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ANALYSIS OF BALD EAGLE SPATIAL USE OF LINEAR HABITAT

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ABSTRACT.—Several techniques are available for areal analysis of animal locations but few are applicable to those that use linear (i.e., riparian) habitats. Bald Eagles (*Haliaeetus leucocephalus*) often are associated with rivers and concentrate perch sites near shorelines. Distribution of cumulative proportion of perches by distance from most recently active nest sites determined by radio tracking were used to compare spatial use among five adult Bald Eagles breeding along the Snake River, Wyoming. Spatial Use Indicators (SUIs) were developed from logistic regression parameters in attempts to: (1) understand and model underlying processes from which the data may have emerged, (2) compare with simple descriptive statistical techniques to evaluate utility for presenting a clear, accurate representation of spatial use differences among eagles, and, (3) relate measures of eagle spatial use with long-term productivity of breeding areas. Distance Indicator (DI) was the distance from the nest including 50% of all detected perches used by a radio-tagged eagle and was representative of the size of the range. Slope Indicator (SI) was the slope of the fitted logistic regression curve at the DI (inflection point). SI was an indicator of linear dispersion of perch sites within the breeding area. Bald Eagles associated with more productive (>0.77 young per occupied nest over 11 years) breeding areas perched closer to nest sites (similar DIs) than eagles of their respective gender in a breeding areas of low productivity (<0.77 young per occupied nest). Male Bald Eagles in highly productive breeding areas dispersed perch sites more evenly throughout the breeding area (flat SI) than a male in a low production breeding area, while the opposite was true for females. Spatial use profiles derived from analysis of mean and confidence intervals and median and Interquartile Ranges were not as descriptive or illustrative of individual or group similarities or differences as SUIs. Logistic analysis suggested Zone II (primary foraging zone) limits recommended in regional Bald Eagle management plans may need to be extended to maintain performance of highly-productive pairs nesting along rivers. SUIs derived from logistic regression models of distance of locations from important habitat components may be indirect indicators of habitat quality and useful tools for describing and comparing spatial use of linear habitats of other species.

KEY WORDS: *Greater Yellowstone Ecosystem;* Haliaeetus leucocephalus*; logistic regression; spatial use indicators; linear habitat; radio-tracking.*

Análisis espacial del uso de habitat lienar del áquila calva

RESÚMEN.—Existen varias técnicas disponibles para el análisis de áreas y de ubicación de animales. Pocos son aplicables a aquellos que utilizan hábitat lineares (i.e., hábitats ribereños). Las águilas calvas (*Haliaeetus leucocephalus*) usualmente estan asociadas a ríos y se concentran en sitios de perchas cerca de las lineas costeras. La distribución acumulada de la proporción de percha por la distancia del sitio del nido mas recientemente activo, (determinado por telemetría), fue utilizada para comparar el uso espacial de cinco águilas calvas adultas que anidaron a lo largo del Río Snake, Wyoming. Los indicadores de uso espacial (IUE) fueron desarrollados a partir de parámetros de regresión logística con el fin de: (1) Comprender y modelar los procesos subyacentes de los cuales los datos hayan emergido, (2) Comparar con técnicas de estadística descriptiva simple y evaluar la utilidad de presentar una clara y acertada representación del uso espacial y sus diferencia entre águilas, (3) Relacionar las medidas del uso espacial de las águilas con la productividad a largo plazo de las áreas de reproducción. El Indicador de distancia (ID) fue la distancia desde el nido incluyendo el 50% de todas las perchas utilizadas por un águila con transmisor y que fuera representativa del tamaño del rango. El indicador de pendiente (IP) fue la pendiente de la curva de la regresión logística en el ID (punto de inflexión). El IP fue un indicador de la dispersión linear de los sitios de percha dentro del área reproducción. Se estudiaron las águilas calvas asociadas a una mayor productividad (>0.77 juveniles por nido ocupado de mas de 11 años), áreas de anidación y de perchas cercanas a los sitios del nido (con ID similares), en contraposición de águilas de su respectivo sexo en áreas de reproducción de baja productividad (<0.77 juveniles por nido ocupado). Los machos de águilas calvas en áreas de reproducción altamente productivas con sitios de perchas dispersas en forma similar a lo largo del área de reproducción (IP plano) en contraposición de un macho en un área de reproducción con un productividad baja, se encontró que lo opuesto ocurrió con las hembras. Los perfiles de uso espacial que se derivaron del análisis de la media y de los intervalos de confianza y de la mediana y los intervalos entre rangos no fueron tan descriptivos ni ilustrativos de las similaridades individuales o de grupo o de las diferencias como los IVE. El análisis logístico sugirió que los limites de la zona 11 (zona de forrajeo primario) recomendada en los planes regionales de manejo de águila calva necesita ser extendida para mantener su ocupación por parte de las parejas altamente productivas que anidan a los largo de los ríos. Los IVE derivados de los modelos de regresión logística de las distancias de localidades provenientes de componentes de hábitat importantes pueden ser indicadores indirectos de la calidad de hábitat y como herramientas valiosas para describir y comparar el uso espacial de los hábitats lineares de otras especies.

