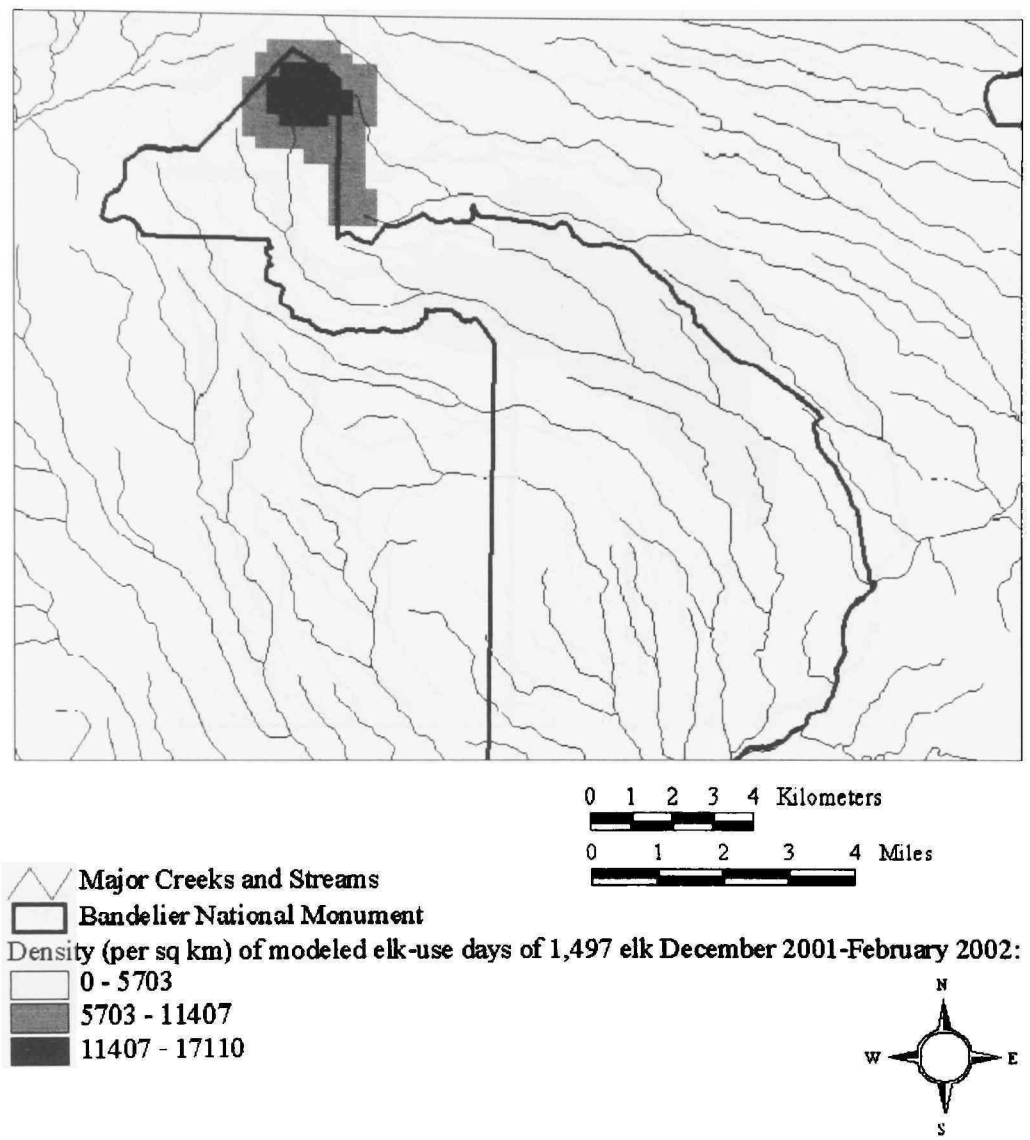

Figure 4.9. Three density (per km^2) classes of modeled elk-use days of 1,497 elk in and near Bandelier National Monument, New Mexico, December 2001-February 2002.

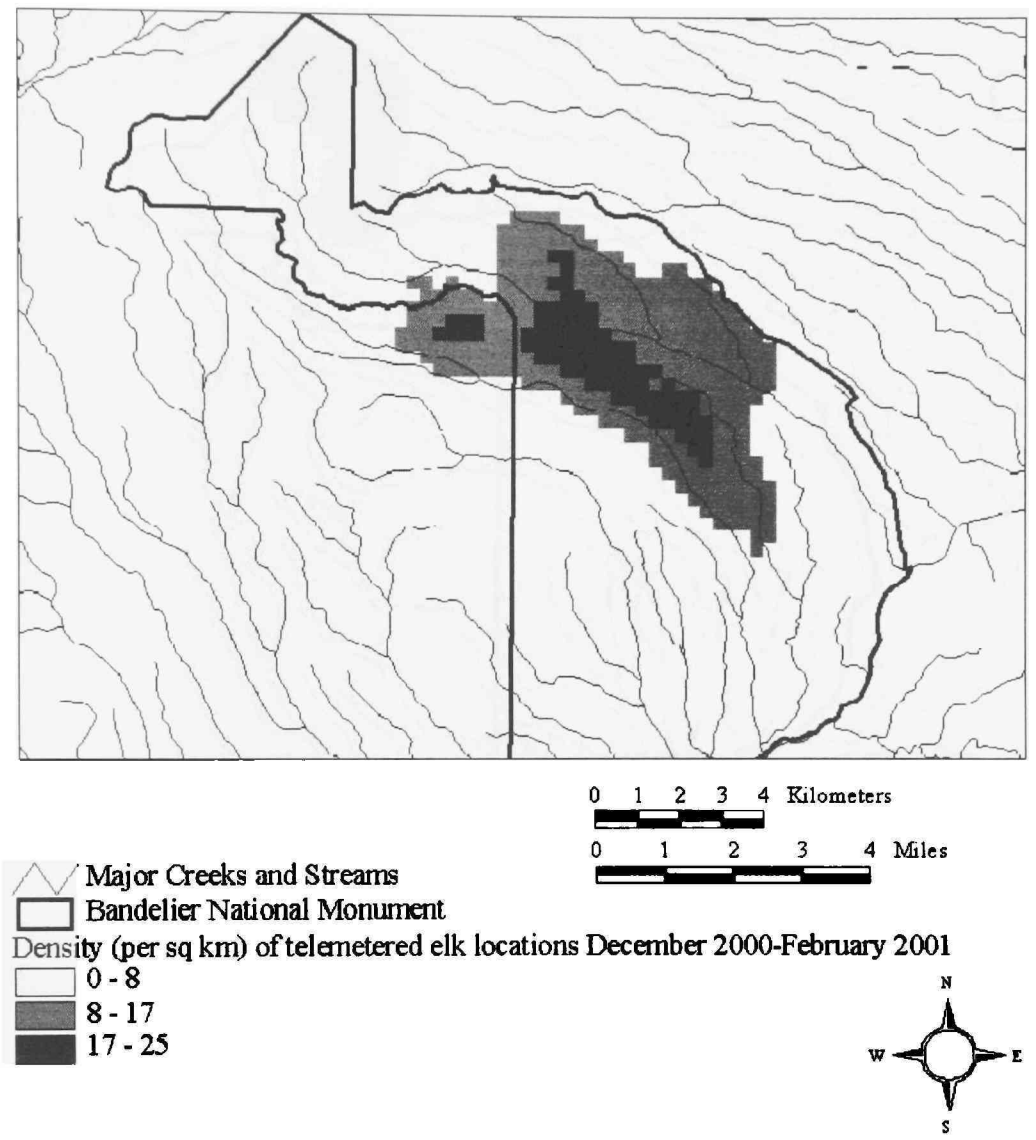

Figure 4.10. Three density (per km^2) classes of telemetered elk locations in and near Bandelier National Monument, New Mexico, December 2000-February 2001.

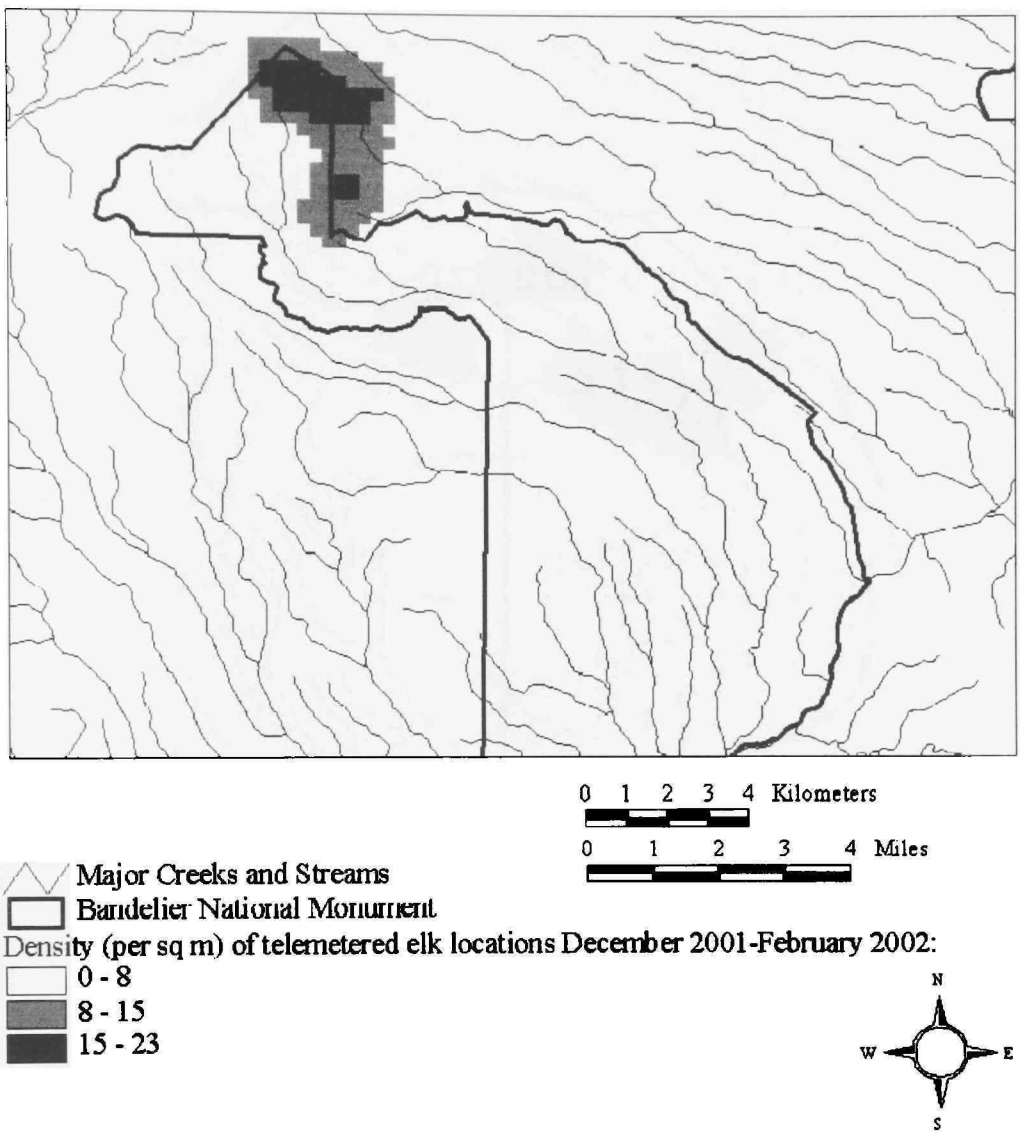

Figure 4.11. Three density (per km^2) classes of telemetered elk locations in and near Bandelier National Monument, New Mexico, December 2001-February 2002.

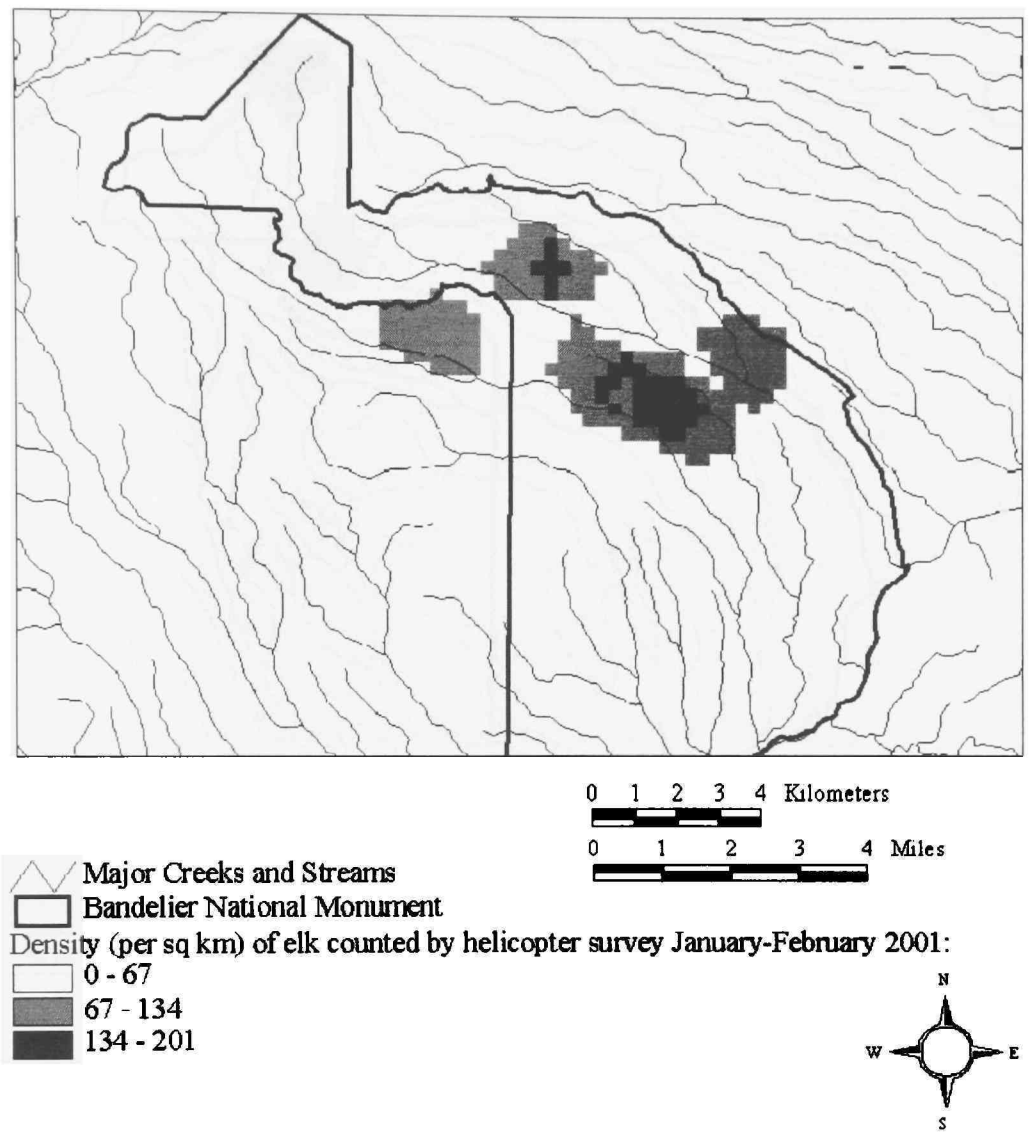

Figure 4.12. Three density (per km^2) classes elk counted by helicopter survey in and near Bandelier National Monument, New Mexico, January-February 2001.

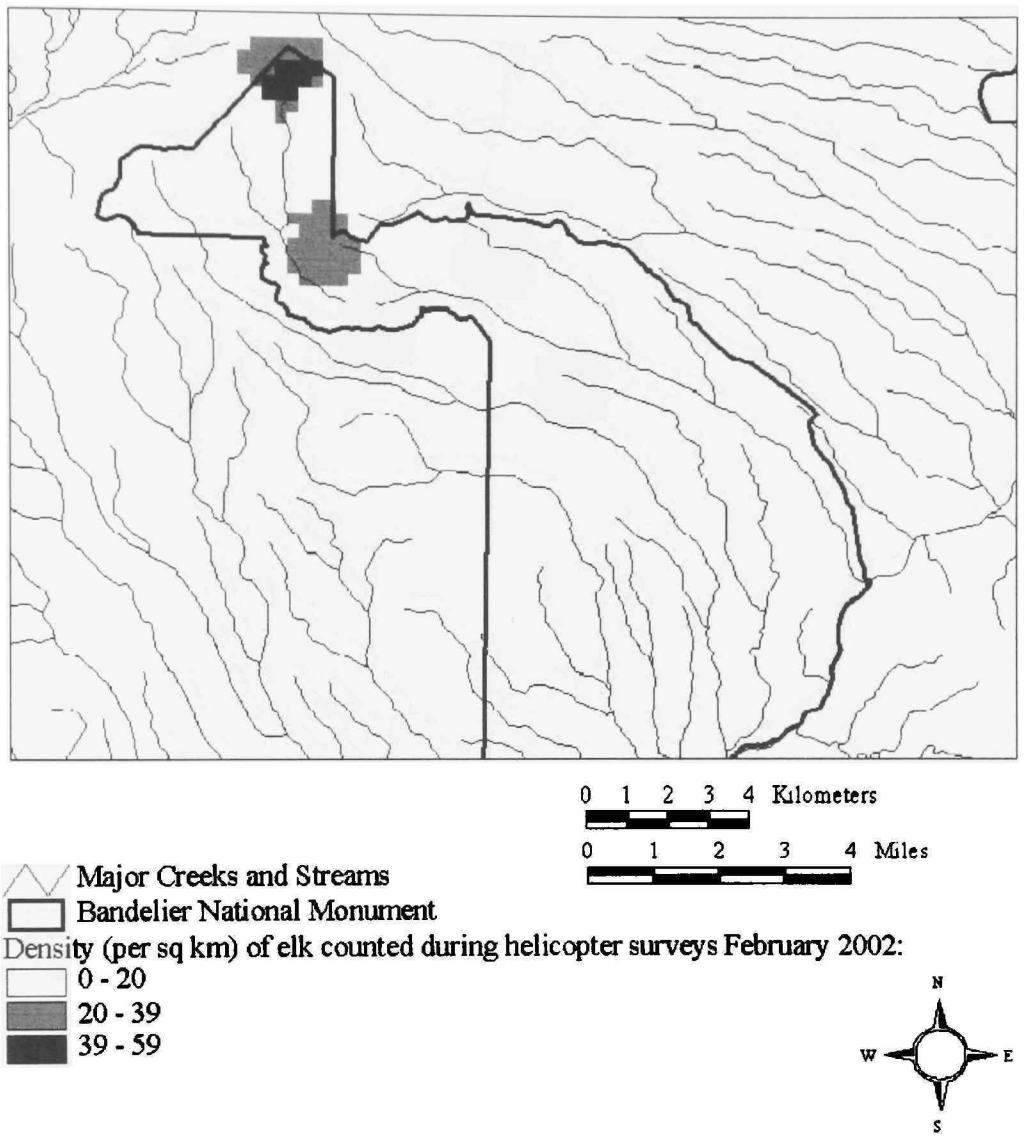

Figure 4.13. Three density (per km^2) classes of elk counted helicopter survey in and near Bandelier National Monument, New Mexico, February 2002.