[Traducción de César Márquez]

Several techniques are available to analyze spatial distribution of animal locations (Mohr 1947, Worden 1989, Andries et al. 1994, Bögel et al. 1995, Kie et al. 1996, Marzluff et al. 1997, Buchanan 1997). Most involve construction of two-dimensional polygons or kernel ellipses that may include increasing proportions of total animal locations as descriptors of spatial use. Such methods are appropriate for animals that distribute their activities somewhat uniformly around activity centers but may be misrepresentative when applied to animals that distribute locations linearly along habitat corridors such as rivers. Here, we present a method for comparative analysis of spatial use of Bald Eagles (*Haliaeetus leucocephalus*) using a mostly linear, riparian corridor and contrast the utility for describing linear spatial use with standard statistical techniques. Analysis was confined strictly to one dimensional spatial distribution of perches within the breeding area and quantified relative to an important component of the habitat, the nest site. Characteristics of spatial use among eagles were compared and related to number of young produced in associated breeding areas, long-term.

METHODS

From 1985 through 1989, movements of nesting Bald Eagles were investigated in the Greater Yellowstone Ecosystem of northwestern Wyoming. Bald Eagles were resident at nest sites along the ≈108 km free-flowing portion of the Snake River in Teton County and Grand Teton National Park (see Swenson et al. 1986 for description of study area and Harmata et al. 1999 for description of Bald Eagle population). Data were collected primarily for development of nest site management plans advocated in the Greater Yellowstone Bald Eagle Management Plan (Greater Yellowstone Bald Eagle Working Group 1996). Resident eagles were randomly chosen for study but ultimately selected based on capture success (some chosen were never caught). Adult Bald Eagles were captured and radio-tagged with tail-mount and solar backpack transmitters. Gender of four eagles was determined by position during copulation post-release and measurements (Bortolotti 1984, Garcelon et al. 1985) and size relationship with the mate for another. Primary function of telemetry was to facilitate continuous visual monitoring. Transmitters assisted in locating marked eagles at the initiation of an observation period and aided relocation when eagles moved out of sight. Observation periods varied from 1 to 4 hr. Monitoring schedule was designed to provide an even distribution of effort over all hour periods in each week as possible.

Bald Eagle perches located during monitoring were plotted on U.S. Geological Survey 7.5-min topographical maps. A perch was defined as any nonflying, diurnal eagle location detected, either visually or triangulated by telemetry. Perches were located on trees and logs, in water, on the ground, or on man-made structures. Triangulated locations were easily distinguished as perched or flying by signal characteristics. Triangulated locations were ± 100 m of actual as determined by locations of test transmitters. Activity (hunting, loafing, territorial signaling, sentinel, etc.) of eagles at perch sites was not evaluated. Night roosts were not included, nor were perches chosen immediately subsequent to infrequent ($N < 5$) observer-induced movements.

Perch locations were analyzed in relation to proximity to the most recently active nest within the radio-tagged eagle's breeding area. The most recently active nest was defined as an elevated structure composed of sticks, situated in a coniferous or deciduous tree, at which resident adult Bald Eagles were last known to be engaged in reproductive activity. Reproductive activity included nest repair, copulation, incubation, brooding, feeding, or fledging young.

Perch and nest locations of each radio-tagged eagle were assigned coordinates based on the Universal Transverse Mercator system within the GSDIG subprogram of GEOSCAN (Montana Department of Fish, Wildlife and Parks 1984), a computer-based system of geographic information programs that related animal locations with geographic/habitat data. Straight-line distances between perch and nest locations were calculated in meters by

GEOSCAN subprogram MDPP (Minimum Distance Point to Point).

Data were compiled for analysis by tabulating distance of each perch detected from the nest site, nearest to farthest for each eagle tracked. Because plots of the cumulative number of perches at each distance displayed sigmoid shape typical of logistic curves, a logistic regression model (Cox 1972, Hosmer and Lemeshow 1989) was developed for each radio-tagged Bald Eagle. Use of logistic regression was an attempt to understand and model underlying processes from which the data may have emerged.

The dependent variable (p) for the logistic model:

$$p = \frac{e^{\beta_0+\beta_1(D_x)}}{1 + e^{\beta_0+\beta_1(D_x)}},$$

was defined as the cumulative proportion of perches detected. The independent variable (D_x) was distance from the most recently active nest site. Model parameters β_0 (intercept) and β_1 (slope) were estimated for each distribution using iteratively reweighted least squares techniques (Montgomery and Peck 1982) so that the models could be compared among eagles.

Two parameters associated with the logistic model were identified as spatial use indicators (SUIs): (1) the distance from the nest including 50% of all perches or distance indicator (DI) and, (2) the slope of the regression curve at the DI (inflection point) or slope indicator (SI). DI was chosen because it reflected the relative size of the breeding area, tended to minimize effect of outliers and mathematically, was the point on the logistic curve where slope was the steepest. SI was considered an indicator of perch site dispersion within the breeding area. Steep slope (large coefficient) at the inflection point indicated that perches were clustered around the DI. A flatter slope (small coefficient) was indicative of a "lazy-*S*" curve, indicating perches were more evenly distributed throughout the breeding area.

DI was calculated by solving for D_x in the logistic equation with $p = 0.5$. Therefore, DI $= -\beta_0/\beta_1$. SI was calculated by differentiating the logistic equation $[dp/dx = \beta_1 p(1 - p)]$ with $p = 0.5$, resulting in SI $= \beta_1/4$.

Construction of confidence intervals of DI and SI for among eagle comparisons required estimates of variance (Var) of both β_0 and β_1. Regression analysis provided estimates of variance of β_0 [Var (β_0)], variance of β_1 [Var (β_1)], and their covariance [Covar (β_0, β_1)] which were used to construct confidence intervals. Variance of the SIs ($\beta_1/4$) was calculated by Var(β_1)/16. However, DIs involved a ratio of two parameters ($-\beta_0/\beta_1$) and variance was estimated using the delta method (Bishop et al. 1975):

$$\mathrm{Var}\left(-\frac{\beta_0}{\beta_1}\right) = \frac{\mathrm{Var}(\beta_0)}{\beta_1^2} - 2\frac{\beta_0}{\beta_1^3}\mathrm{Covar}(\beta_0, \beta_1) + \left(\frac{\beta_0}{\beta_1^2}\right)^2\mathrm{Var}(\beta_1).$$

Data also were analyzed by simple mean, median, and post-hoc tests. Results were compared to SUIs to evaluate which methods more accurately depicted Bald Eagle spatial use. P value accepted as significant was adjusted for experiment-wise error using Bonferroni criteria ($P \leq \alpha = 0.05/10 = 0.005$). Differences in spatial use profiles among eagles were indicated by nonoverlap of Interquartile Ranges (IQRs) and 95% confidence intervals of DIs, SIs, and means.