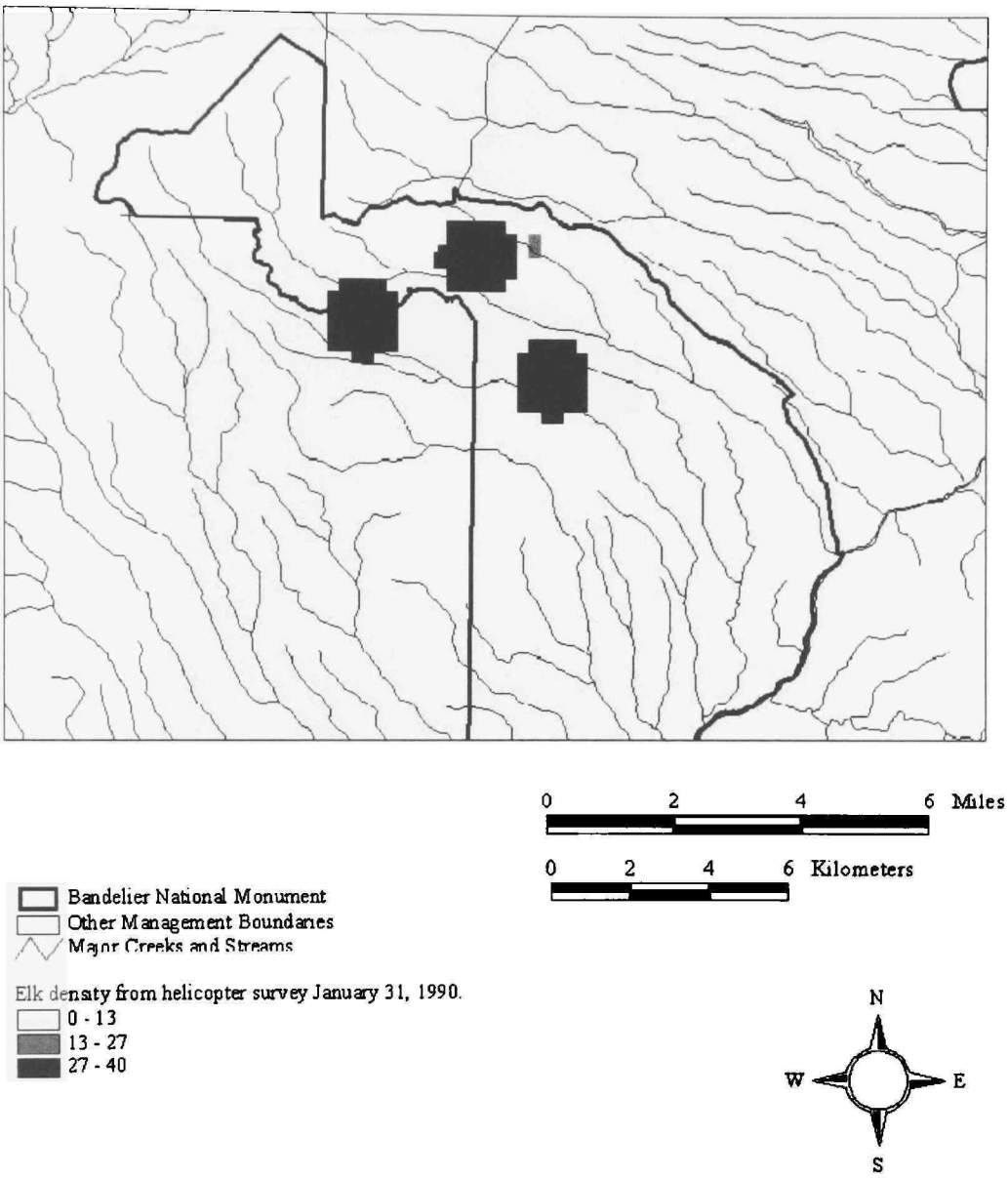

Figure 4.14. Three density (per km^2) classes of elk counted *(n=504)* helicopter survey in and near Bandelier National Monument, New Mexico, January 31, 1990.

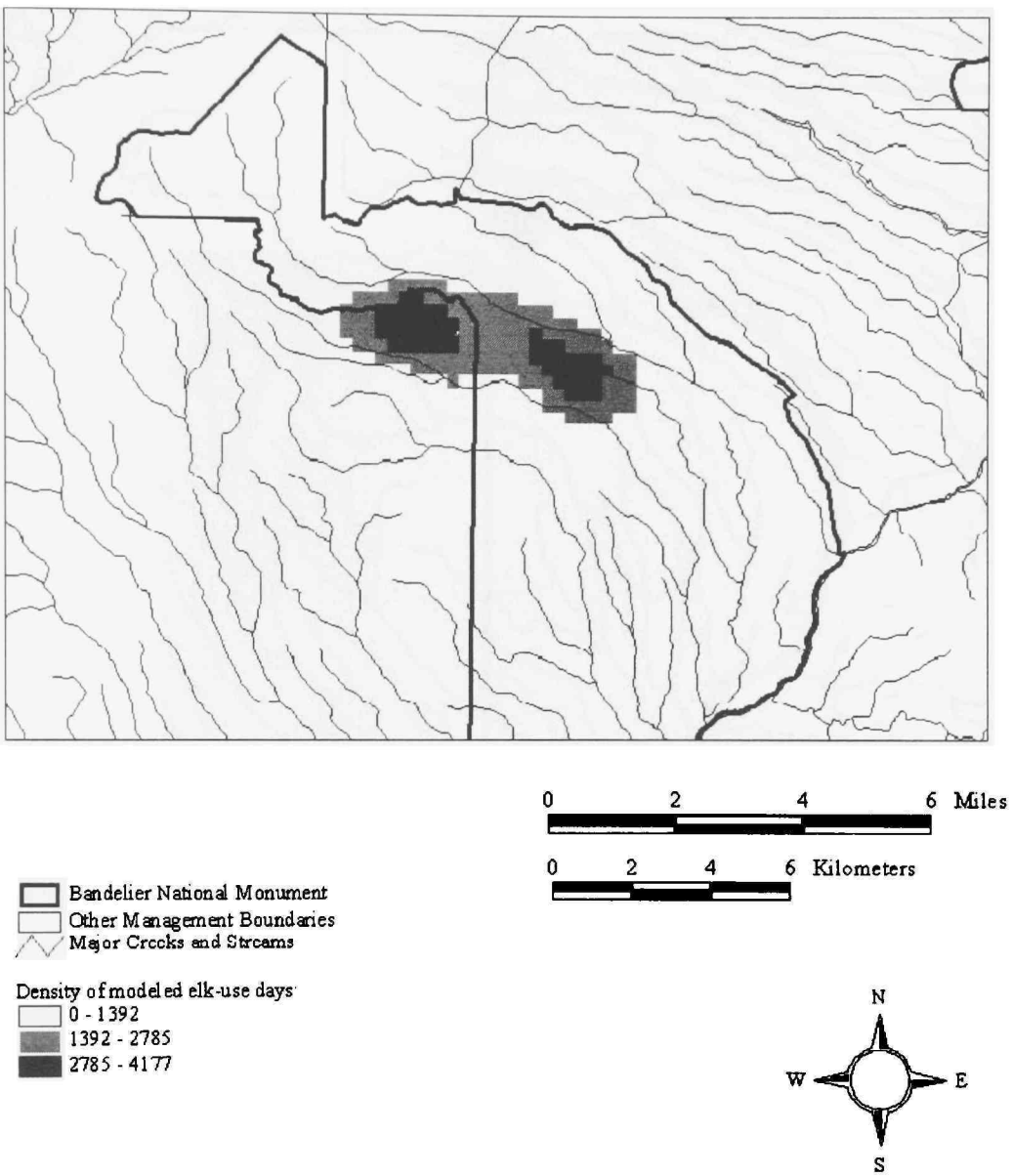

Figure 4.15. Three density (per km^2) classes of modeled elk-use days of 1,211 elk in and near Bandelier National Monument, New Mexico, December 01-January 31, 1990.

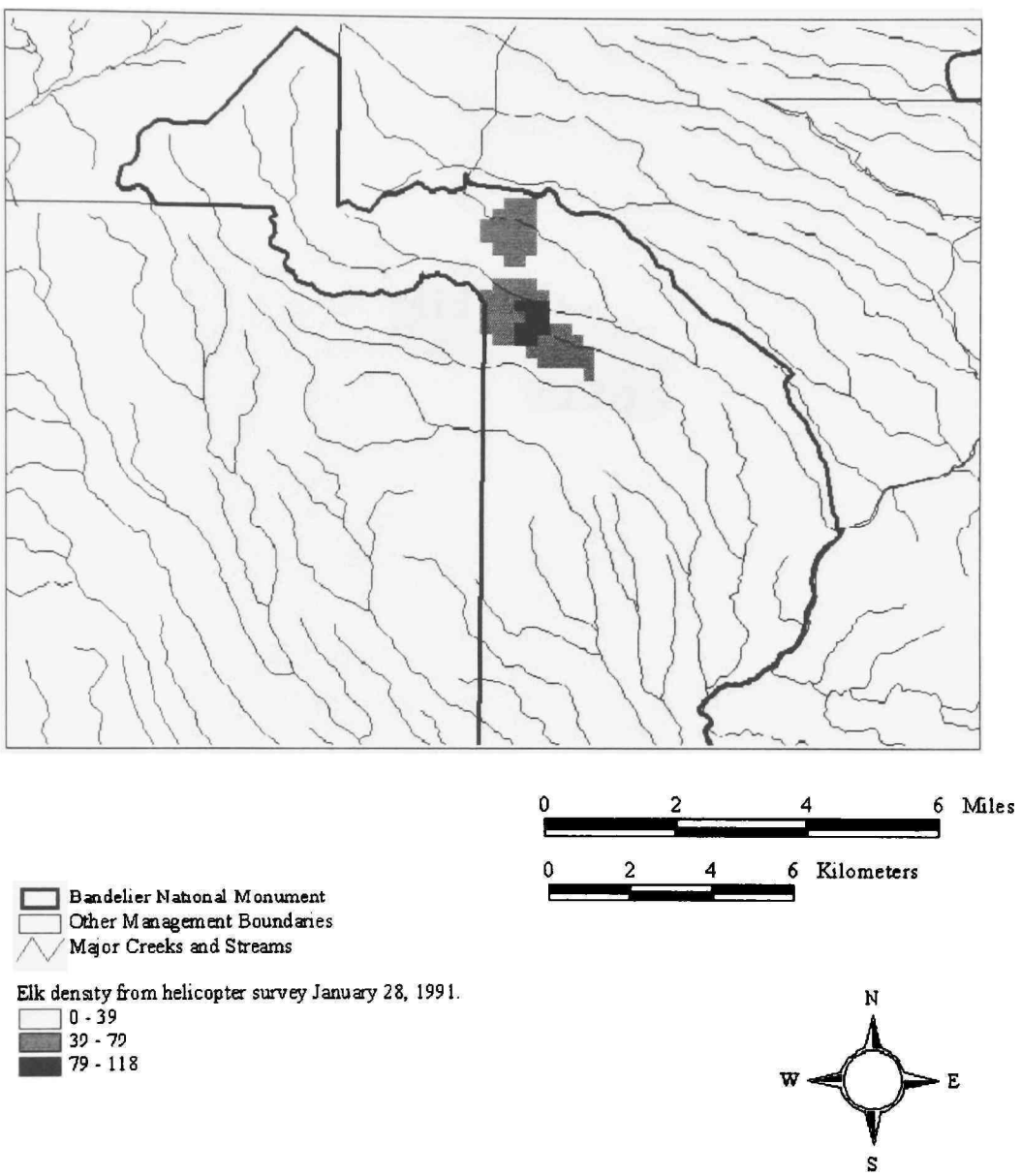

Figure 4.16. Three density (per km^2) classes of elk counted *(n=907)* helicopter survey in and near Bandelier National Monument, New Mexico, January 28, 1991.

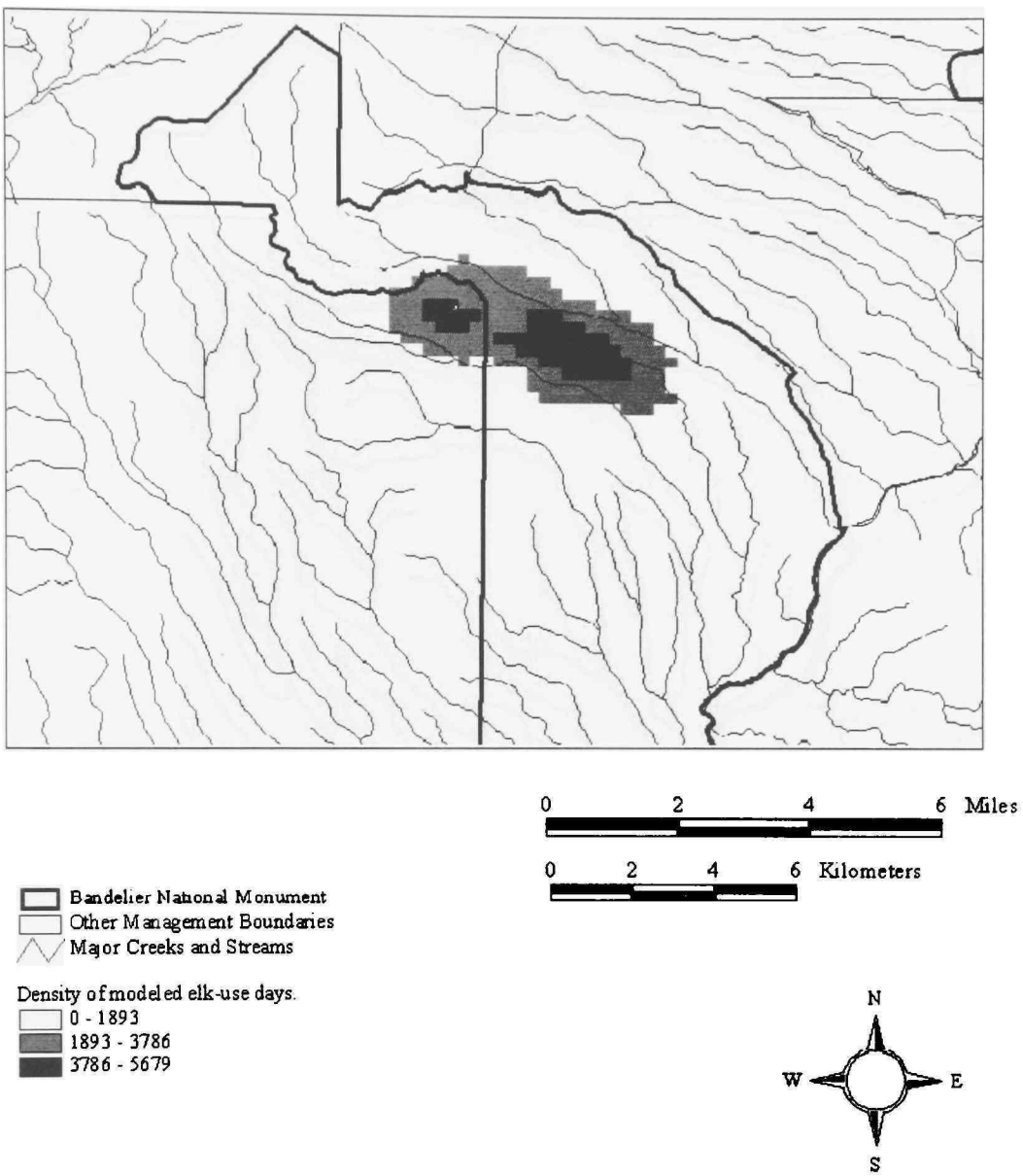

Figure 4.17. Three density (per km^2) classes of modeled elk-use days of 2,180 elk in and near Bandelier National Monument, New Mexico, December 01-January 28, 1991.

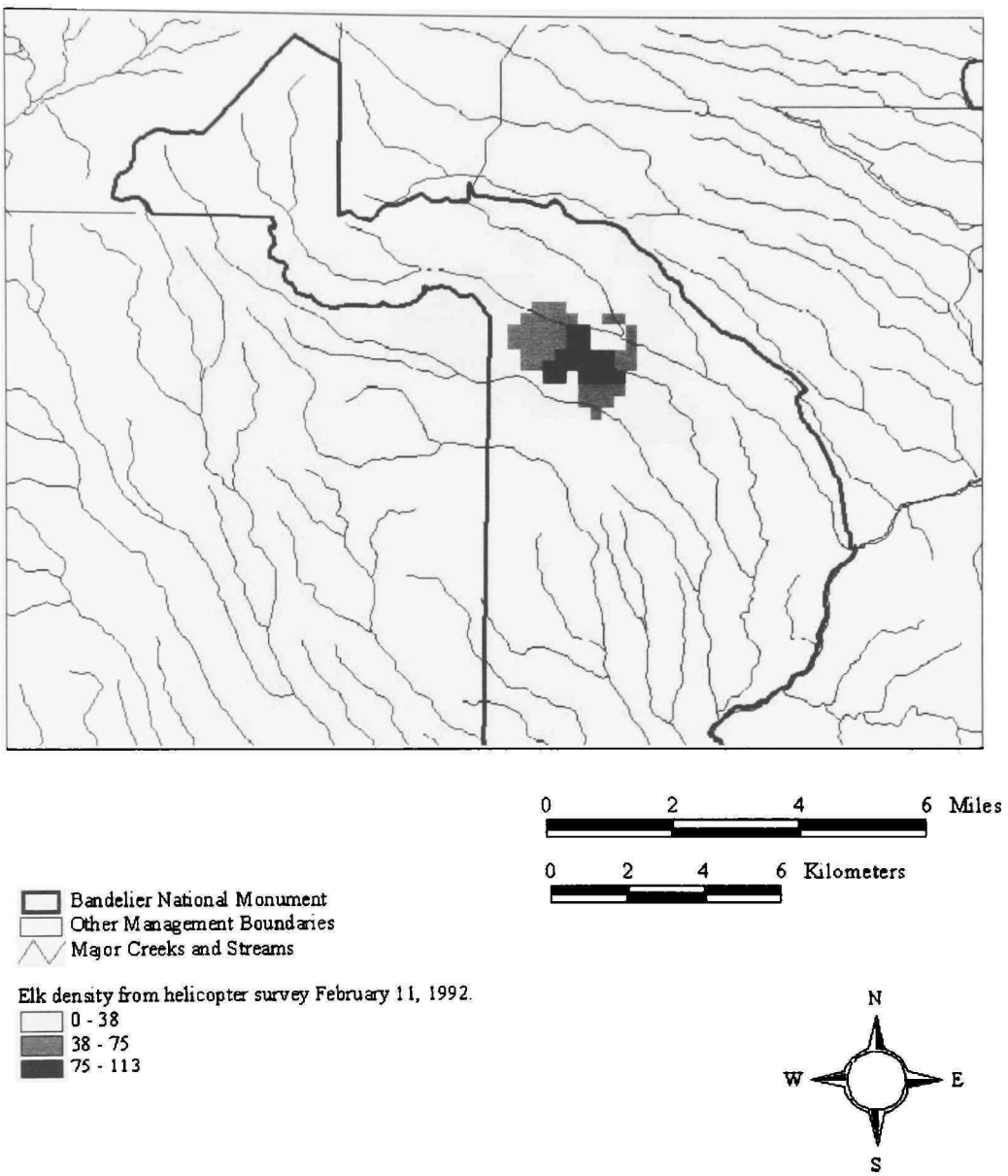

Figure 4.18. Three density (per km^2) classes of elk counted *(n=867)* during helicopter survey in and near Bandelier National Monument, New Mexico, February 11, 1992.

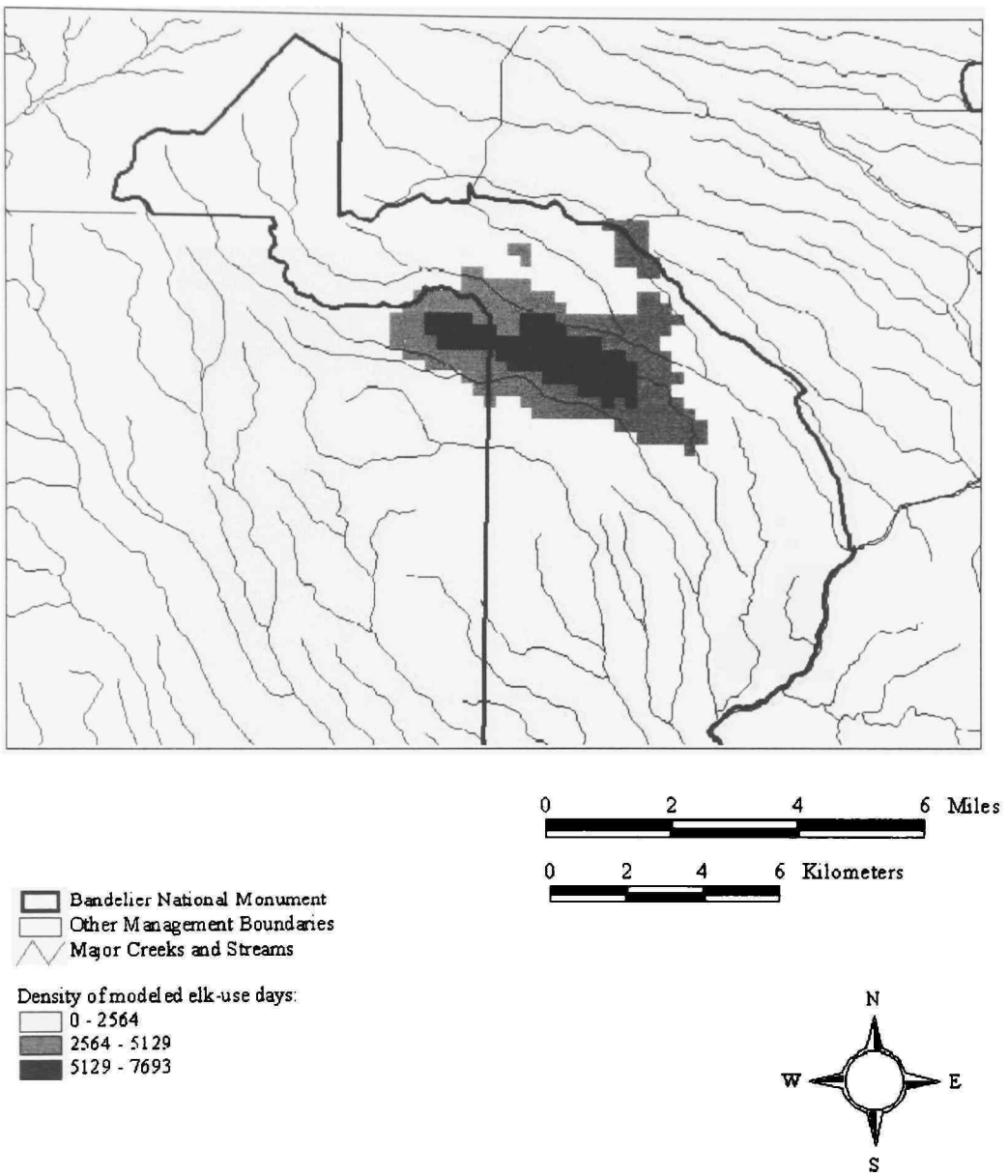

Figure 4.19. Three density (per km^2) classes of modeled elk-use days of 2,083 elk in and near Bandelier National Monument, New Mexico, December 01-February 11, 1992.