Table 1. Perch sites and events detected during monitoring of adult Bald Eagles along the Snake River, Wyoming, 1985–89.

BREEDING AREA	GENDER	MONITORED		PERCHES DETECTED	
		HOURS	DAYS	SITES	EVENTS
Butler	♀	169	21	16	75
Cabin Creek	♂	364	77	46	187
Oxbow	♀	448	118	22	412
Sheep Gulch	♂	274	74	26	63
Schwabacher	♂	463	164	184	433

SUI of radio-tagged eagles was related to productivity of the breeding area and gender. Average number of young produced per occupied breeding area between 1979 and 1990 (Greater Yellowstone Bald Eagle Working Group 1996) was used to classify productivity as high or low for comparisons. This long-term productivity was considered more representative of resident eagles' performance than productivity coincident with period of radiotracking because severity of early spring weather affected productivity of Bald Eagles in the Greater Yellowstone Ecosystem (Harmata and Oakleaf 1992) and weather varied from mild to severe between 1985 and 1989. Additionally, some eagles in sample breeding areas were resident up to 11 years (Harmata et al. 1999). Because Sprunt et al. (1973) indicated at least 0.77 young per occupied breeding area was required for Bald Eagle populations to maintain stability, high productivity was considered >0.77 young produced per occupied breeding area between 1979 through 1990. Low productivity was considered ≤0.77 young per occupied breeding area for the same period.

RESULTS

Five radio-tagged adult Bald Eagles were monitored an average of 343.6 hr (SD = 123.4) over 90.8 d (SD = 53.5) (Table 1). Monitoring covered at least two-thirds of the nesting period (mid Feb–mid Jul) for all eagles. Mean number of perch events and perch sites detected per eagle was 234 (SD = 179) and 59 (SD = 71), respectively. Perch events detected were correlated with hr ($r = 0.917$, $P < 0.028$) and d ($r = 0.888$, $P = 0.044$) monitored. However, number of perch sites detected was not correlated with either hr ($P > 0.296$) or d ($P > 0.117$) monitored.

Linear breeding range varied from 2.2 km to 10.7 km from the nest site (Fig. 1). Logistic regression models for each eagle fit the data well,

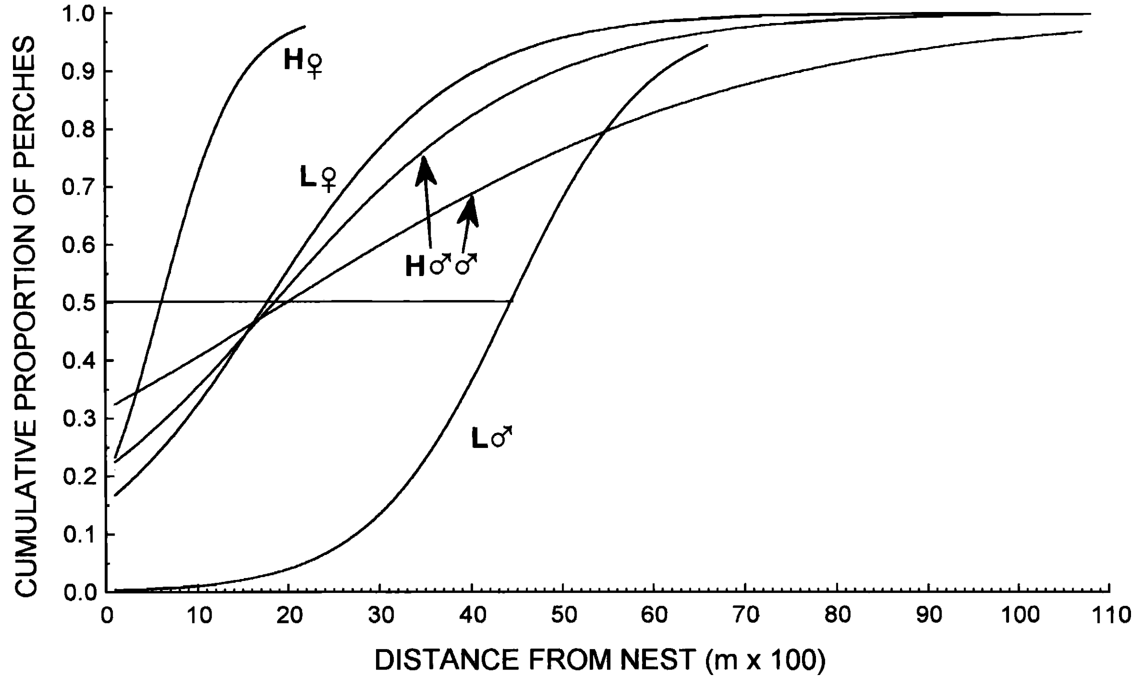

Figure 1. Logistic regression curves of cumulative proportion of perches by distance from most recently active nest site for five adult Bald Eagles monitored along the Snake River, Wyoming, 1985–89. "H" or "L" before gender icon indicates high or low reproductive history of the associated breeding area (see text).

i.e., all $R^2 \geq 0.90$ (Table 2). Two males and one female exhibited similar DIs but SIs differed among all eagles (Fig. 2). Two males and a female were associated with high productivity breeding areas and one male and a female were associated with low productivity breeding areas (Table 2).

DI of the Sheep Gulch male (low productivity breeding area) was twice as far as DIs of both the Cabin Creek and Schwabacher males' (high productivity breeding areas) (Fig. 2). DI of the Oxbow female (low productivity breeding area) was nearly three times farther than that of the Butler Creek

Table 2. Logistic regression parameters of cumulative perch site distribution, Spatial Use Indicators, and productivity of five radio-tagged adult Bald Eagles monitored along the Snake River, Wyoming, 1985–89. P for all regressions < 0 001.

BALD EAGLE (GENDER)	β_0	β_1	R^2	SPATIAL USE INDICATOR[1] DISTANCE (m)[2]	SPATIAL USE INDICATOR[1] SLOPE	PRODUCTIVITY
Butler Creek (♀)	−1.4290	0.2341	0.95	610	0.0585	High (1.73)[3]
Oxbow (♀)	−1.6987	0.0958	0.98	1774	0.0239	Low (0.58)
Cabin Creek (♂)	−1.3122	0.0708	0.97	1854	0.0177	High (1.62)
Sheep Gulch (♂)	−5.7644	0.1300	0.90	4434	0.0325	Low (0.11)
Schwabacher (♂)	−0.7724	0.0389	0.90	1986	0.0097	High (1.23)

[1] At 50th percentile (see text).
[2] From most recently active nest.
[3] Young per occupied breeding area recorded annually 1979–90.