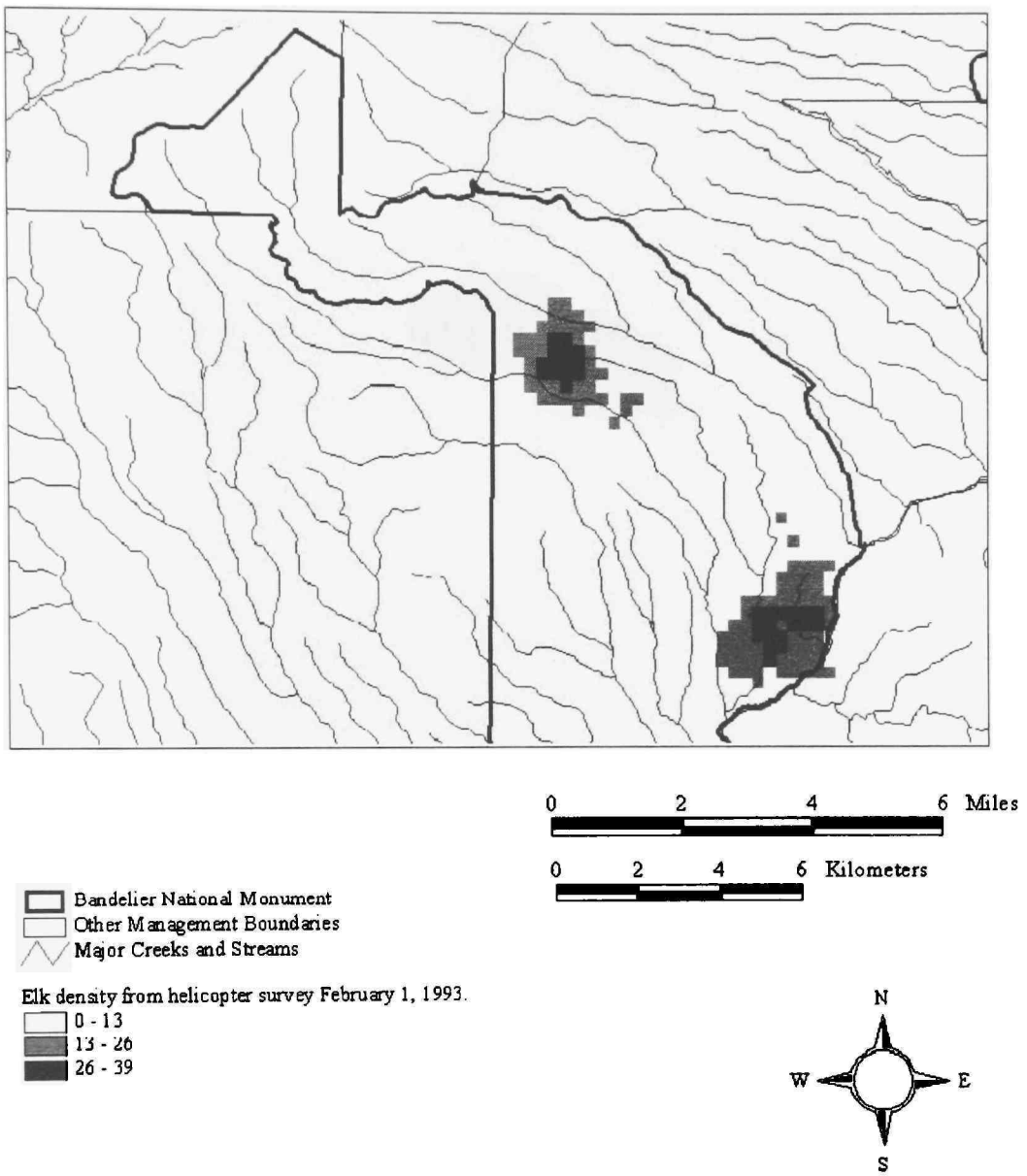

Figure 4.20. Three density (per km^2) classes of elk counted *(n=499)* during helicopter survey in and near Bandelier National Monument, New Mexico, February 01, 1993.

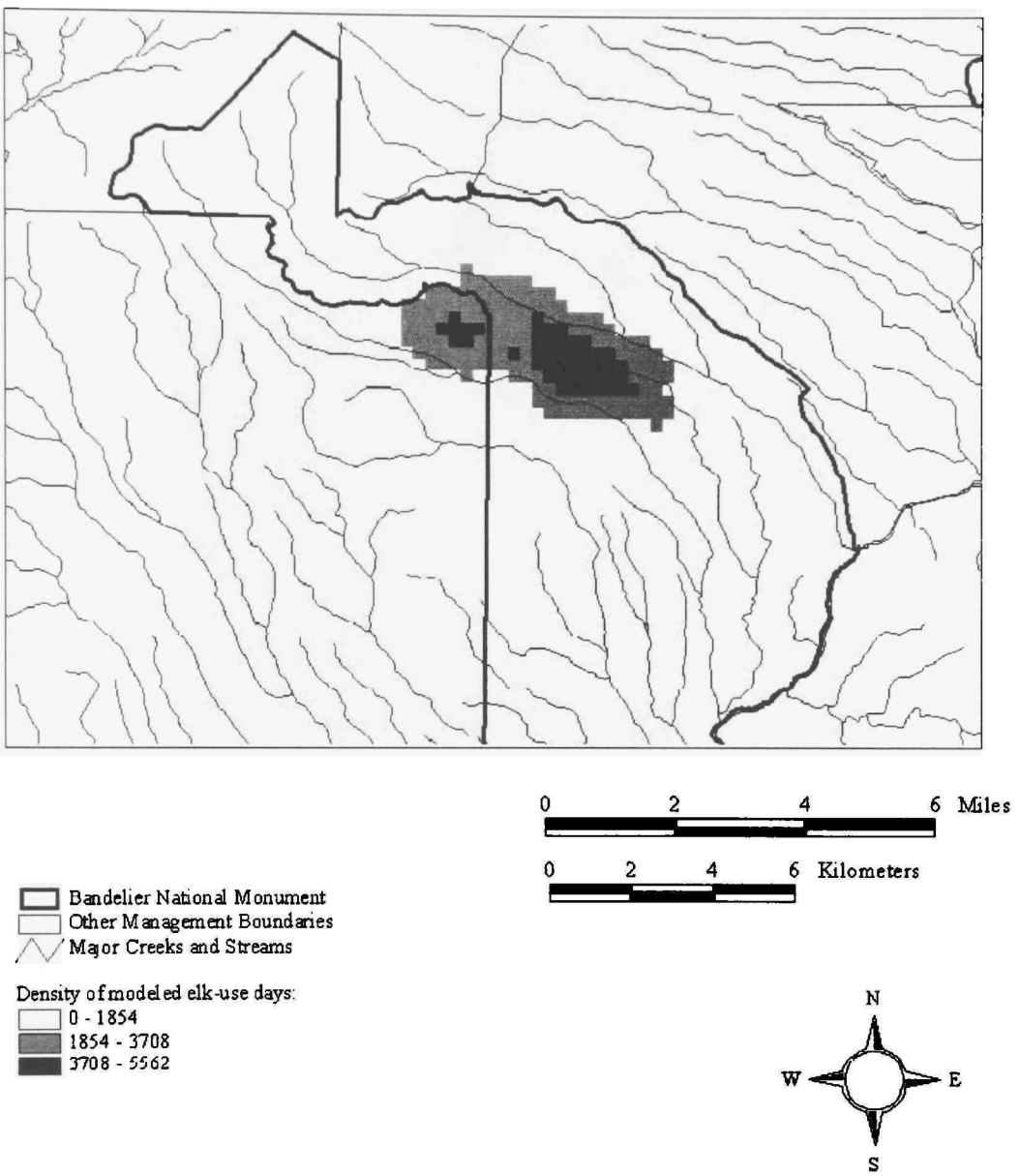

Figure 4.21. Three density (per km^2) classes of modeled elk-use days of 1,198 elk in and near Bandelier National Monument, New Mexico, December 01-February 01, 1993.

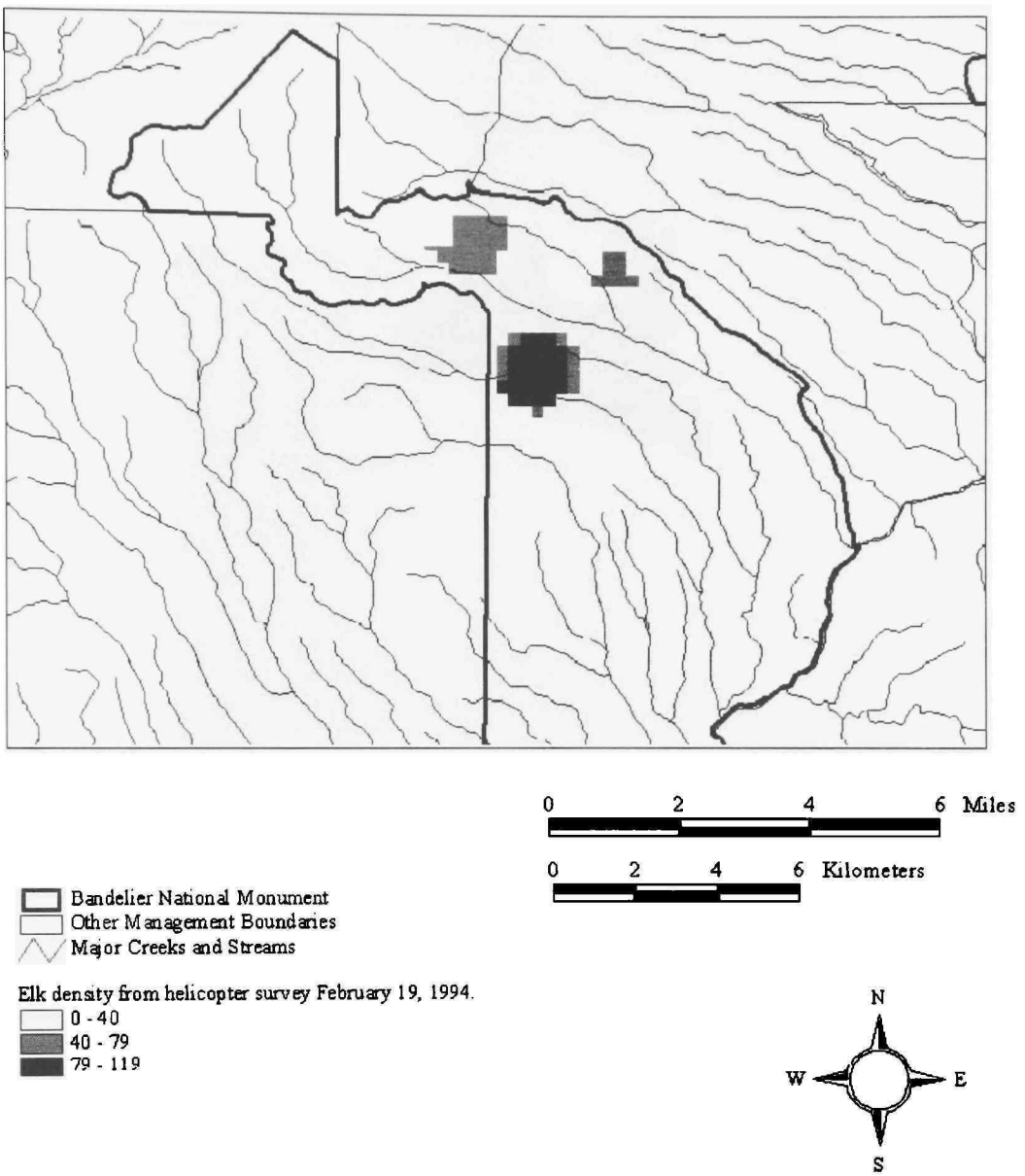

Figure 4.22. Three density (per km^2) classes of elk counted *(n=939)* during helicopter survey in and near Bandelier National Monument, New Mexico, February 17, 1994.

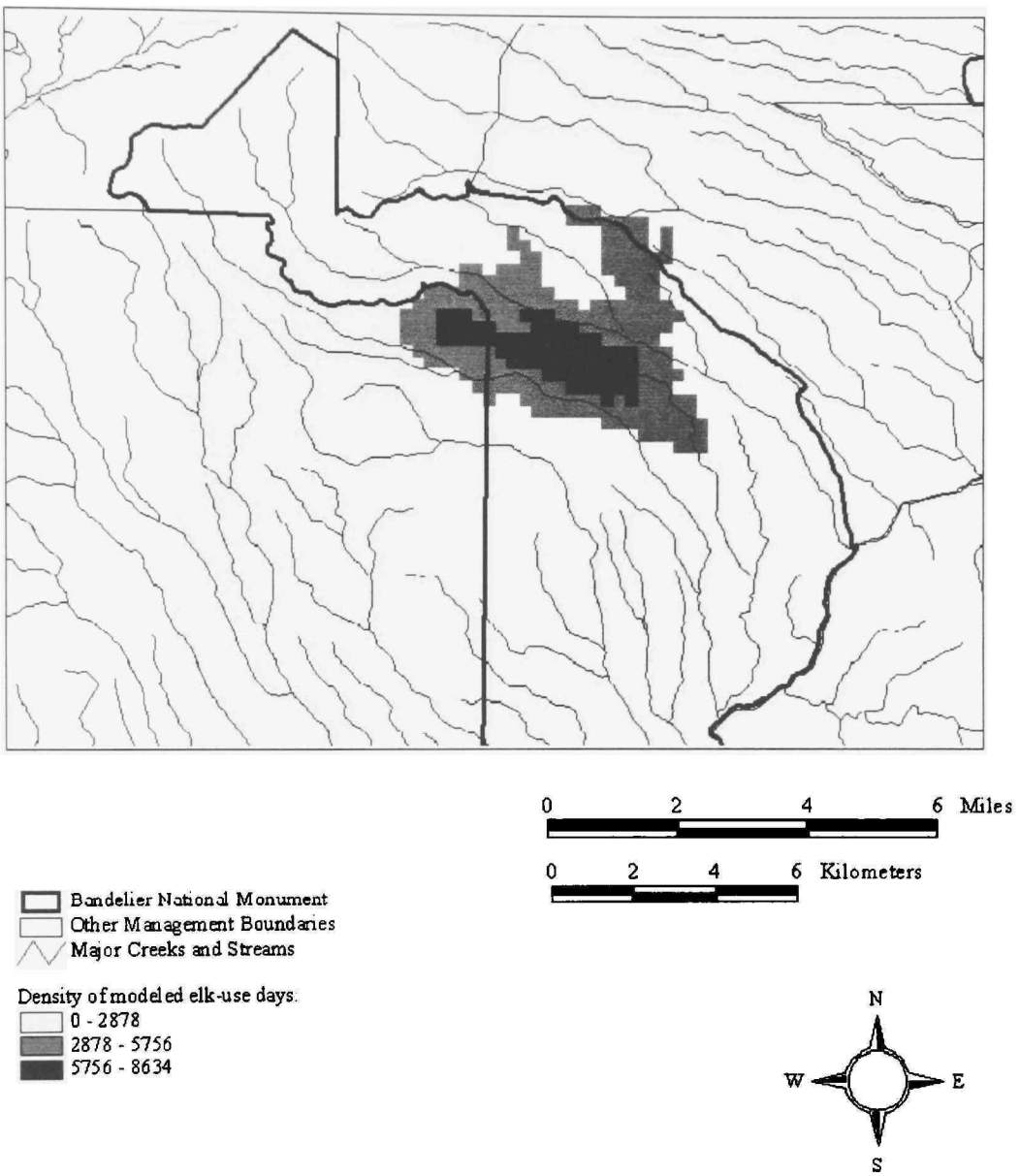

Figure 4.23. Three density (per km^2) classes of modeled elk-use days of 2,255 elk in and near Bandelier National Monument, New Mexico, December 01-February 17, 1994.

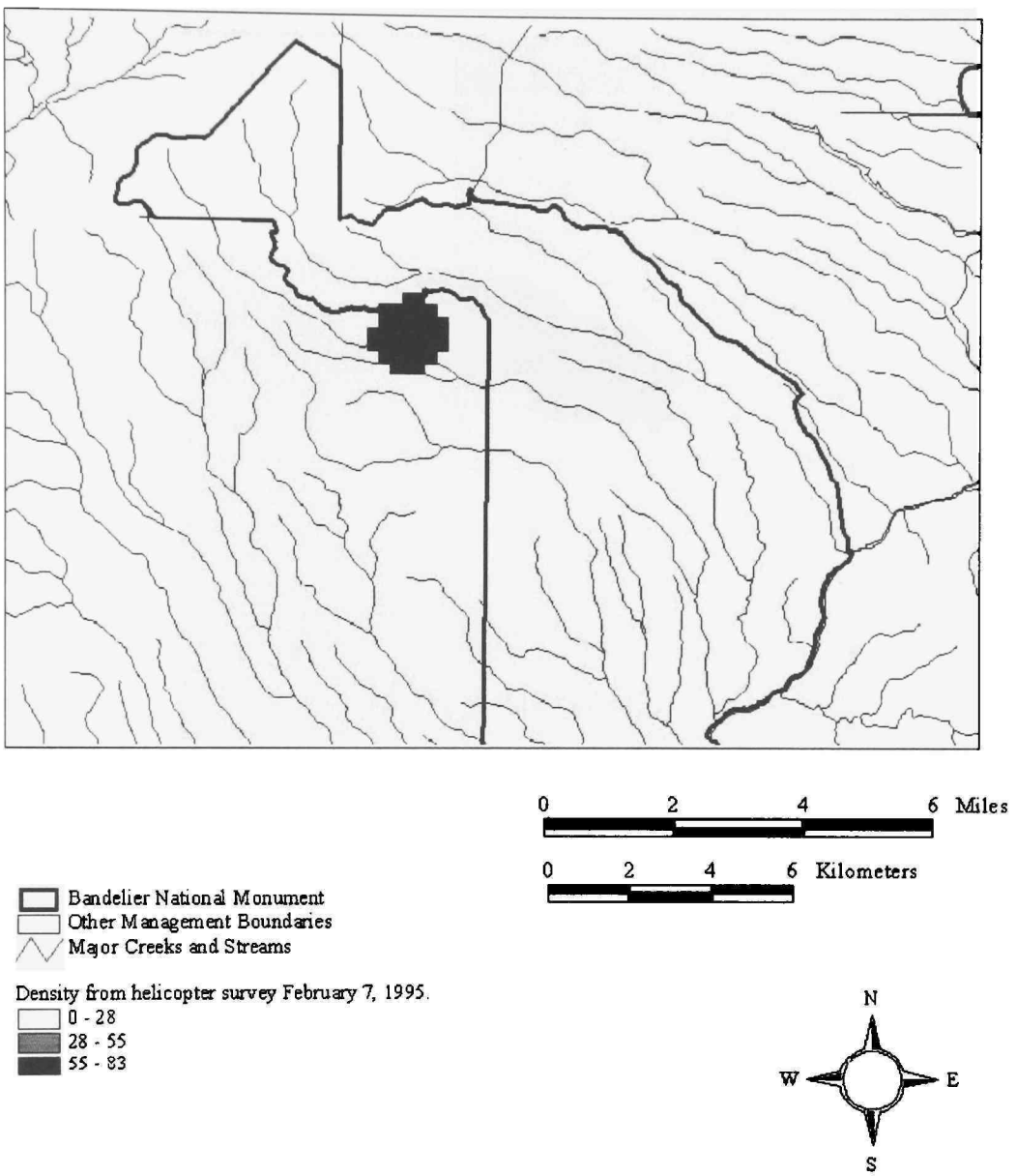

Figure 4.24. Three density (per km^2) classes of elk counted *(n=548)* during helicopter survey in and near Bandelier National Monument, New Mexico, February 07, 1995.

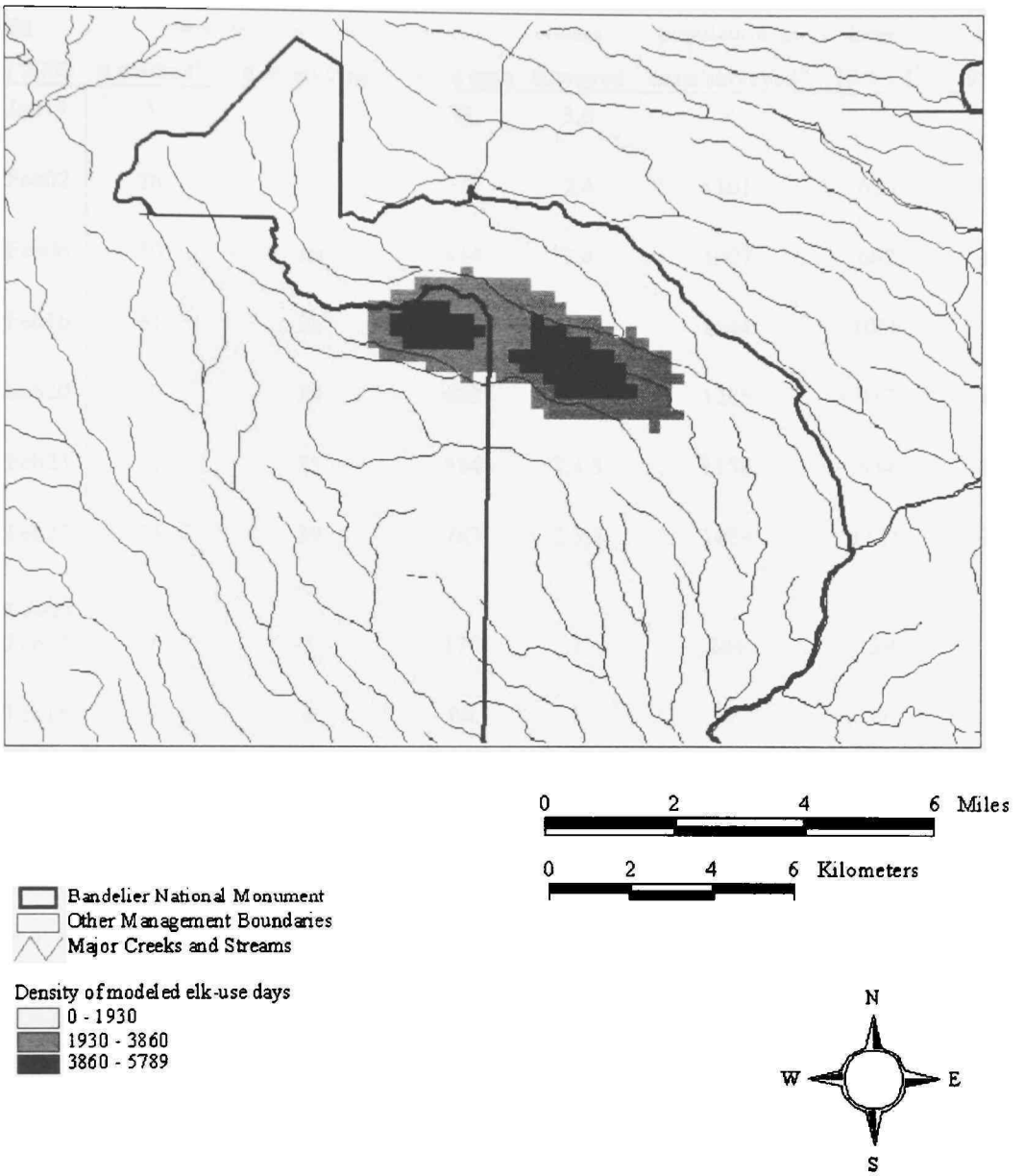

Figure 4.25. Three density (per km^2) classes of modeled elk-use days of 1,316 elk in and near Bandelier National Monument, New Mexico, December 01-February 07, 1995.

Table 4.1. Estimated elk population on surveyed units in Bandelier National Monument during January 2001 and February 2001 and 2002 helicopter survey flights. Lincoln-Peterson estimate is based on the proportion of radio-collared elk known to be in surveyed unit to those counted during helicopter survey. Confidence intervals (95%)calculated using Poisson distribution.

date winter 2000	# marked[1]	# recaptured[2]	# elk seen	units surveyed	estimated population in units surveyed[3]	lower 95% CI[4]	upper 95% CI
2001Jan19	3	0	91	5,6			
2001Feb02	28	9	379	2,4	1101	620	2018
2001Feb06	50	20	414	2,4	1007	682	1532
2001Feb16	61	23	597	2,4	1544	1058	2329
2001Feb20	70	34	633	2,3,4,6	1285	937	1818
2001Feb23	71	31	514	2,4,3	1158	834	1658
2001Feb27	75	39	783	2,3,4	1489	1121	2074
winter 2001							
2002Feb12	9	5	170	1	284	139	575
2002Feb15	5	4	64	1	77	36	164
2002Feb26	5	3	63	1	95	41	210
2002Feb28	7	1	44	1	179	56	342

[1]Number of marked elk detected in surveyed unit by fixed-wing telemetry immediately prior to helicopter survey

[2]Number of radio-collared elk recaptured (seen) by observers during helicopter survey

[3]Lincoln-Peterson population estimate (Seber 1982) where N=[(# marked + 1)*(# elk seen+1)]/(# recaptured + 1)]-1

[4]Confidence interval (95%) calculated using Poisson distribution (Krebs 1989)

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[4]Confidence interval (95%) calculated using Poisson distribution (Krebs 1989)

Table 4.2. Proportion of known radio-collared elk from fixed-wing telemetry flight seen in each search unit during helicopter survey flights during 2001-2002 on Bandelier National Monument and adjacent Santa Fe National Forest, New Mexico.

unit	date	# collars known	# collars seen		% seen
2	2001Feb02	8	2		25.0
2	2001Feb06	18	12		66.7
2	2001Feb16	25	8		32.0
2	2001Feb20	20	7		35.0
2	2001Feb23	20	9		45.0
2	2001Feb27	30	10		33.3
				mean:	39.5
3	2001Feb20	35	21		60.0
3	2001Feb23	33	15		45.5
3	2001Feb27	16	9		56.3
				mean:	53.9
4	2001Feb02	20	7		35.0
4	2001Feb06	32	8		25.0
4	2001Feb16	36	15		41.7
4	2001Feb20	15	6		40.0
4	2001Feb23	18	7		38.9
4	2001Feb27	29	20		69.0
				mean:	41.6
1	2002Feb12	9	5		55.6
1	2002Feb15	5	4		80.0
1	2002Feb26	5	3		60.0
1	2002Feb28	7	1		14.3
				mean:	52.5
5	no collars sighted		0		-
6	no collars sighted		0		-

P=0.089

Table 4.3. Total estimated elk and (percent of radio-collared elk) on survey units in and near Bandelier National Monumnent during February 2001 and 2002 helicopter surveys. Total estimated population is based on the distribution of known radio-collared elk across all units.

date							# radio-collared elk	estimated population	lower	upper
winter 2000-2001	unit 1[1]	unit 2	unit 3	unit 4	unit 5	unit 6	in all units	in all units[2]	95% C.I.[3]	95% C.I.[3]
2001Feb02	39 (2.5)	315 (20.0)	0 (0.0)	786 (50.0)	39* (2.5)	393* (25.0)	40	1573	886	2883
2001Feb06	95 (6.4)	342* (23.1)	57 (3.8)	608* (41.0)	19 (1.3)	361(24.4)	78	1482	1004	2255
2001Feb16	114 (6.1)	568* (30.5)	136 (7.3)	840* (45.1)	45 (2.4)	159 (8.5)	82	1862	1276	2809
2001Feb20	141(9.8)	405* (28.0)	616* (42.7)	264* (18.3)	18 (1.2)	0 (0.0)	82	1443	1053	2042
2001Feb23	113 (8.9)	322* (25.3)	531* (41.8)	306* (24.1)	0 (0.0)	0 (0.0)	79	1271	915	1819
2001Feb27	137 (8.4)	588* (36.1)	313* (19.3)	588* (36.1)	0 (0.0)	0 (0.0)	83	1626	1224	2265
winter 2002-2002										
2002Feb12	284* (39.1)	158 (21.7)	158 (21.7)	95 (13.0)	32 (4.3)	0 (0.0)	23	726	474	1497
2002Feb15	77* (27.8)	0 (0.0)	154 (55.6)	46 (16.7)	0 (0.0)	0 (0.0)	18	277	158	517
2002Feb26	95* (50)	19 (10)	57 (30)	19 (10)	0 (0.0)	0 (0.0)	10	190	112	506
2002Feb28	179* (70.0)	26 (10.0)	26 (10.0)	26 (10.0)	0	0	10	256	136	826

*Units actually surveyed by helicopter

[1]Calculated by estimating total population in surveyed unit (Table 2) and applying proportion of known-radio-collared elk in each unit at the time of helicopter survey to estimate total # of elk in unsurveyed units

[2]Total estimated elk population calculated by summing estimates (before rounding) from all units

[3]Confidence intervals based on Poisson distribution (Krebs 1989) where:

R=number of radio-collared elk seen by helicopter survry in a survey unit,
M=number of radio-collared elk known to be in each survey unit
N=number of all elk seen by helicopter in a survey unit

We assumed that proportion of radio-collars that would be observed in un-surveyed units = mean proportion seen during surveys of each unit. We assumed maximum proportion seen on any unit (0.54) in units 5 and 6 since no collared elk were sighted in those units.

Table 4.4. Winter herbage standing crop estimated by visual obstruction (VO) in 12 vegetative communities in Bandelier National Monument, New Mexico (October and November 2000 and 2001).

vegetative community:	mean VO (dm)	variance:	est.standing crop (kg ha^{-1}):*
riparian *(n=31)*	3.73	2.68	7,189
mixed conifer *(n=199)*	1.16	2.01	2,481
aspen *(n=29)*	1.13	0.45	2,426
montane grass *(n=51)*	1.11	0.64	2,389
grass/shrubland *(n=63)*	1.10	2.01	2,371
ponderosa pine/mixed conifer forest *(n=180)*	1.09	1.03	2,353
oak-shrubland *(n=28)*	1.07	0.24	2,316
meadow *(n=34)*	0.90	0.59	2,012
grassland (all other grassland) *(n=53)*	0.90	0.55	2,007
ponderosa pine forest *(n=93)*	0.84	0.76	1,895
ponderosa pine/pinion-juniper forest *(n=57)*	0.76	1.84	1,747
pinon-juniper woodland *(n=51)*	0.49	0.69	1,255

* estimated standing crop = 183 ($\bar{x}$ VO cm) + 358 = kg ha^{-1} (Vermeire et al. 2002)

Table 4.5. Sensitivity analysis of elk movement model as evaluated by correlation between elk-use days days calculated under original model parameters and elk-use days calcualted under a range of altered parameters (DI = cell desirability index).

proportional change	snow depth at which elk are excluded		maximum elk allowed per cell		standing crop estimates	
	value	r^2	value	r^2	value	r^2
0.25	5	0.47	5	0.53	x 0.25	0.62
0.50	10	0.81	10	0.94	x 0.50	0..82
*1.00	21	1.00	20	1.00	x 1.00	1.00
2.00	42	0.41	40	0.98	x2.00	0.77
4.00	54	<0.01	80	0.94	x4.00	0.62

	daily elk intake (kg/day)		threshold at which reduction of original crop value reduces DI		amount DI is reduced when crop reduction threshold is reached	
	value	r^2	value	r^2	value	r^2
0.25	1.35	0.58	5%	0.67	5%	0.76
0.50	2.7	0.77	10%	0.83	10%	0.87
*1.00	5.4	1.00	20%	1.00	20%	1.00
2.00	10.8	0.82	40%	0.59	40%	0.87
4.00	21.6	0.62	60%	0.76	60%	0.87

*indicates original model parameters

CHAPTER V

DISCUSSION

Telemetry

Mortality in this elk population was low. Elk hunting did not take a major proportion ($n=8$ [only 7%]) of the telemetered population in this study. Despite increased hunting pressure on SFNF during fall 2000, an equal number of elk died ($n=8$) of predation and age-related factors during the course of this study as were harvested (legally or illegally).

Elk population estimates we present here had large confidence intervals due to the limited data set and available estimation methods. The small number of units ($n < 3$) searched by helicopter during each survey in winter 2000 and winter 2001 further restricted population estimates. Broad assumptions made about the percent of elk that would be seen in units that were not surveyed and lack of adequate estimates of elk seen in many units precluded more precise estimation of elk populations on BAND.

Considering the differences in range use by elk captured in 2000 and those captured in 2001, it appears likely that 2000 capture efforts collared a subset (obligate migrators) of the larger population that habitually move to winter range on BAND even with the lack of restrictive snow accumulations (Nelson 1995). The higher snow accumulations in winter 2001 forced a much greater number of elk (conditional migrators) to move onto BAND (Nelson 1995).

Most elk moved from summer range on the VCNP to wintering range on BAND, LANL and adjacent portions of SFNF during in October-November of both 2000 and 2001. By March-April of 2001 and 2002 elk use shifted away from BAND and back onto the VCNP. The number of elk that moved to BAND winter range was greater in winter 2000 with greater than average snowfall, than in winter 1999 and 2001. The increased percent of locations in the American Springs region of SFNF in October-November indicated both the timing and location of fall elk migration from VCNP to BAND.

Number of elk wintering in BAND was directly related to accumulated snow depths. As snow depths increased on higher elevations, more intensive use on BAND occurred. Boyce (1989) found that heavy snow accumulations in November led to a high proportion of the Jackson Hole elk herd to migrate. Our data on BAND show a similar pattern. Conversely, the inverse correlation of the number of elk on the VCNP to snow depth in the area provided evidence of seasonal movement off the VCNP and on to BAND. Number of elk locations on LANL was poorly correlated to snow depths, evidence of a more resident population there.

We observed little winter use of the American Springs SFNF (Cerro Grande burn area) in winter 1999 or winter 2000. However, 1 growing season after the 2000 Cerro Grande fire, telemetry data indicate that the burn and subsequent vegetative regeneration increased winter use by elk. Additional data from continued monitoring of this telemetered population, especially under varying winter conditions and with further

examination of winter use of American Springs SFNF would be valuable components to a greater understanding the dynamics of elk use in and around BAND.

Elk density, estimated from telemetered animals, illustrated key use areas in winter when elk moved increasingly into ponderosa habitats, (between ~2,100m and 2,460m) on Mesa del Rito in SFNF-Dome and the mesa between Frijoles and Alamo Canyons. However, when elk were able to remain in mixed conifer habitats during winter, they used Cerro Grande above State Route 4 at elevations >2,500m. Of particular interest was the increased use of American Springs SFNF in winter 2001-2002. Habitat changes associated with the Cerro Grande Fire near BAND will likely reduce the number of elk using BAND when winter conditions push elk to winter at middle elevations. This pattern would mirror a similar range shift previously documented in the area by a LANL study (White 1981) when winter use by elk shifted from an 25 year-old burn area in SFNF to the La Mesa fire area < 3 years post-burn. Irwin and Peek (1983) and Peck and Peek (1991) also reported elk winter ranges concentrated in areas historically impacted by fires.

Model

Our Desirability Index quantified and successfully ranked features important to wintering elk on BAND (Table 3.2). Our choices of model criteria were corroborated by the good correlation ($r^2 = 0.60$) of DI with telemetered elk locations per cell during 3 winters of study (Figure 4.3). Correlations of cumulative elk-days use (model output) and helicopter survey data were lower due to poor sightability of elk from the helicopter,

and the fact that estimates of elk density derived from helicopter observations (especially from 1990-1995) presented only a limited snapshot of elk distribution on BAND rather than estimates of elk distribution over the entire winter. Density of model output elk-days use was correlated to density of telemetered elk locations in both winters 2000 (r^2 = *0.67)* and 2001 (r^2 = *0.68)*. However, correlation to the results of concurrent helicopter surveys in winters 2000 and 2001 was not as strong (r^2 = *0.35)* both winters. Helicopters saw only about half of the elk present and helicopter data was not well correlated to telemetered data in winter 2000 (r^2 = *0.44)* and winter 2001 (r^2 = *0.51)*. Model output correlation with helicopter data was comparable to the telemetered data correlation with the helicopter data.

Corroboration in historic years (1990-1995) was better during winters of above average snow accumulations, except in 1993 when snow conditions were unique. Winter elk distribution was atypical in 1993 due to freezing rains and snow crust conditions (Allen 1996). This was reflected in the lack of correlation with model output (r^2 = *0.06)*. Low correlations in years with below average snow accumulations (r^2= *0.13, 0.14)* were likely due to model input values for snow depth. Snow depth estimates were based on QMZNswe data (recorded as inches of snow water detected by a pressure-sensitive snow pillow), which was poorly correlated with snow depth at PJMT during low snow winters. Snow accumulations were > average in 1991 and 1992 and correlations to model output (r^2= *0.22, 0.36* respectively) were comparable to those found in winters 2000 and 2001. Winter 1995 also had > average snow accumulations over the course of the winter but Allen (1996) reported little snow cover in the study area at the time of the survey, likely

influencing elk distribution on that day. Correlation to model output was $r^2 = 0.16$. Examination of these data illustrated another major potential source for error for our corroboration effort using these historic data. The density of elk counted by helicopter during the single survey of 1995 (Figure 4.25) was dominated by a single location of a herd of 250 elk (nearly half of the 548 elk counted). Observers during 1990-1995 'high-graded' aerial survey routes specifically seeking out large groups (Allen 2003-pers. comm.), and with only 1 observation day, such large groups will skew the density distribution and mask the influence of other, smaller groups. A similar pattern occurred in 1990 (Figure 4.15), another year with low correlation to model output.

Model output behaved realistically under a range of different environmental conditions. Correlation of model output to both elk telemetry and helicopter data remained consistent during winter 2000 and 2001 despite widely disparate conditions. Model performance declined under low snow conditions. We suspect that with the greater availability of resources under low-snow conditions, there would be less impetus for animals to choose the most desirable cell. Furthermore, with movements unrestricted by snow accumulation, more areas would be available to elk and elk use would be dispersed beyond the boundaries of our modeled study area.

Factors related to snow depth had the greatest effects on predicted elk use output by the model. Model output was most sensitive to variations in snow depth at which elk were excluded from cells. As the critical snow depth threshold was decreased, elk were allowed to disperse to cells that had been closed to them under baseline conditions. As the critical snow depth threshold was increased, elk were excluded from preferred cells.

The critical snow depth threshold at which elk were excluded from cells (21cm) fit observed elk response to snow depths well.

The model proved to be quite robust around median values. Output diverged widely under only extreme variation of input conditions. Only a large reduction (75%) to the maximum number of elk allowed per cell resulted in a substantial change in correlation. With only 5 elk allowed per cell, model animals would be widely dispersed across very broad area (very unlike observed behavior of elk in winter). However, as maximum number of elk allowed per cell was increased (from 20 to 80), correlation to base line data changed very little. Elk continued to use highest ranked cells just in greater numbers. This in turn depleted cell resources more quickly, and caused elk to move to similar cells and decreased DI score much as they did under baseline conditions.

The relative stability of the standing crop-related parameters except at extreme values indicates that daily forage intake, the threshold at which reduction of original crop reduces DI, or the total amount of crop available were not central driving mechanisms in the function of the model. Daily forage intake showed greater sensitivity as values were decreased than when increased, evidence that our estimated intake rate is appropriate to the model structure.

Sensitivity analysis and corroboration permit examination of model process to determine if it resembles the system process understudy. It also allows the modeler to examine the factors that most strongly contribute to output variability and that may require additional research to strengthen the knowledge base (Saltelli 2000). Our model performed well in the light of current biological understanding of the factors and

processes involved. The model parameter that most strongly drives the process is snow depth in cells by way of the critical threshold (21cm) at which elk are excluded. Our simple linear regression of snow depth on BAND was very imprecise as it was based solely on elevation. A more precise prediction of snow accumulations would increase model precision. Carrera et al. (1993) reminded us that a model always agrees better with the particular set of data used for its calibration than with another independent data set. We suggest that this model would be applicable under a variety of conditions and robust under a wide range of values. The ability to input snow depth, standing crop, and DI scores as separate text files adds the flexibility to change model inputs as conditions, knowledge base, and understanding of the system changes. Standing crop values can be changed pending subsequent crop estimates, or from calculated values based on designation of the previous growing season as likely to result in above or below average productivity. The output of model results as a text file facilitates statistical analysis and import into GIS, allowing a range of display options including cumulative elk-days use, standing crop remaining, or snow depth in cells at end of each model run. As more data are accumulated, the DI ranking system can be easily modified or replaced all together with a new ranking system without any modifications to model process or programming code. The application is presented as an executable file that can be run on any computer. We have created a robust, flexible dynamic model that approximates the process intended, produces results that can be quantitatively corroborated, and easily analyzed and displayed, reflects current biological understanding of elk and their interaction with their environment, and can be readily modified to reflect a growing knowledge base.