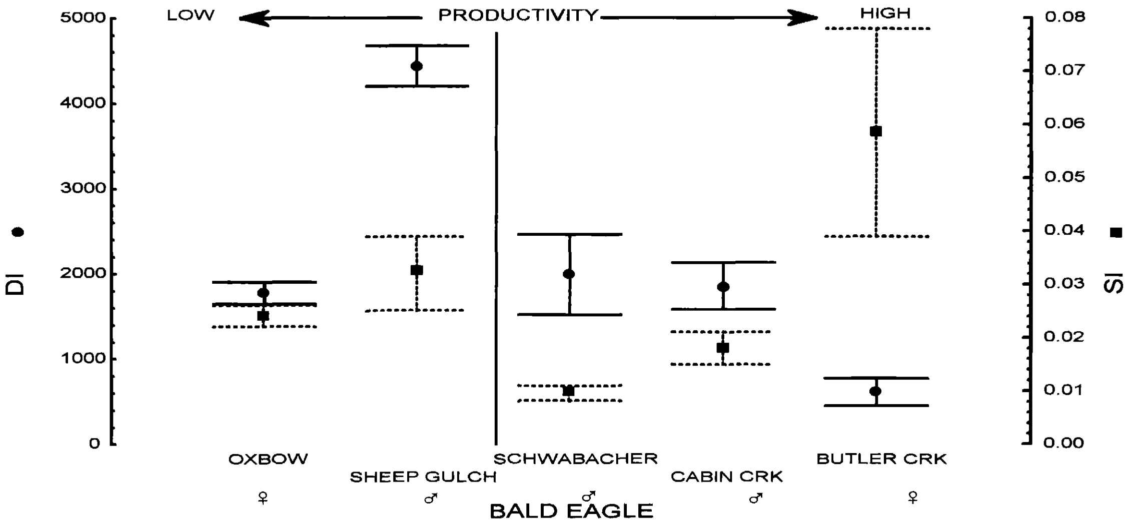

Figure 2. Confidence interval (95%) estimates of Distance Indicator (DI) and Slope Indicator (SI) derived by logistic regression of cumulative proportion of perches by distance from most recently active nest. Estimates plotted in relation to long-term productivity of the breeding area of radio-tagged adult Bald Eagles monitored along the Snake River, Wyoming, 1985–89.

female (high productivity breeding area) (Table 2). Males associated with more highly productive breeding areas also had flatter SIs than the male associated with a breeding area of low productivity (Fig. 1). However, SI of the female associated with a highly productive breeding area was twice as steep as that of the female associated with a low productive breeding area (Table 2).

Pairwise comparisons of median perch distance revealed similar relationships among eagle gender-productivity groups as did DIs, but differences were not as pronounced (cf., Fig. 2, 3). Median perch distance was greater for the highly productive female than a female exhibiting low productivity ($U = 4656.5$, $P < 0.005$) but the low production male's median perch distance was different ($U = 3737$, $P < 0.001$) only from the male with the highest production (Fig. 3). While SIs were different among all eagles, IQRs of perch distances suggested dispersion of perches around median distance was not substantially different among eagles, except for the Sheep Gulch Male (Fig. 3). Means and confidence intervals of perch distances mirrored gender-productivity relationships illustrated by DI results (cf., Fig. 2, 3).

DISCUSSION

Monitoring effort affected the number of perch events but not number of sites detected, indicating virtually all sites (distance categories) within eagle ranges were detected. Increased monitoring probably would have detected increased use of previously recorded sites only, not expansion of the breeding range or changes in SUIs.

SUIs of all Bald Eagles were different but similarities among groups were evident. Bald Eagles associated with more productive breeding areas tended to perch closer to the nest site (proximate DIs) than eagles of their respective gender in breeding areas with a history of low productivity. Breeding areas that permit more even distribution of foraging opportunities over a larger area for males (flat SIs) yet allow females to concentrate activities close to the nest (steep SIs) also may favor higher productivity. Because the male is the primary provider during incubation and early to mid-nestling phases of the breeding cycle (Stalmaster 1987), localized, temporal (daily, seasonal) disruptions in resource patch availability (e.g., human recreational presence) would be less severe in breeding areas with more dispersed or larger resource patches than in breeding areas where resource patches were few and concentrated. Close proximity of the attendant female would facilitate quick access to the nest, permitting more effective, timely defense against predators (e.g., Corvids), sheltering from inclement weather, and frequent