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APPENDIX A

DOCUMENTATION

Table A.1. Fate of all radio-telemetered elk captured in January 2000 and January-February in and near Bandelier National Monument, New Mexico. 2002 no longer being monitored (censored) as of 28 February, 2002.

ear tag#	collar frequency	sex	capture date	last located	cause for censor*
61	166.243	female	1/6/2000	7/13/2000	3
57	165.956	female	1/6/2000	2/29/2000	2
66	166.493	female	1/6/2000	9/30/2000	2
52	166.281	female	1/6/2000	10/26/2000	1
59	166.056	female	1/6/2000	10/26/2000	1
63	165.918	female	1/6/2000	10/26/2000	1
65	166.368	male	1/6/2000	10/26/2000	1
69	166.343	female	1/6/2000	10/26/2000	1
19	166.606	female	1/7/2000	4/27/2000	6
5	165.706	male	1/7/2000	7/13/2000	2
7	166.443	female	1/8/2000	12/22/2000	3
25	166.181	female	1/8/2000	7/16/2001	2
15	166.481	female	1/8/2000	10/26/2000	1
29	166.169	female	1/8/2000	10/26/2000	1
55	165.768	male	1/11/2000	2/11/2000	4
56	166.256	male	1/11/2000	4/23/2001	4
38	165.743	female	1/10/2001	12/7/2001	3
108	167.393	female	1/11/2001	4/23/2001	4
107	167.381	female	1/11/2001	5/8/2001	3
116	167.493	female	1/12/2001	1/30/2001	5
50	166.131	female	1/12/2001	7/16/2001	3
43	166.093	male	1/12/2001	1/22/2002	2
148	166.706	male	2/5/2001	10/12/2001	1

*cause for censor:

1: hunting (includes legal harvest and poaching) *(n=8)*

2: predation (mountain lion) *(n=5)*

3: undetermined *(n=5)*

4: age-related (> 9-years-old with no other mortality factors indicated) *(n=3)*

5: capture-related (died proximate to capture location <18 days later) *(n=1)*

6: missing after Cerro Grande fire *(n=1)*

Table A.2. Kaplan-Meier (Pollack et al. 1988) survival estimates from radio-collared elk population on Bandelier National Monument, New Mexico, January 6, 2000 - February 28, 2002.

date	# at risk	# died	# added	survival	S.E.
1/6/2000	15	0	15	1.000	0.0000
1/7/2000	28	0	13	1.000	0.0000
1/8/2000	40	0	12	1.000	0.0000
1/11/2000	42	0	2	1.000	0.0000
2/11/2000	42	1	0	0.976	0.0232
2/12/2000	41	0	0	0.976	0.0235
2/28/2000	41	1	0	0.952	0.0325
3/1/2000	40	0	0	0.952	0.0329
7/13/2000	40	2	0	0.905	0.0441
7/14/2000	38	0	0	0.905	0.0453
9/30/2000	38	1	0	0.881	0.0493
10/1/2000	37	0	0	0.881	0.0500
10/26/2000	37	7	0	0.714	0.0628
10/27/2000	30	0	0	0.714	0.0697
12/22/2000	30	1	0	0.690	0.0701
12/23/2000	29	0	0	0.690	0.0713
1/10/2001	38	0	9	0.690	0.0623
1/11/2001	47	0	9	0.690	0.0560
1/12/2001	62	0	15	0.690	0.0488
1/30/2001	62	1	0	0.679	0.0489
1/31/2001	61	0	0	0.679	0.0493
2/3/2001	75	0	14	0.679	0.0444
2/4/2001	95	0	20	0.679	0.0395
2/5/2001	100	0	5	0.679	0.0385
4/23/2001	100	2	0	0.666	0.0385
4/24/2001	98	0	0	0.666	0.0389
4/27/2001	98	1	0	0.659	0.0389
4/28/2001	97	0	0	0.659	0.0391
5/8/2001	97	1	0	0.652	0.0391
5/9/2001	96	0	0	0.652	0.0393
7/16/2001	96	2	0	0.639	0.0392
7/17/2001	94	0	0	0.639	0.0396
10/12/2001	94	1	0	0.632	0.0395
10/13/2001	93	0	0	0.632	0.0398
12/7/2001	93	1	0	0.625	0.0397
12/8/2001	92	0	0	0.625	0.0399
1/22/2002	92	1	0	0.618	0.0398
1/23/2002	91	0	0	0.618	0.0400
2/28/2002	91	0	0	0.618	0.0400

Table A.3. Percentage of telemetered locations by management units in and near Bandelier National Monument, New Mexico during 3 winters from January 07, 2000 to February 28, 2002.

	percentage of total locations		
	winter 2000 (January-February 2000)	winter 2000-2001 (December 2000-February 2001)	winter 2001-2002 (December 2001-February 2002)
Management Unit:	(*n=375*)	(*n=979*)	(*n=957*)
Bandelier National Monument	16.0	63.5	19.5
Valles Caldera National Preserve	60.0	0.3	46.1
Santa Fe National Forest:			
Dome	8.0	14.1	6.8
American Springs	0.8	2.7	21.1
north of VCNP/Santa Clara			2.1
south of LANL		1.2	
s/w of VCNP corner	-	-	0.3
Los Alamos National Laboratory	16.0	17.5	3.7
Santa Clara Pueblo			0.4
San Ildefonso Pueblo		0.7	-

Table A.4. Percentage of telemetered locations by management units in and near Bandelier National Monument, New Mexico, comparing winter locations (December 07, 2001-February 28, 2002) of elk captured in 2000 to those captured in 2001.

	percentage of total locations	
	elk captured in 2000	elk captured in 2001
Management Unit:	(286 locations of 26 animals)	(724 locations of 91 animals)
Bandelier National Monument	26.2	15.3
Valles Caldera National Preserve	11.9	55.8
Santa Fe National Forest:		
Dome	14.7	3.2
American Springs	27.6	16.9
north of VCNP/Santa Clara		2.9
s/w of VCNP corner		0.4
Los Alamos National Laboratory	12.2	0.1
Santa Clara Pueblo	1.4	-

Table A.5. Summary of data from helicopter surveys in January and February 2001 *(n=8)* and February 2002 *(n=4)* on Bandelier National Monument and adjacent Santa Fe National Forest, New Mexico

		observed by helicopter:			collars
Date	search unit	elk	collars	deer	actually present
2001Jan19	5	12	0	8	0
	6	79	0	19	3
2001Feb02	2	145	2	12	8
	4	234	7	12	20
2001Feb06	2	159	12	6	18
	4	255	8	2	32
2001Feb16	2	216	8	3	25
	4	381	15	2	36
2001Feb20	2	197	7	0	20
	4	102	6	5	15
	6	0	0	5	0
	3	334	21	0	35
2001Feb23	2	183	9	0	20
	4	98	7	4	18
	3	233	15	0	33
2001Feb27	2	211	10	0	30
	4	395	20	0	29
	3	177	9	0	16
2002Feb12	1	170	5	2	9
2002Feb15	1	64	4	0	5
	1*	182*	9*	0	15*
2002Feb26	1	63	3	0	5
2002Feb28	1	44	1	0	7
	1*	52*	2*	0	11*

*Search included a portion of the American Springs region of SFNF south of Canyon de Valles (not included in analysis)

Table A.6. Summary of multiple linear regression (PROC REG, SAS 1999) with telemetry data from 3 winters analyzing relationships among number of telemetered locations per cell and cell habitat variables of GIS grid overlay of Bandelier National Monument, New Mexico, and adjacent areas.

winter 1999 (January-February 2000)	variable	parameter estimate	standard error	standardized estimate
$r^2 = 0.185$	*intercept*	1.149	0.074	0.000
(adj. $r^2 = 0.149$)	% 60-90 percent slope	-1.029	0.484	-0.170
	% mixed conifer-spruce forest	0.989	0.639	0.121
	% ponderosa pine forest	0.348	0.185	0.152
	% mixed conifer-ponderosa pine forest*	0.882	0.217	0.364
	% 60-69 percent canopy closure	0.497	0.197	0.198
	% 70-79 percent canopy closure	-0.558	0.319	-0.155
winter 2000 (December 2000-February 2001)				
$r^2 = 0.182$	*intercept*	1.934	0.449	0.000
(adj. $r^2 = 0.166$)	mean elevation	< -0.001	< -0.001	-0.094
	% southern aspect	0.460	0.178	0.105
	% oak shrubland	1.238	0.575	0.086
	% ponderosa pine forest	0.573	0.178	0.134
	% all other grasslands*	1.623	0.185	0.364
	% grass-shrub	0.652	0.153	0.178
	% ponderosa pine-juniper shrub forest	-0.820	0.488	-0.067
	% ponderosa pine-piñon/juniper forest	0.468	0.151	0.134
	% industrialized	3.571	2.328	0.061
	% 20-29 percent canopy closure	0.952	0.437	0.088
winter 2001 (December 2001-February 2002)				
$r^2 = 0.287$	*intercept*	-2.219	0.636	0.000
(adj. $r^2 = 0.271$)	mean elevation*	0.001	< -0.001	0.318
	% montane grassland	-1.507	0.977	-0.088
	% felsenmeer/talus	-6.361	3.569	-0.096
	% 0-9 percent canopy closure	0.375	0.177	0.121
	% 20-29 percent canopy closure*	3.219	0.490	0.369
	% 70-79 percent canopy closure	0.804	0.252	0.186

*cell variables most important in explaining variation of elk abundance (number of elk per cell)

Table A.7. Standardized canonical coefficients for variables discriminating between GIS grid cells with telemetered locations (used by telemetered elk) and cells with no telemetered locations (not used by telemetered elk) December 2000-February 2001 in and near Bandelier National Monument, New Mexico.

variable	coefficient	means of canonical variables	percent correct predicted classifications
% grasslands*	0.917		
% ponderosa pine-all types*	0.594	-	
% northern aspect	-0.178		-
% = 90 percent slope	0.243		-
% southern aspect	0.149	-	
% 0-9 percent canopy closure	-0.377	-	-
% 80-89 percent canopy closure	-0.132	-	-
% oak shrubland	0.114		-
% 20-29 percent canopy closure	-0.090		-
% 60-69 percent canopy closure	-0.101		
% canyonwall complex	0.210		
used by elk (p = 0.206)		0.866	28.538
not used by elk (p = 0.794)		-0.224	93.403
total	-	-	80.058

*cell variables most important in discriminating between used and unused cells.

Table A.8. Standardized canonical coefficients for variables discriminating between GIS grid cells with = 4 telemetered locations per cell (higher-use) and cells with 1 telemetered location per cell (lower-use) December 2000-February 2001 in and near Bandelier National Monument, New Mexico.

variable	coefficient	means of canonical variables	percent correct predicted classifications
% all other grasslands*	0.888		
% southern aspect*	0.309	-	-
% ponderosa pine-piñon/juniper forest	0.135		
% ponderosa pine-mixed confer forest	0.303		
% 90-99 percent canopy closure	-0.202	-	-
% flat	-0.211		
% piñon/junper woodland	-0.203		
% 20-29 percent canopy closure	0.183	-	-
% 50-59 percent canopy closure	0.155		
higher-use cells (p = 0.073)	-	1.996	38.095
lower-use cells (p = 0.927)		-0.157	96.255
total	-	-	92.014

*cell variables most important in discriminating between higher-use and lower-use cells.

Table A.9. Snow depths (cm) recorded at LANL weather stations and at monitoring stations at different elevations November 2000-February 2001 in and near Bandelier National Monument, New Mexico and their correlation (r^2) to snow depth predicted by the equation: [PJMT snow depth]+([PJMT elevation]-[elevation on BAND]) * (-0.024627) = [predicted BAND snow]

station:		1	2	3	4	5	TA-6	6	7	8	9	10	11	12	PJMT	
elevation (m):		1960	2028	2114	2198	2240	2263	2315	2507	2501	2768	2737	2741	2665	3158	r^2
date																
11/10/2000	actual	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.4	7.9	20.3	11.4	7.9	18.4	27.9	
	predicted	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.9	11.7	18.3	17.5	17.6	15.8	27.9	*0.86*
11/27/2000	actual	0.0	8.6	17.5	14.9	22.9	10.2	22.9	24.1	17.5	56.2	32.7	21.6	58.1	73.7	
	predicted	8.8	10.5	12.6	14.7	15.7	16.3	17.6	57.7	57.5	64.1	63.3	63.4	61.6	73.7	*0.55*
11/28/2000	actual	0.0	0.0	9.2	8.6	17.5	10.2	16.5	19.7	8.9	53.3	25.1	10.8	50.5	68.6	
	predicted	6.2	7.8	10.0	12.0	13.1	13.6	14.9	52.6	52.4	59.0	58.2	58.3	56.5	68.6	*0.50*
11/29/2000	actual	0.0	0.0	7.3	7.6	17.1	10.2	15.6	17.8	7.3	51.1	23.2	8.6	49.5	68.6	
	predicted	6.2	7.8	10.0	12.0	13.1	13.6	14.9	52.6	52.4	59.0	58.2	58.3	56.5	68.6	*0.47*
11/30/2000	actual	0.0	0.0	2.5	5.7	14.6	7.6	13.3	16.2	4.8	50.2	21.3	7.3	47.9	66.0	
	predicted	4.8	6.5	8.6	10.7	11.7	12.3	13.6	50.0	49.8	56.4	55.6	55.7	53.9	66.0	*0.48*
12/1/2000	actual	0.0	0.0	0.6	5.1	14.6	7.6	13.3	16.8	0.6	41.3	19.7	6.4	47.3	63.5	
	predicted	3.5	5.2	7.3	9.4	10.4	11.0	12.3	47.5	47.3	53.9	53.1	53.2	51.4	63.5	*0.46*
12/4/2000	actual	0.0	0.0	0.3	3.8	14.0	7.6	13.0	15.9	0.0	46.7	19.7	4.1	46.4	58.4	
	predicted	0.9	2.5	4.7	6.7	7.8	8.3	9.6	42.4	42.2	48.8	48.0	48.1	46.3	58.4	*0.45*
12/5/2000	actual	0.0	0.0	0.0	0.0	14.0	7.6	12.4	15.2	0.0	45.7	19.7	6.4	46.4	53.3	
	predicted	0.0	0.0	2.0	4.1	5.1	5.7	7.0	37.3	37.1	43.7	42.9	43.0	41.2	53.3	*0.48*

Table A.9. Continued.

station:		1	2	3	4	5	TA-6	6	7	8	9	10	11	12	PJMT	
elevation (m):		1960	2028	2114	2198	2240	2263	2315	2507	2501	2768	2737	2741	2665	3158	r^2
date																
12/6/2000	actual	0.0	0.0	0.0	0.0	13.7	7.6	12.4	14.6	0.0	45.4	18.7	4.8	46.0	53.3	
	predicted	0.0	0.0	2.0	4.1	5.1	5.7	7.0	37.3	37.1	43.7	42.9	43.0	41.2	53.3	*0.47*
12/7/2000	actual	0.0	0.0	0.0	0.0	13.3	7.6	11.7	14.3	0.0	44.5	19.1	0.0	45.7	50.8	
	predicted	0.0	0.0	0.7	2.8	3.8	4.4	5.7	34.8	34.6	41.2	40.4	40.5	38.7	50.8	*0.43*
12/8/2000	actual	0.0	0.0	0.0	0.0	13.3	5.1	10.8	13.0	0.0	43.8	18.7	0.0	44.1	50.8	
	predicted	0.0	0.0	0.7	2.8	3.8	4.4	5.7	34.8	34.6	41.2	40.4	40.5	38.7	50.8	*0.44*
1/10/2001	actual	0.0	0.0	2.5	4.1	4.1	0.0	5.7	18.7	2.2	50.2	14.9	0.0	54.0	45.7	
	predicted	0.0	0.0	0.0	0.1	1.2	1.7	3.0	29.7	29.5	36.1	35.3	35.4	33.6	45.7	*0.47*
1/11/2001	actual	0.0	0.0	0.6	3.2	3.8	0.0	6.7	19.7	0.0	48.9	14.6	0.0	53.0	43.2	
	predicted	0.0	0.0	0.0	0.0	0.0	0.4	1.7	27.2	27.0	33.6	32.8	32.9	31.1	43.2	*0.47*
1/12/2001	actual	0.0	0.0	0.0	0.0	3.8	2.5	4.8	16.8	0.0	48.9	14.6	0.0	52.1	50.8	
	predicted	0.0	0.0	0.7	2.8	3.8	4.4	5.7	34.8	34.6	41.2	40.4	40.5	38.7	50.8	*0.48*
1/13/2001	actual	3.5	5.4	4.4	3.8	3.8	0.0	4.4	19.4	2.5	54.0	13.7	6.7	64.1	43.2	
	predicted	0.0	0.0	0.0	0.0	0.0	0.4	1.7	27.2	27.0	33.6	32.8	32.9	31.1	43.2	*0.45*
1/14/2001	actual	0.0	2.2	2.2	2.2	2.9	0.0	3.2	19.7	1.6	52.4	13.3	6.7	62.9	43.2	
	predicted	0.0	0.0	0.0	0.0	0.0	0.4	1.7	27.2	27.0	33.6	32.8	32.9	31.1	43.2	*0.49*
1/16/2001	actual	17.1	19.7	21.6	22.2	23.2	22.9	35.6	58.4	52.7	>91	69.9	28.6	>91	81.3	
	predicted	12.8	14.5	16.6	18.6	19.7	20.2	21.5	65.3	65.1	71.7	70.9	71.0	69.2	81.3	*0.74*

Table A.9. Continued.

station:		1	2	3	4	5	TA-6	6	7	8	9	10	11	12	PJMT	
elevation (m):		1960	2028	2114	2198	2240	2263	2315	2507	2501	2768	2737	2741	2665	3158	r^2
date																
1/17/2001	actual	6.4	12.7	17.8	22.9	25.4	20.3	36.8	57.2	55.2	>91	68.6	52.1	>91	78.7	
	predicted	11.4	13.1	15.2	17.3	18.3	18.9	20.2	62.7	62.5	69.1	68.3	68.4	66.6	78.7	*0.91*
1/18/2001	actual	2.5	10.2	15.2	17.8	21.6	17.8	33.0	52.1	50.2	>91	61.0	27.9	>91	73.7	
	predicted	8.8	10.5	12.6	14.7	15.7	16.3	17.6	57.7	57.5	64.1	63.3	63.4	61.6	73.7	*0.78*
1/19/2001	actual	1.3	9.5	14.6	15.2	19.1	17.8	30.5	48.3	42.5	>91	53.3	25.4	>91	71.1	
	predicted	7.5	9.1	11.3	13.3	14.4	14.9	16.2	55.1	54.9	61.5	60.7	60.8	59.0	71.1	*0.77*
1/21/2001	actual	1.3	6.4	12.1	12.7	13.3	15.2	25.4	44.5	30.5	90.8	43.2	16.5	>91	66.0	
	predicted	4.8	6.5	8.6	10.7	11.7	12.3	13.6	50.0	49.8	56.4	55.6	55.7	53.9	66.0	*0.60*
1/22/2001	actual	1.3	6.4	12.1	12.7	13.3	15.2	25.4	44.5	29.8	90.8	43.2	16.5	>91	63.5	
	predicted	3.5	5.2	7.3	9.4	10.4	11.0	12.3	47.5	47.3	53.9	53.1	53.2	51.4	63.5	*0.60*
1/23/2001	actual	0.0	6.4	12.7	13.3	15.2	15.2	26.7	41.9	29.2	88.9	48.3	22.2	>91	63.5	
	predicted	3.5	5.2	7.3	9.4	10.4	11.0	12.3	47.5	47.3	53.9	53.1	53.2	51.4	63.5	*0.64*
1/25/2001	actual	10.2	15.2	22.9	23.5	25.4	20.3	35.6	50.8	30.5	>91	39.4	21.0	>91	63.5	
	predicted	3.5	5.2	7.3	9.4	10.4	11.0	12.3	47.5	47.3	53.9	53.1	53.2	51.4	63.5	*0.53*
1/26/2001	actual	2.5	14.0	21.6	18.4	22.2	20.3	33.0	47.6	27.3	>91	35.6	17.8	>91	63.5	
	predicted	3.5	5.2	7.3	9.4	10.4	11.0	12.3	47.5	47.3	53.9	53.1	53.2	51.4	63.5	*0.50*
1/29/2001	actual	16.5	26.7	38.1	35.6	34.3	35.6	48.9	73.7	61.0	>91	66.0	35.6	>91	63.5	
	predicted	3.5	5.2	7.3	9.4	10.4	11.0	12.3	47.5	47.3	53.9	53.1	53.2	51.4	63.5	*0.60*

Table A.9. Continued.

station:		1	2	3	4	5	TA-6	6	7	8	9	10	11	12	PJMT	
elevation (m):		1960	2028	2114	2198	2240	2263	2315	2507	2501	2768	2737	2741	2665	3158	r^2
date																
1/30/2001	actual	7.6	22.9	34.3	33.0	31.8	35.6	45.1	68.6	55.9	>91	61.0	33.0	>91	63.5	
	predicted	3.5	5.2	7.3	9.4	10.4	11.0	12.3	47.5	47.3	53.9	53.1	53.2	51.4	63.5	*0.60*
2/6/2001	actual	0.0	5.1	19.7	21.9	20.0	20.3	28.6	48.3	24.1	>91	45.1	21.6	>91	58.4	
	predicted	0.9	2.5	4.7	6.7	7.8	8.3	9.6	42.4	42.2	48.8	48.0	48.1	46.3	58.4	*0.61*
2/8/2001	actual	0.0	0.0	15.9	15.6	17.8	22.9	26.0	45.7	25.4	>91	45.4	21.0	>91	76.2	
	predicted	10.1	11.8	13.9	16.0	17.0	17.6	18.9	60.2	60.0	66.6	65.8	65.9	64.1	76.2	*0.62*
2/10/2001	actual	0.0	1.9	13.3	18.7	16.5	20.3	29.2	50.8	26.7	>91	51.4	26.0	>91	71.1	
	predicted	7.5	9.1	11.3	13.3	14.4	14.9	16.2	55.1	54.9	61.5	60.7	60.8	59.0	71.1	*0.70*
2/11/2001	actual	0.0	0.0	13.3	17.8	15.2	20.3	27.0	47.6	21.6	>91	47.6	22.9	>91	68.6	
	predicted	6.2	7.8	10.0	12.0	13.1	13.6	14.9	52.6	52.4	59.0	58.2	58.3	56.5	68.6	*0.65*
2/17/2001	actual	0.0	0.0	0.0	0.0	8.3	15.2	16.5	43.8	12.1	>91	45.1	21.0	>91	66.0	
	predicted	4.8	6.5	8.6	10.7	11.7	12.3	13.6	50.0	49.8	56.4	55.6	55.7	53.9	66.0	*0.70*
2/18/2001	actual	0.0	0.0	0.0	0.0	5.1	10.2	13.7	41.9	7.6	90.5	44.5	21.0	>91	66.0	
	predicted	4.8	6.5	8.6	10.7	11.7	12.3	13.6	50.0	49.8	56.4	55.6	55.7	53.9	66.0	*0.62*
2/20/2001	actual	0.0	0.0	0.0	0.0	0.0	7.6	8.3	38.1	0.0	88.9	43.2	20.3	>91	66.0	
	predicted	4.8	6.5	8.6	10.7	11.7	12.3	13.6	50.0	49.8	56.4	55.6	55.7	53.9	66.0	*0.59*
2/21/2001	actual	0.0	0.0	0.0	0.0	0.0	5.1	7.3	36.5	0.0	87.9	42.9	19.1	>91	66.0	
	predicted	4.8	6.5	8.6	10.7	11.7	12.3	13.6	50.0	49.8	56.4	55.6	55.7	53.9	66.0	*0.60*

Table A.9. Continued.

station:		1	2	3	4	5	TA-6	6	7	8	9	10	11	12	PJMT	
elevation (m):		1960	2028	2114	2198	2240	2263	2315	2507	2501	2768	2737	2741	2665	3158	r^2
date																
2/22/2001	actual	0.0	0.0	0.0	0.0	0.0	2.5	5.1	33.0	0.0	84.5	39.4	17.8	>91	63.5	
	predicted	3.5	5.2	7.3	9.4	10.4	11.0	12.3	47.5	47.3	53.9	53.1	53.2	51.4	63.5	*0.59*
2/24/2001	actual	0.0	0.0	0.0	0.0	0.0	0.0	8.3	35.6	6.4	88.3	41.3	24.4	>91	63.5	
	predicted	3.5	5.2	7.3	9.4	10.4	11.0	12.3	47.5	47.3	53.9	53.1	53.2	51.4	63.5	*0.65*
															$\bar{x}$ =	*0.58*
															±	*0.12*

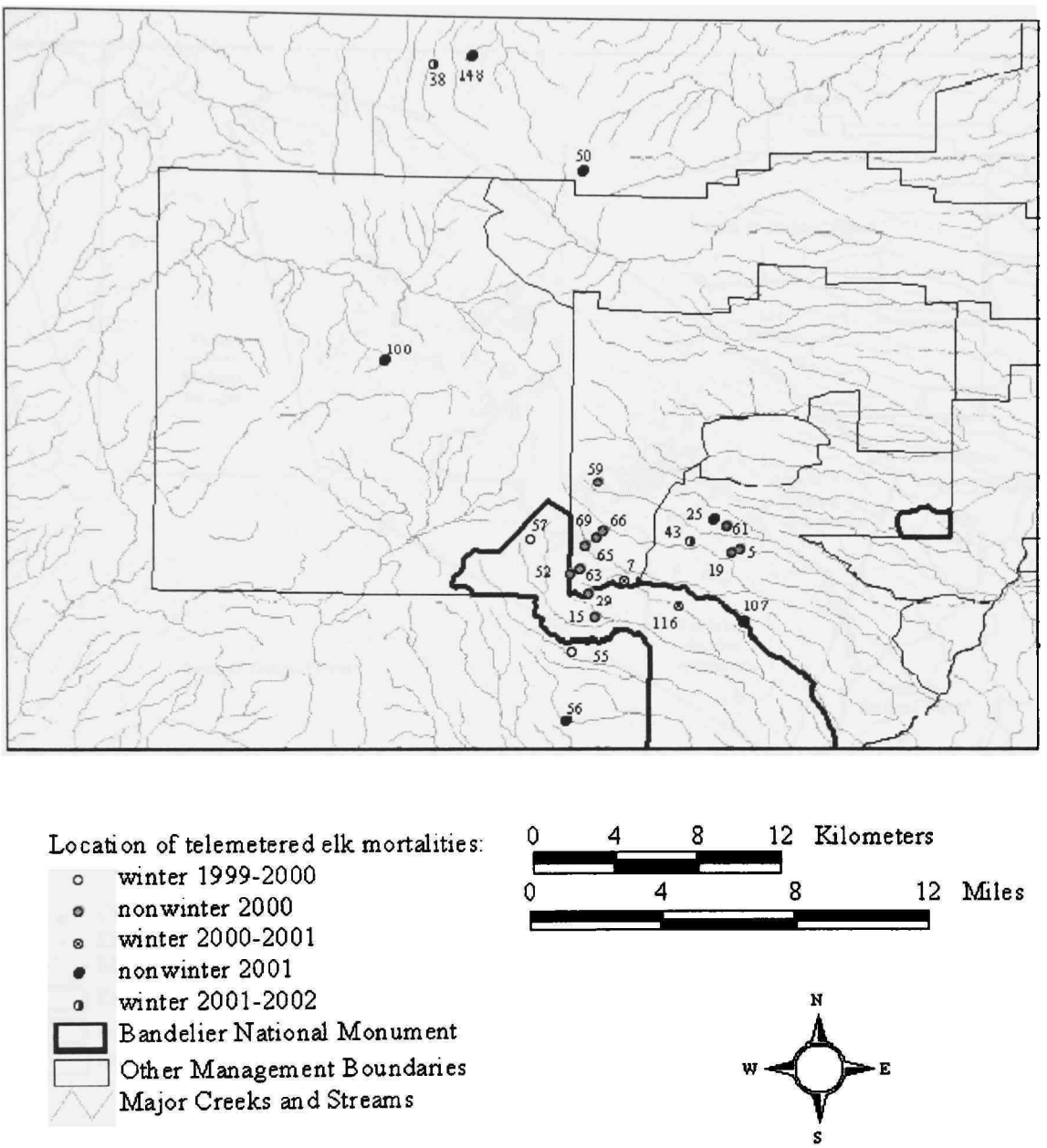

Figure A.1. Location of radio-collared elk mortalities in and near Bandelier National Monument, New Mexico, January 06, 2000-February 28, 2002. Elk harvested in 2000 hunt (#15, 29, 52, 59, 63, 65, 69) and elk #19 (missing after Cerro Grande fire) are reported at last known location.

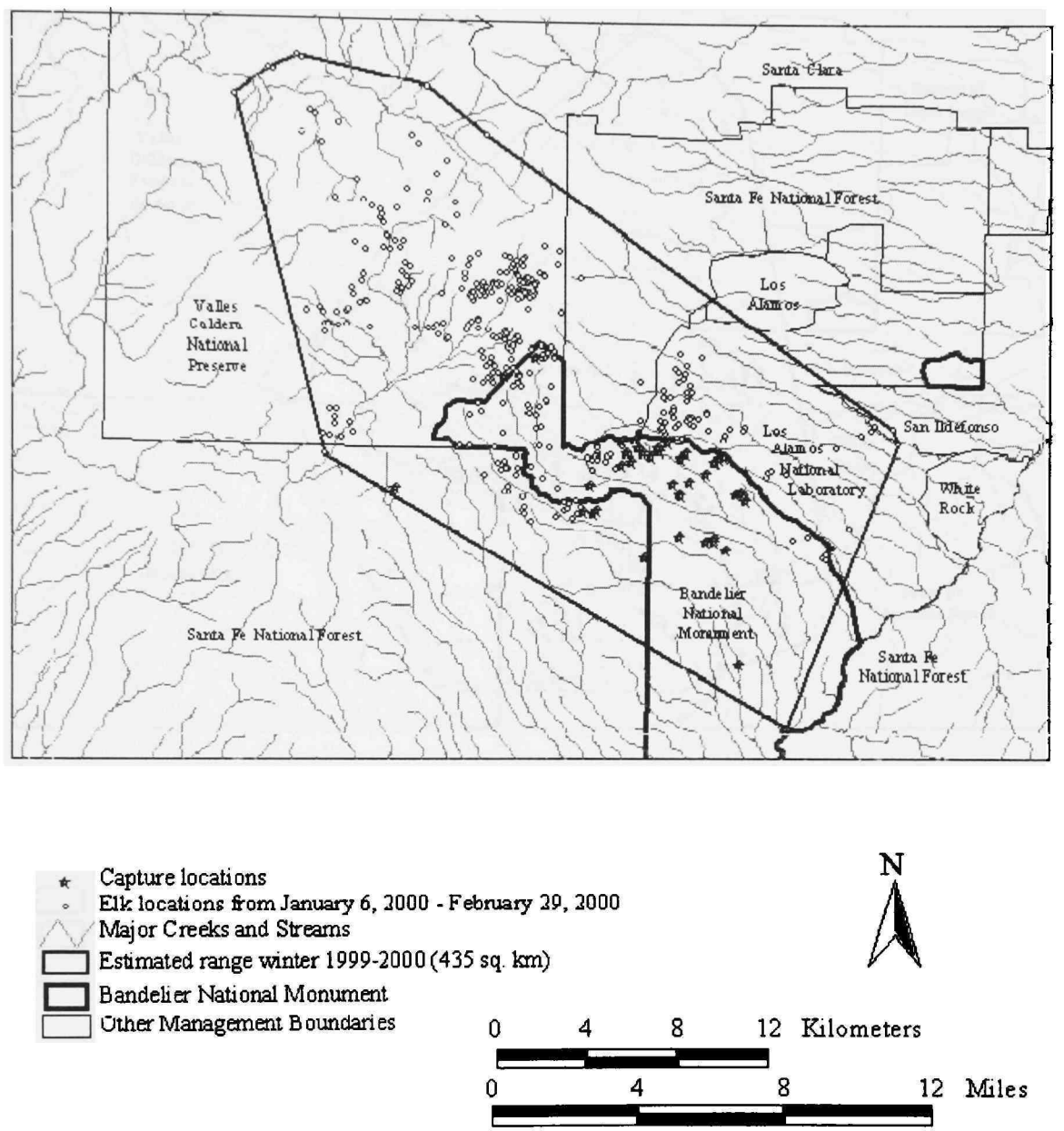

Figure A.2. Winter 1999 herd *(n=42 elk)* home range estimated by minimum convex polygon based on 42 capture locations and 377 telemetered locations gathered by fixed-wing aircraft January 06-February 29, 2000, in and near Bandelier National Monument, New Mexico.

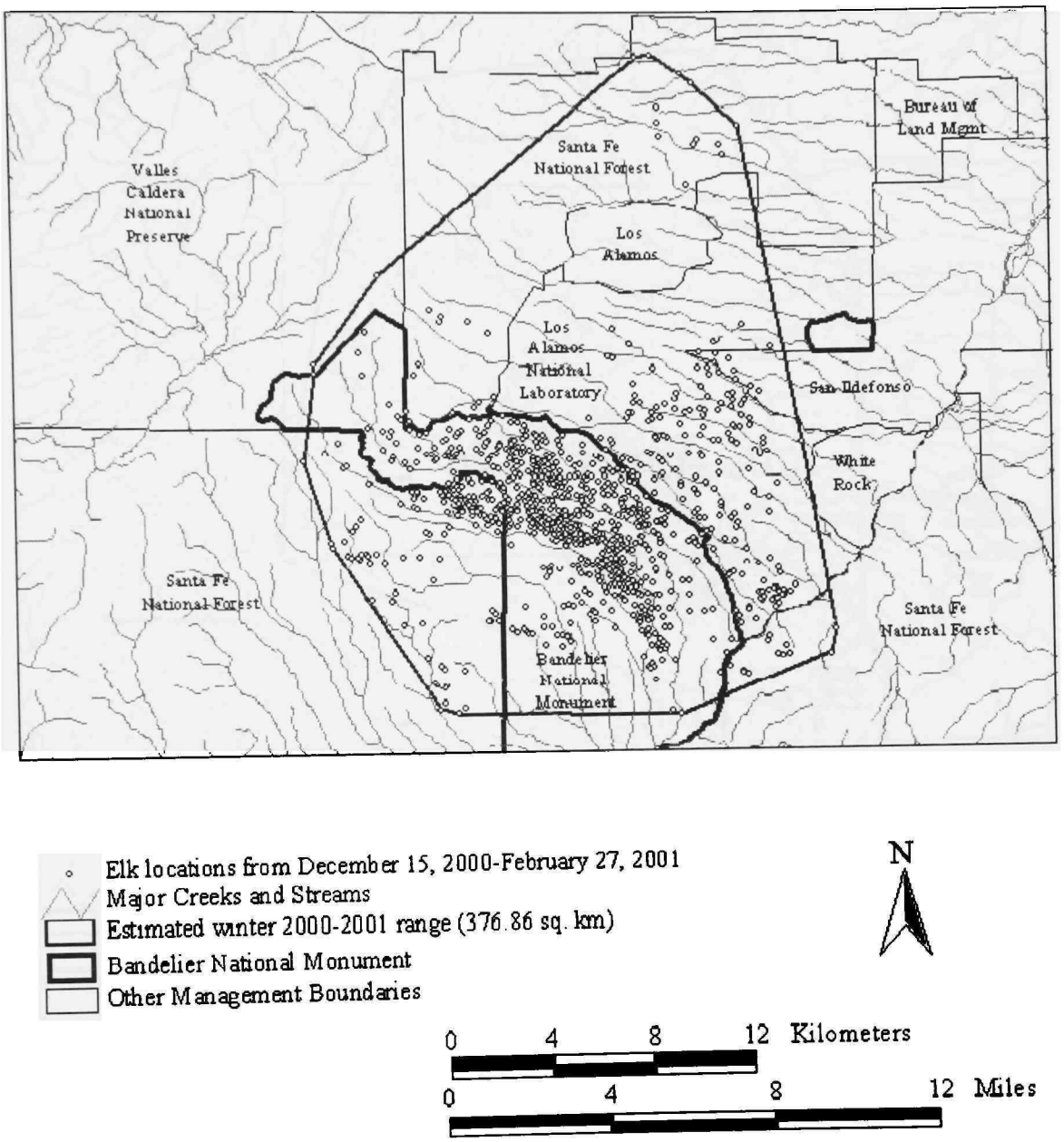

Figure A.3. Winter 2000 herd *(n=29-101 elk)* home range estimated by minimum convex polygon based on 979 telemetered locations gathered by fixed-wing aircraft December 15, 2000-February 27, 2001, in and near Bandelier National Monument, New Mexico.

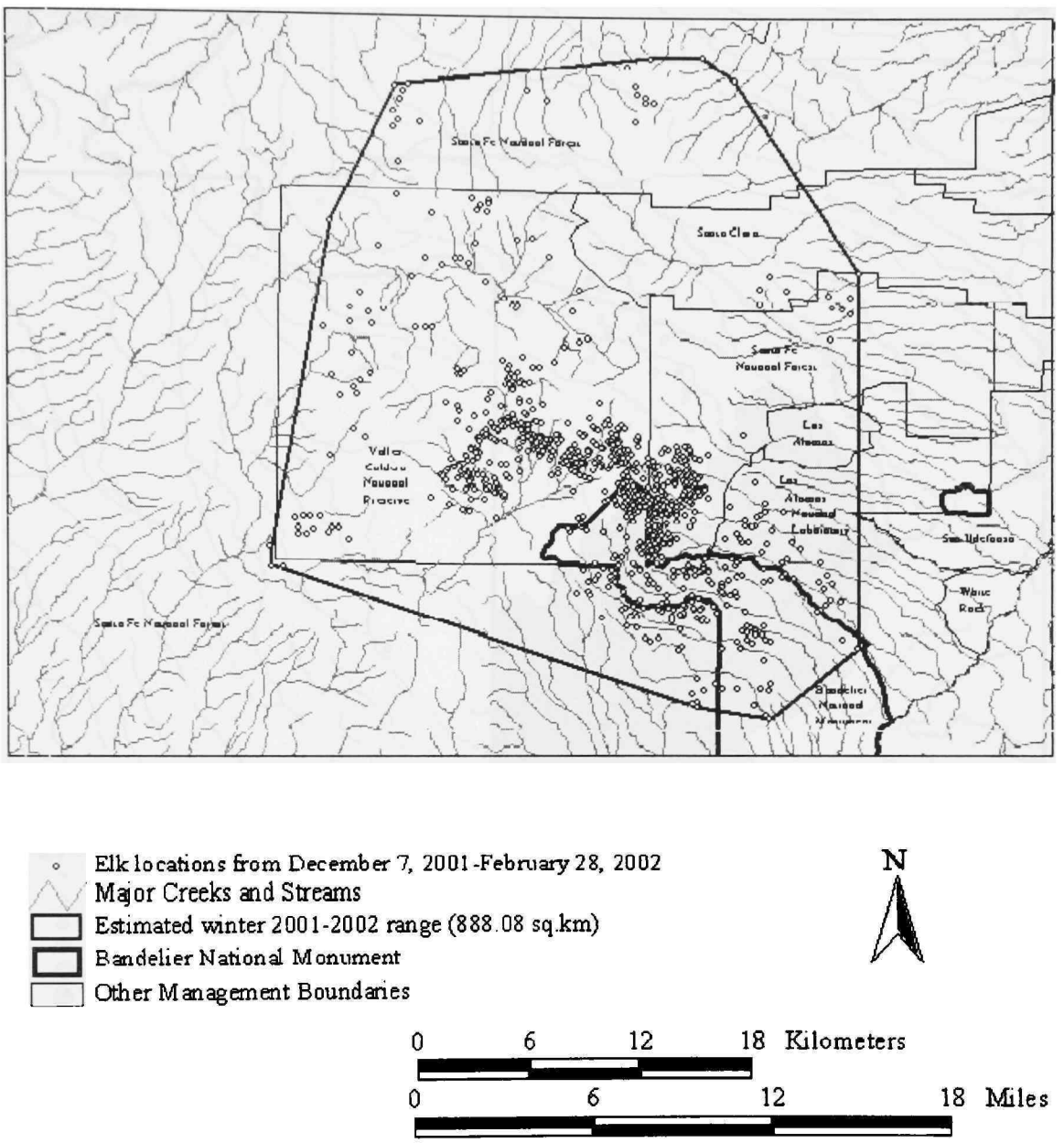

Figure A.4. Winter 2001 herd *(n=91-93 elk)* home range estimated by minimum convex polygon based on 951 telemetered locations gathered by fixed-wing aircraft December 07, 2001-February 28, 2002, in and near Bandelier National Monument, New Mexico.