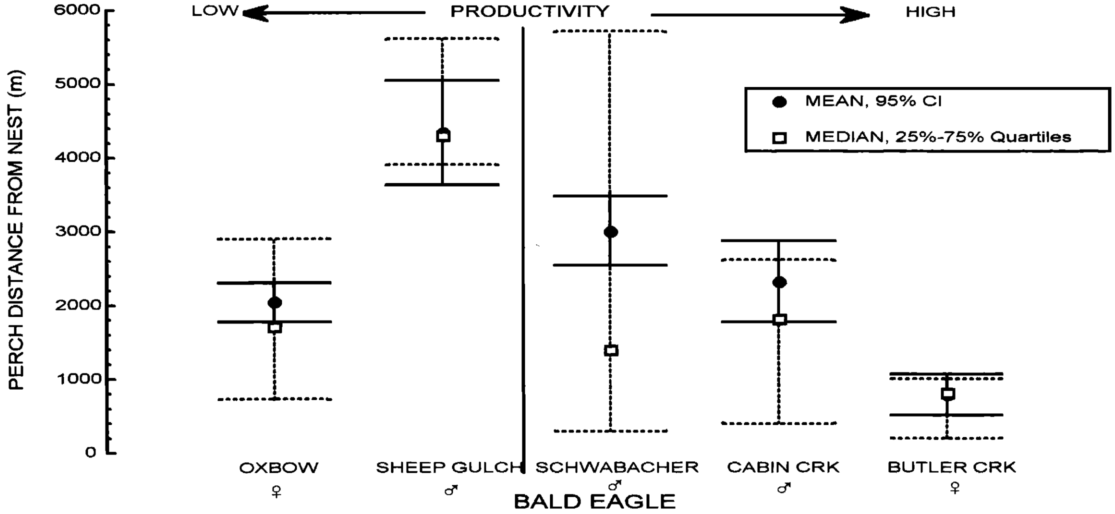

Figure 3. Measures of central tendency and dispersion of perch distance from the nest and associated long-term productivity of the breeding area recorded for five radio-tagged adult Bald Eagles monitored along the Snake River, Wyoming, 1985–89.

feedings. Higher productivity would be manifest in pairs with increased female attentiveness and more effective provisioning by the male.

Results imply more productive Bald Eagle breeding areas along rivers may require a larger primary use area (i.e., Zone II), at least along shorelines, than recommended in regional Bald Eagle management plans (e.g., Montana Bald Eagle Working Group 1994, Greater Yellowstone Bald Eagle Working Group 1996). Maintenance of reproductive performance of highly productive pairs may require extension of Zone II up to 2 km from the active nest to include 50% of male perches and 4 km to include 75% of male perches (Fig. 1).

Hall et al. (1997) defined habitat quality as "the ability of the environment to provide (for) . . . population persistence." Comparative SUIs of resident adults therefore may be indirect measures of habitat quality within Bald Eagle breeding areas along rivers and predictive of relative productivity among pioneering pairs or among pairs with unknown reproductive history. Further, temporal changes in SUIs may be indicative of changing habitat quality.

Analysis of use of linear habitat by Bald Eagles with parametric tests (means & confidence intervals) may be appropriate when data are few, approximately normally distributed, and statistical testing is desired. However, results of such tests were inconsistent with DI results (cf. Fig. 2, 3). Median analysis may be appropriate when data are sparse and no statistical testing for concentration is needed. When data are adequate ($N > 25$), comparisons of SUIs derived from logistic regression analysis may be more descriptive of linear habitat use than simple comparisons of medians and means and their respective measures of variability. SUI analysis provided opportunities for objective statistical testing, possibly modeled underlying processes and was less labor intensive and costly than GIS analysis.

Comparisons of SUIs derived from logistic regression may have applicability to other species associated with linear habitats (e.g., escarpments, streams, power line and open space corridors). However, relationships among DIs, SIs, long-term productivity, and habitat quality presented here are admittedly tenuous due to small sample size and require further investigation for confirmation.

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