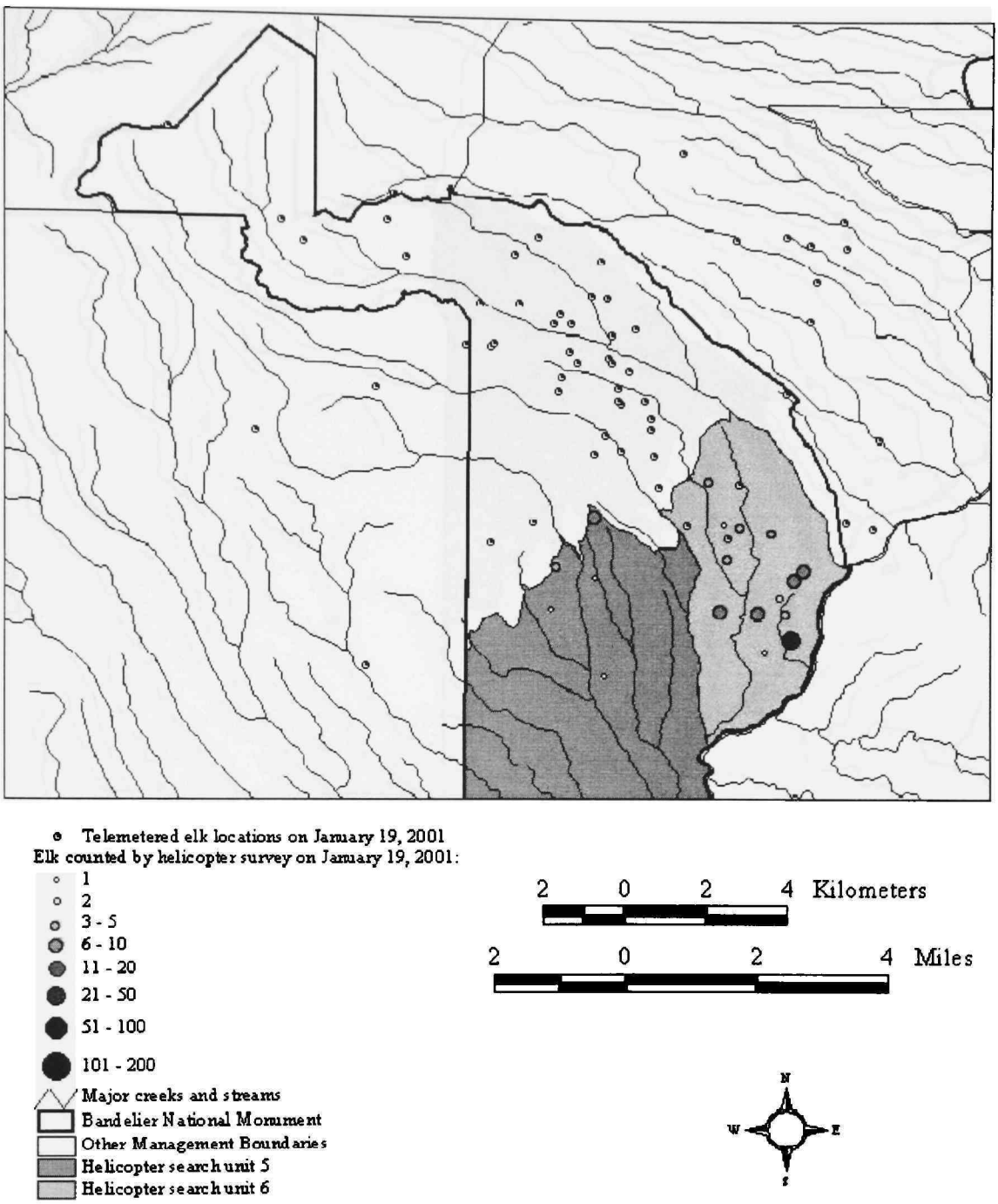

Figure A.5. Telemetered elk locations gathered by fixed-wing aircraft and elk counted by helicopter survey on January 19, 2001, in and near Bandelier National Monument, New Mexico (shaded areas = units searched during helicopter surveys).

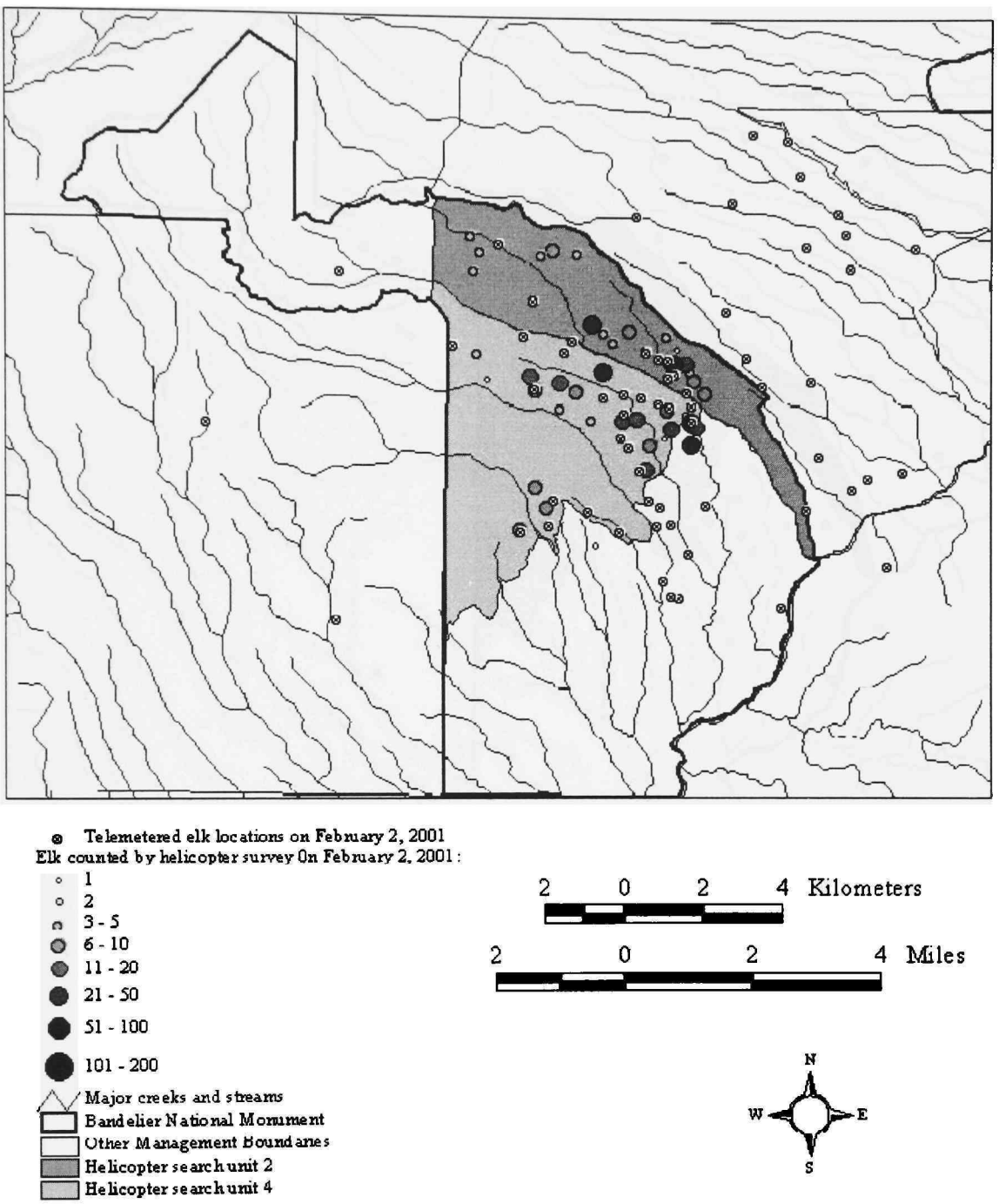

Figure A.6. Telemetered elk locations gathered by fixed-wing aircraft and elk counted by helicopter survey on February 02, 2001, in and near Bandelier National Monument, New Mexico (shaded areas = units searched during helicopter surveys).

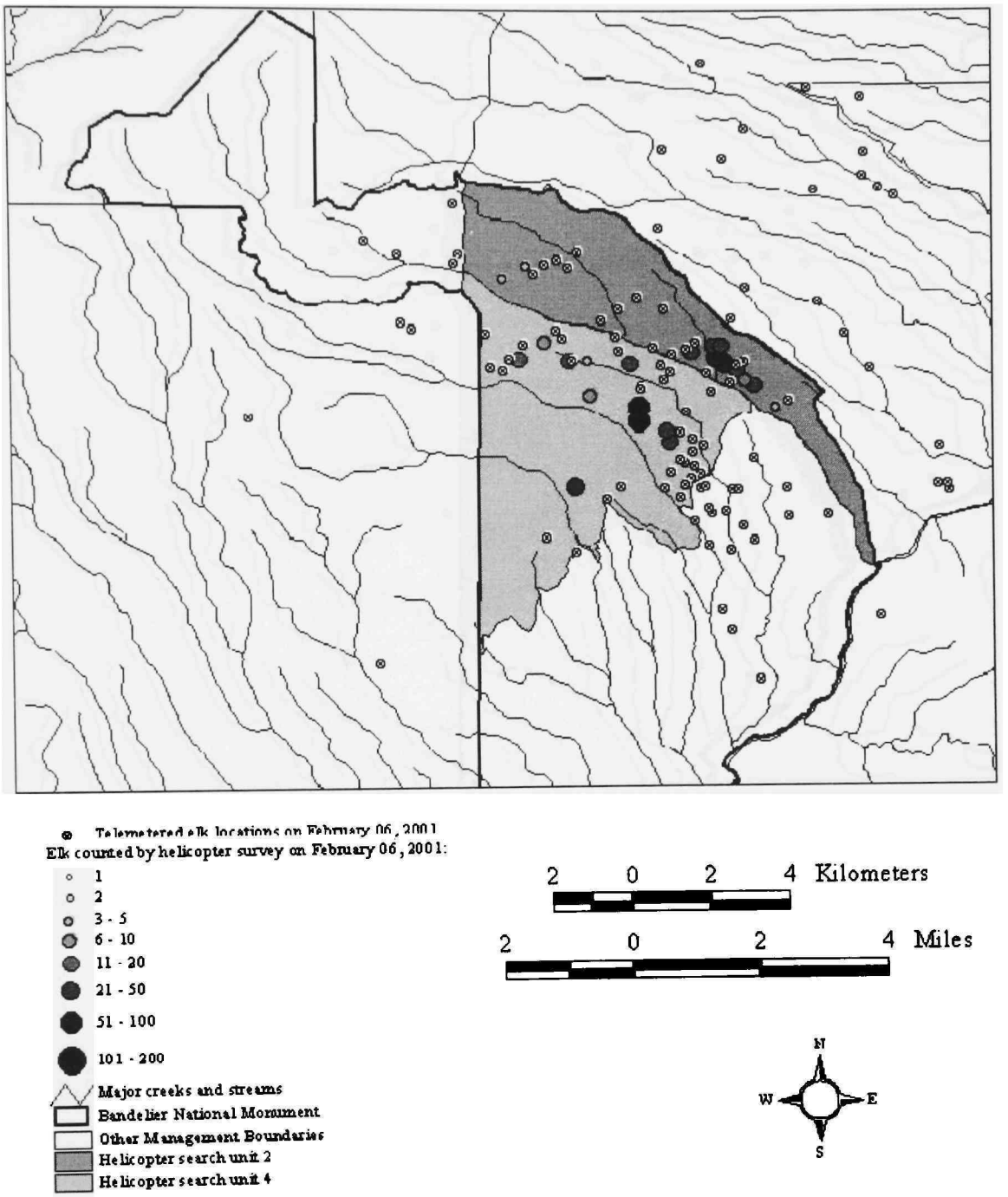

Figure A.7. Telemetered elk locations gathered by fixed-wing aircraft and elk counted by helicopter survey on February 06, 2001, in and near Bandelier National Monument, New Mexico (shaded areas = units searched during helicopter surveys).

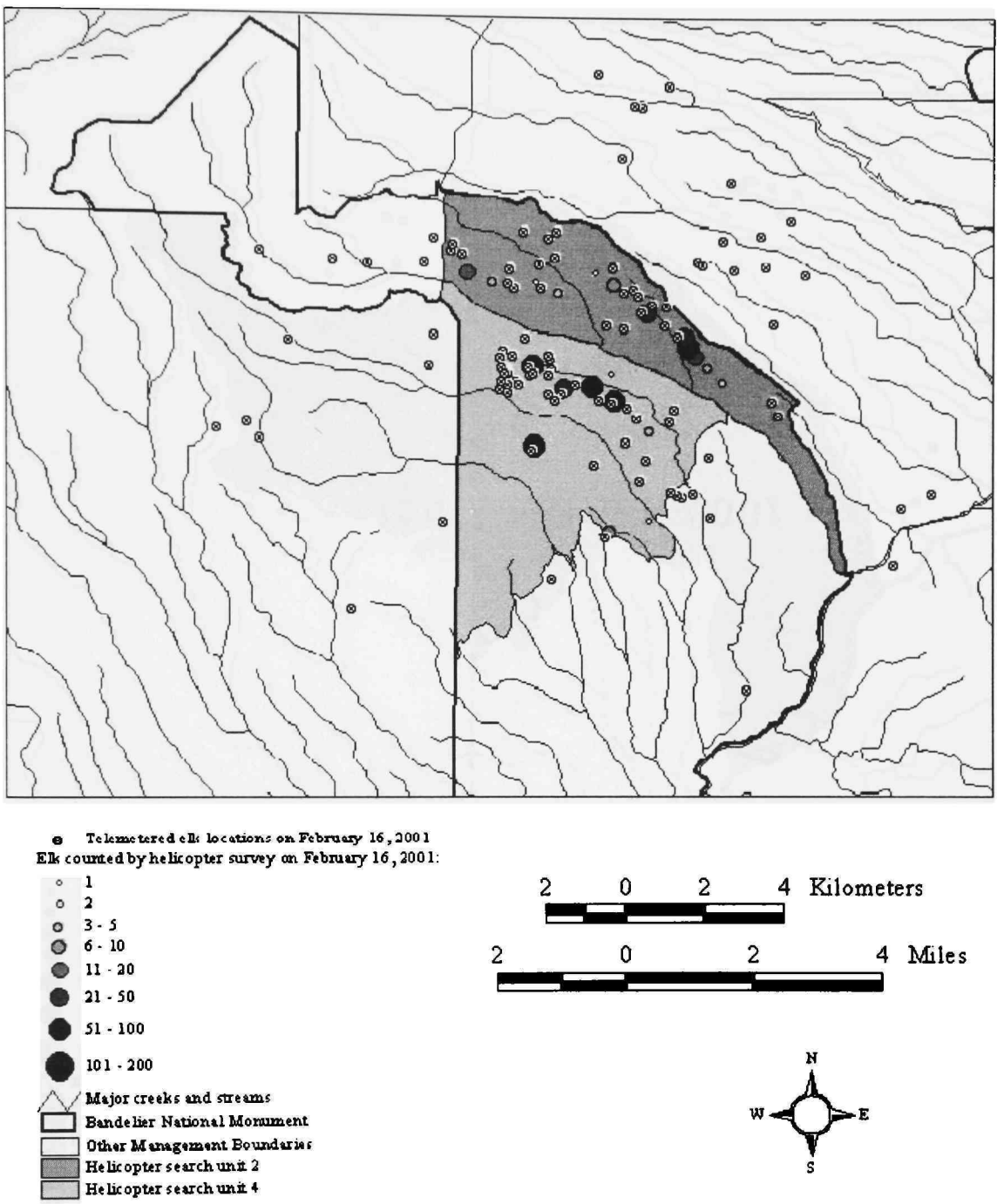

Figure A.8. Telemetered elk locations gathered by fixed-wing aircraft and elk counted by helicopter survey on February 16, 2001, in and near Bandelier National Monument, New Mexico (shaded areas = units searched during helicopter surveys).

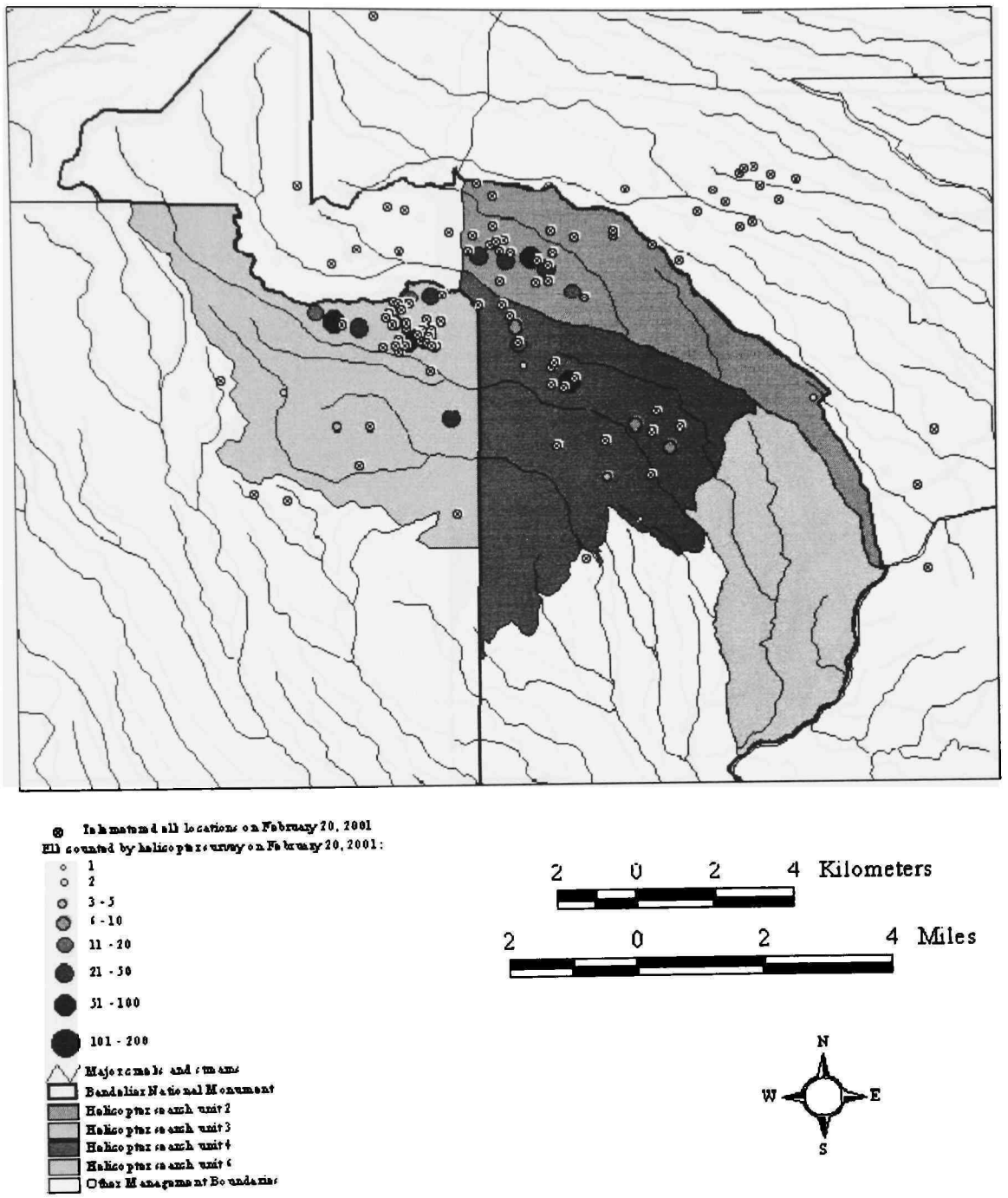

Figure A.9. Telemetered elk locations gathered by fixed-wing aircraft and elk counted by helicopter survey on February 20, 2001, in and near Bandelier National Monument, New Mexico (shaded areas = units searched during helicopter surveys).

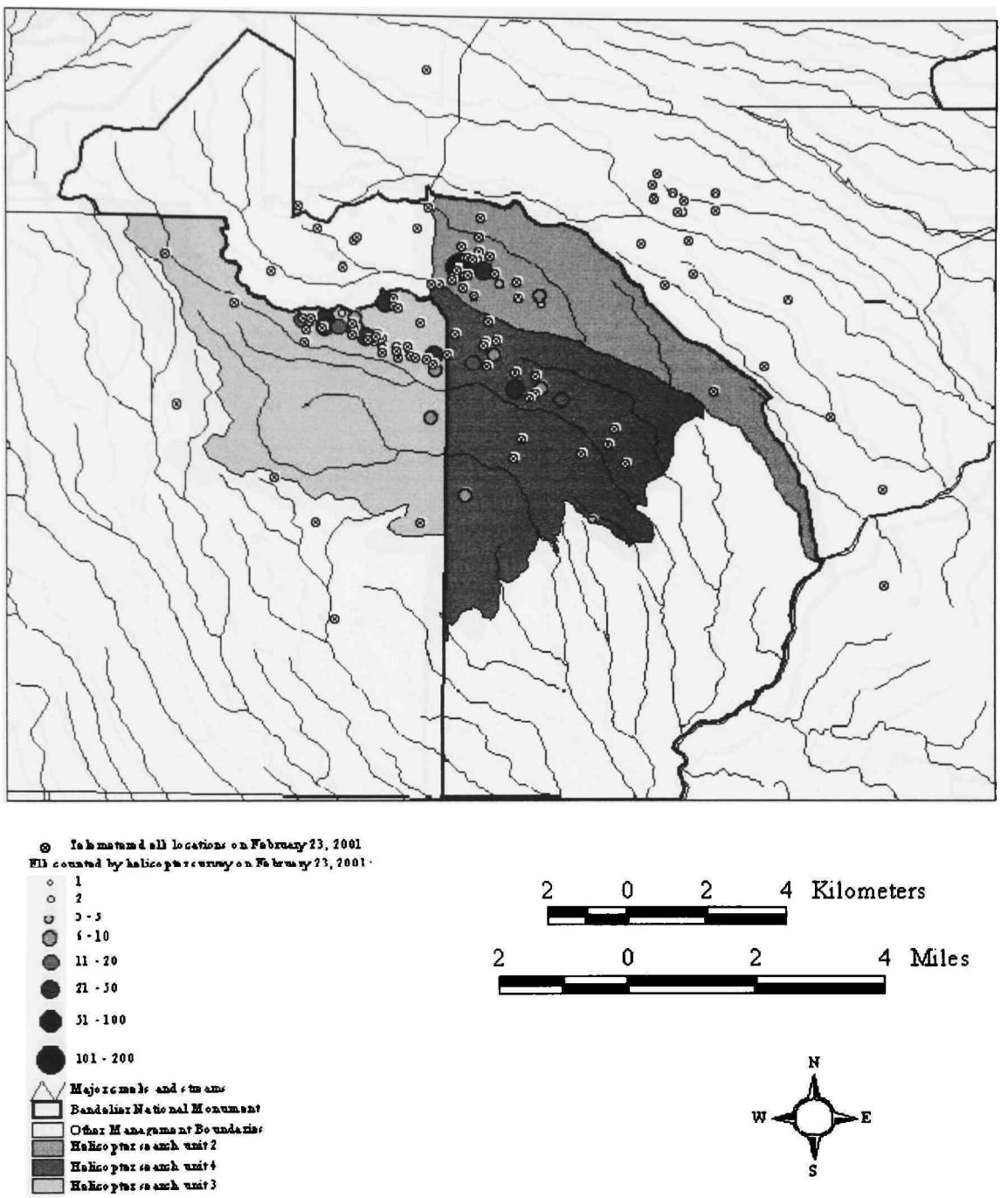

Figure A.10. Telemetered elk locations gathered by fixed-wing aircraft and elk counted by helicopter survey on February 23, 2001, in and near Bandelier National Monument, New Mexico (shaded areas = units searched during helicopter surveys).

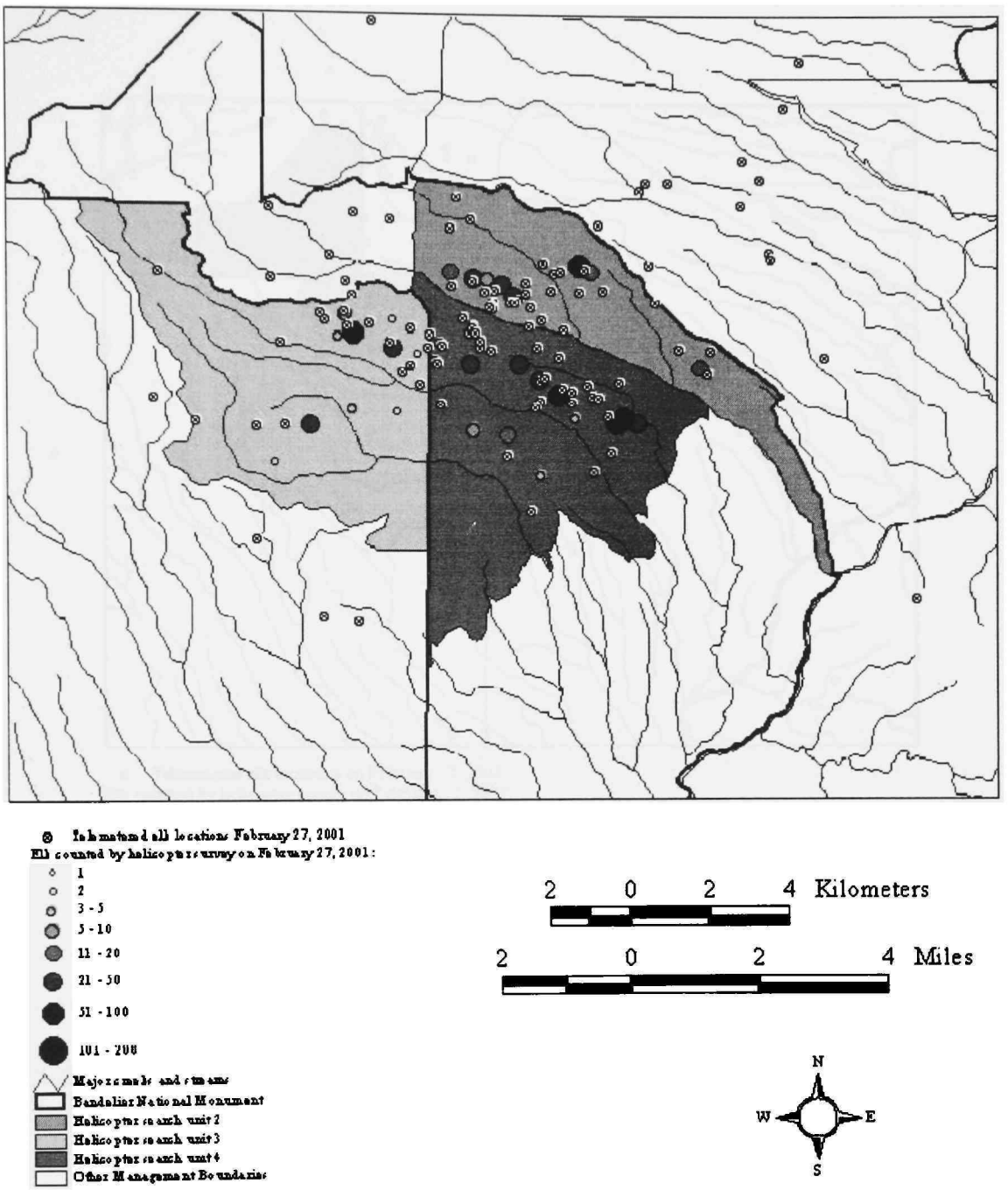

Figure A.11. Telemetered elk locations gathered by fixed-wing aircraft and elk counted by helicopter survey on February 27, 2001, in and near Bandelier National Monument, New Mexico (shaded areas = units searched during helicopter surveys).

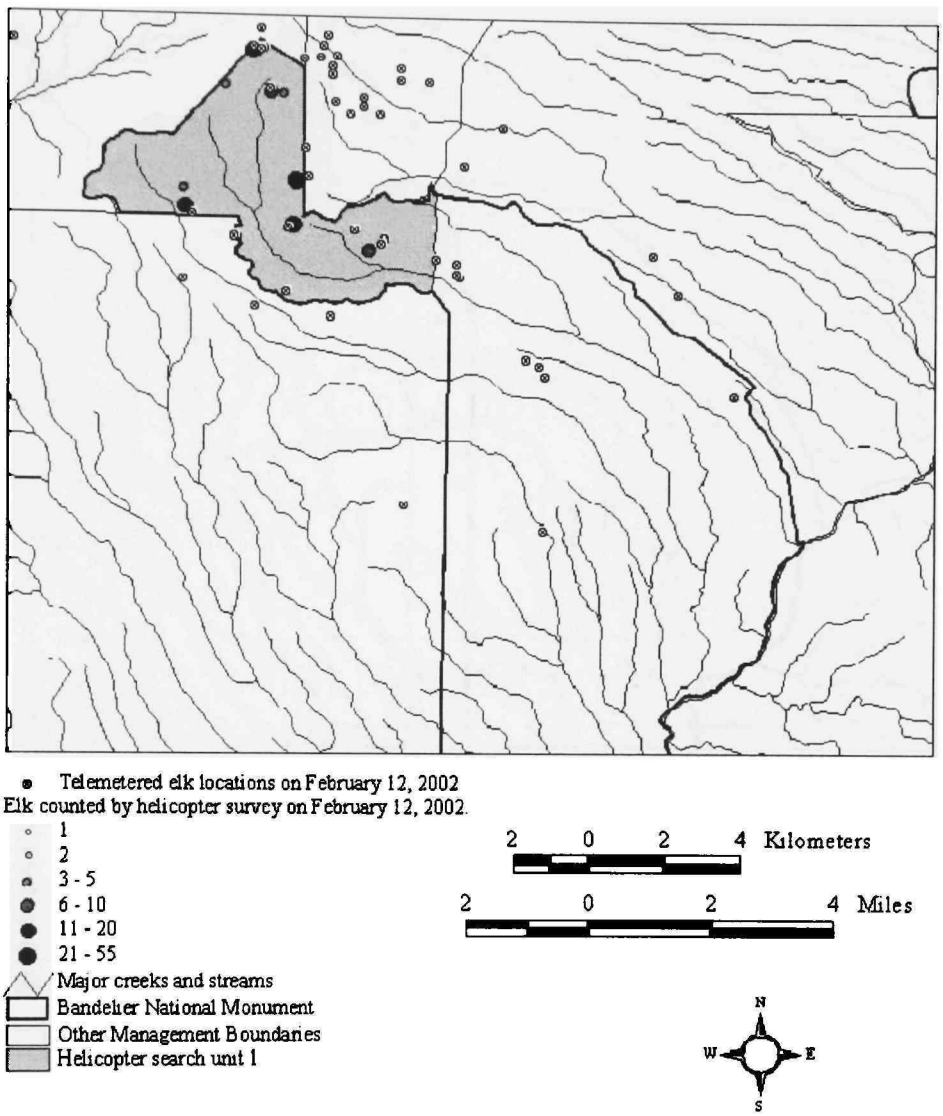

Figure A.12. Telemetered elk locations gathered by fixed-wing aircraft and elk counted by helicopter survey on February 12, 2002, in and near Bandelier National Monument, New Mexico (shaded areas = units searched during helicopter surveys).

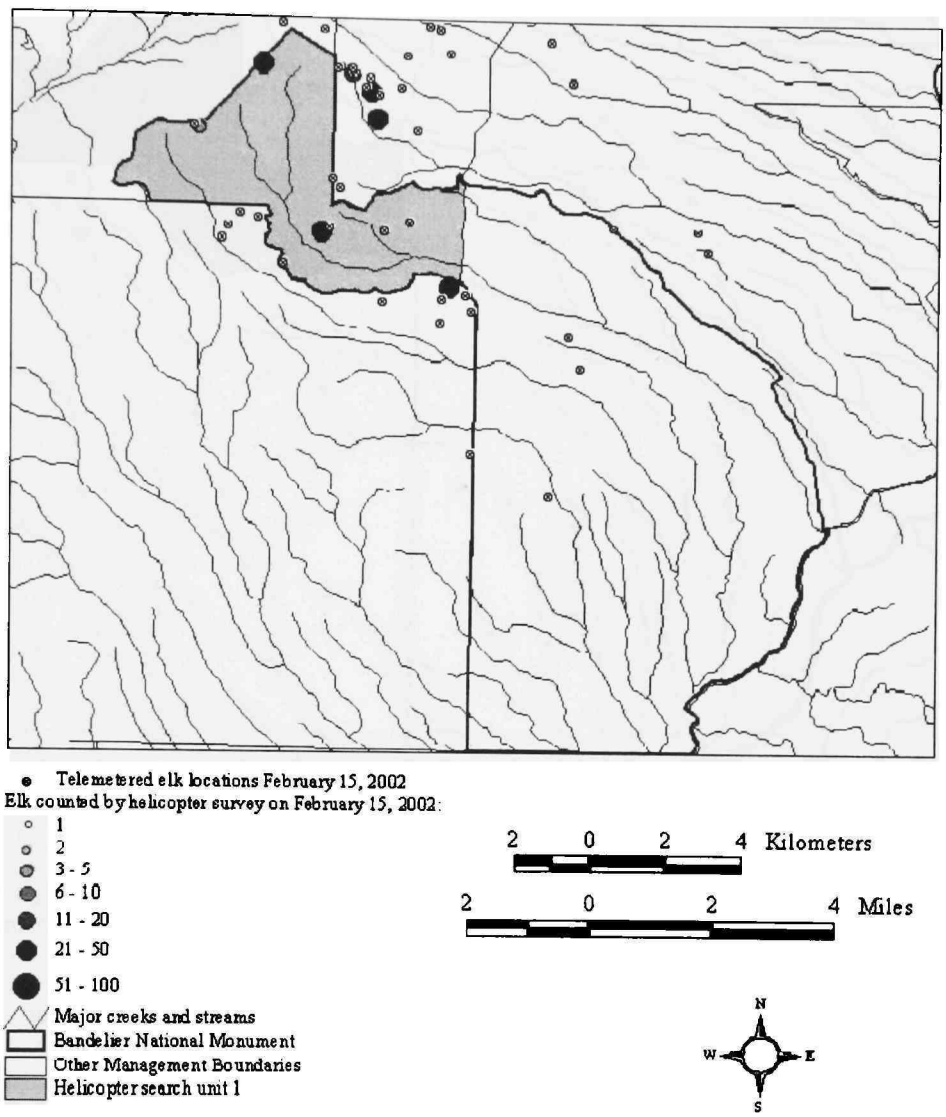

Figure A.13. Telemetered elk locations gathered by fixed-wing aircraft and elk counted by helicopter survey on February 15, 2002, in and near Bandelier National Monument, New Mexico (shaded areas = units searched during helicopter surveys).

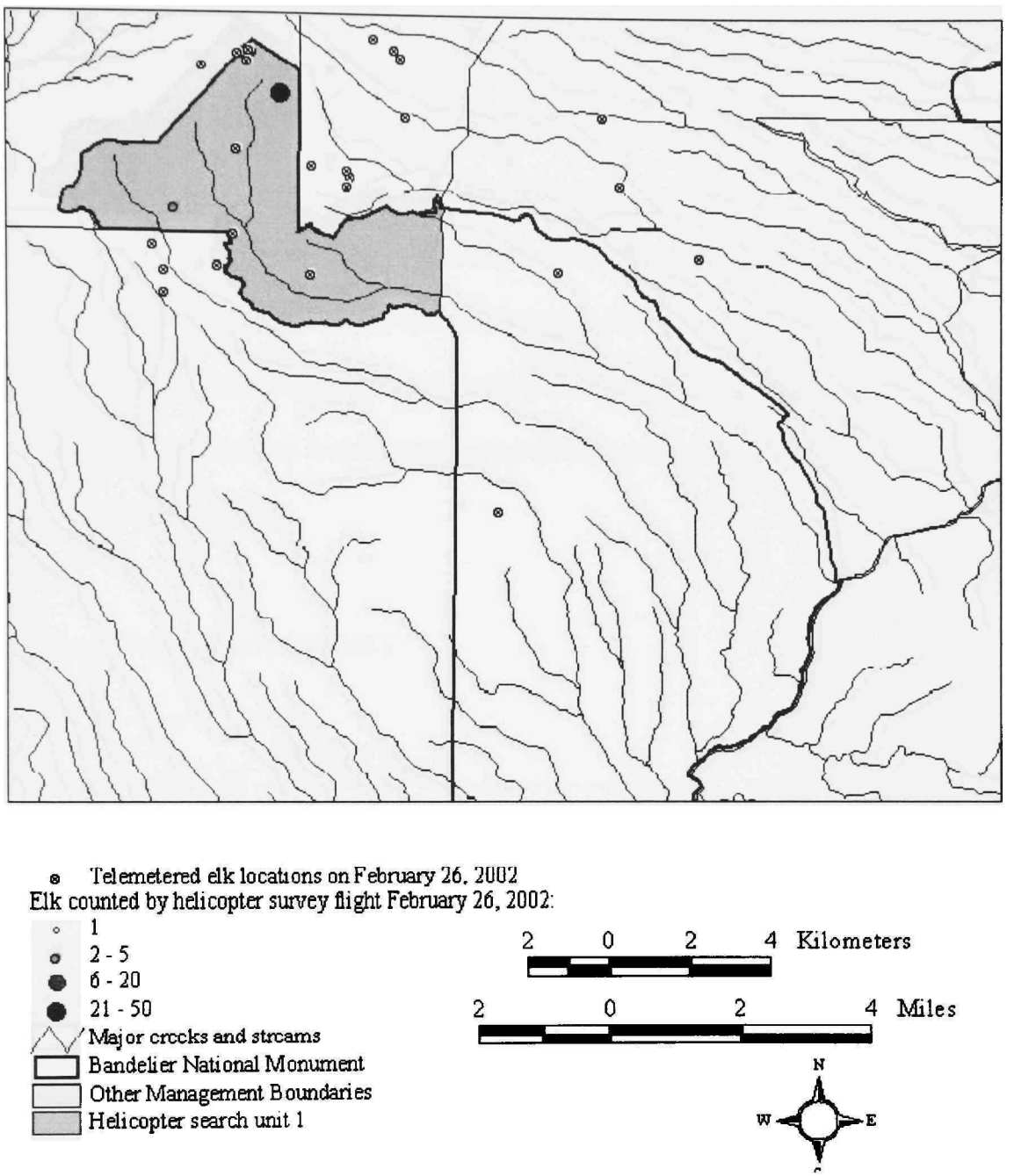

Figure A.14. Telemetered elk locations gathered by fixed-wing aircraft and elk counted by helicopter survey on February 26, 2002, in and near Bandelier National Monument, New Mexico (shaded areas = units searched during helicopter surveys).

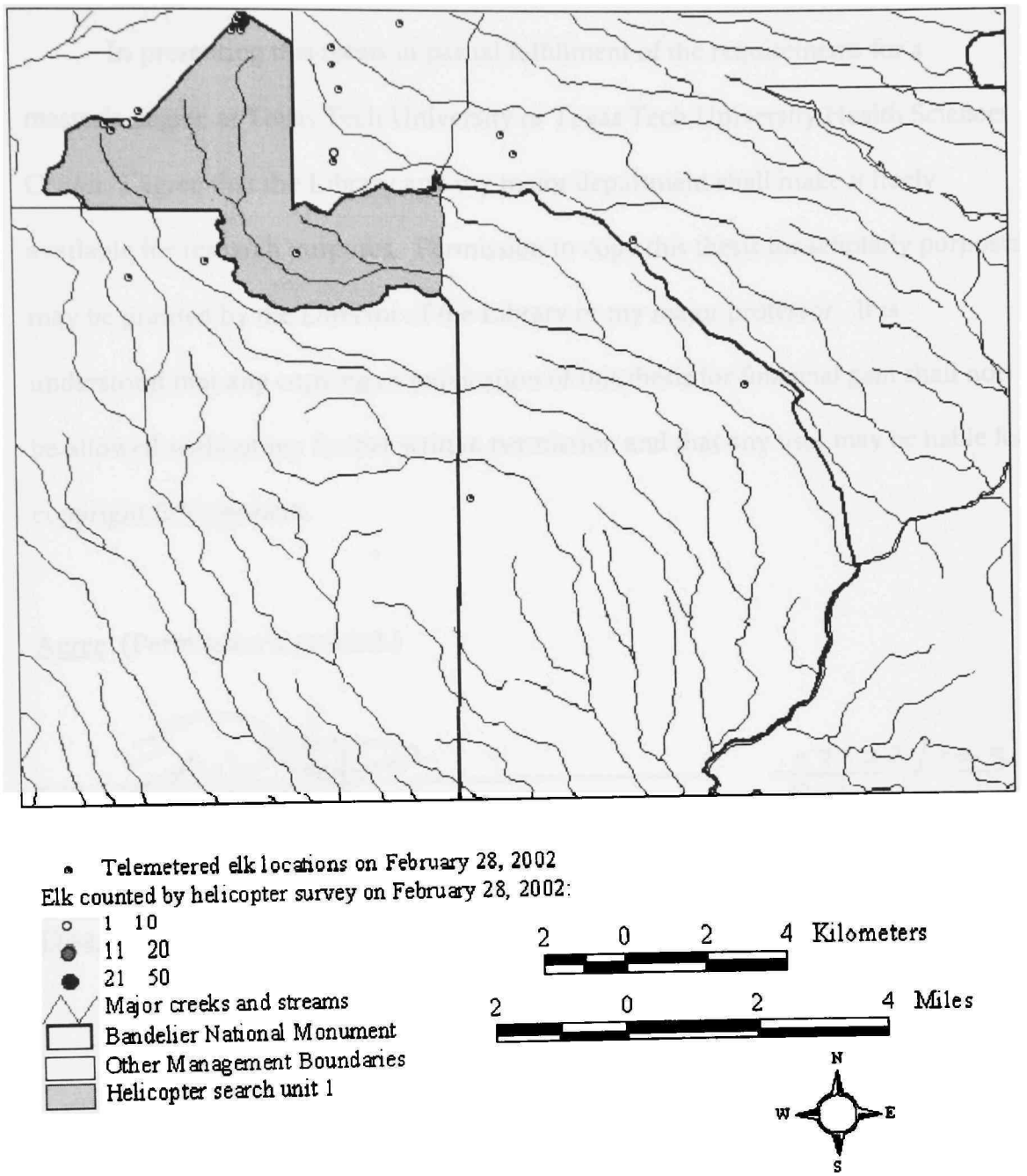

Figure A.15. Telemetered elk locations gathered by fixed-wing aircraft and elk counted by helicopter survey on February 28, 2002, in and near Bandelier National Monument, New Mexico (shaded areas = units searched during helicopter surveys).

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