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# A Prospective Power Analysis and Review of Habitat Characteristics Used in Studies of Tree-Roosting Bats

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We identified 25 studies published between 1988 and 2001 that measured characteristics of roosting sites of tree-roosting bats, and where measures were compared to characteristics of random or available locations. The most frequently measured habitat characteristics were roost-tree diameter ($n = 23$), roost-tree height (21), roost-tree canopy cover (16), roost height (14), and slope (10). Habitat characteristics of the roost tree itself were measured more frequently than stand or landscape characteristics; a total of 31 different habitat characteristics was used to describe stand or landscape conditions as opposed to 23 different habitat characteristics used to describe features of the roost tree. The overall mean ($\pm$ SE) number of habitat characteristics examined per study was $8.0 \pm 1.1$, with an average of $4.2 \pm 0.7$ characteristics reported to be significant ($P < 0.05$). Mean estimated effect size, or the absolute value of the difference between means divided by the population standard deviation, of habitat characteristics ranged from 0.83 to 1.52. A sample size of 11 radio-tagged bats was sufficient to achieve acceptable power, i.e., 0.80, for all habitat characteristics examined when only using the upper limit of the 95% confidence intervals for estimated effect sizes. In contrast, a sample size of 39 radio-tagged bats was sufficient in achieving the same level of power for only 50% of the habitat characteristics evaluated at the lower end of the 95% confidence intervals. We encourage researchers to conduct pilot studies, and estimate effect sizes and variances to assess the level of sampling effort required to evaluate habitat characteristics in studies of tree-roosting bats.

*Key words*: bats, effect size, habitat, power analysis, sample size, tree roosts, variance

## INTRODUCTION

Application of power analysis to clarify inference drawn in statistical analysis of data has found favor in the fields of wildlife management and conservation biology (e.g., Taylor and Gerrodette, 1993; Reed and Blaustein, 1995; The Wildlife Society, 1995; Hayes and Steidl, 1997; Steidl *et al.*, 1997). Most attention has centered on the use or misuse of retrospective power analysis (Steidl *et al.*, 1997; Thomas, 1997; Gerard *et al.*, 1998), which is calculation of power after the data are already collected

and where a significant difference was not found relative to some effect or standard of comparison. One purpose of retrospective power analysis is to help investigators qualify or temper their conclusions. This is true when a statistical test shows no difference or other type of effect in the data and where power of the test is estimated to be low and the chance of committing a Type II error is high (Steidl *et al.*, 1997; Thomas, 1997; Gerard *et al.*, 1998). In prospective power analysis, effect size and the variance for the parameter in question are estimated and power of the test

calculated before the study takes place (Eberhardt and Thomas, 1991; Steidl *et al.*, 1997). Prospective power analysis also can be used to estimate the sample size needed to meet a specified level of power given a fixed effect size and estimate of the variance before testing a parameter of interest (Cohen, 1988; Thomas, 1997). This information could facilitate the study of tree-roosting bats, where data collection often is costly and labor intensive and where no recommendations presently exist on the amount of sampling required to detect biologically meaningful differences in use of forest habitat by bats.

A heightened awareness of the importance of above ground habitat for tree-roosting bats has resulted in an increasing demand for data and recommendations by agencies charged with responsible use of forest lands and by private land owners that actively manage forests. Recent symposia on forest bats (Brigham and Barclay, 1996) and the tree-roosting Indiana bat, *Myotis sodalis* (Lacki, 2002), attest to the level of attention being paid to uncovering critical habitat requirements of tree-roosting bat species. A unified goal of all these efforts should be identification of habitat characteristics or construction of predictive habitat models that effectively discriminate habitats used by bats from random or available habitats at the stand or landscape scale (Fenton, 1997). Such information would be helpful in the planning stage where the implementation of different forest management prescriptions is evaluated and where existing data on bats could possibly sway the outcome of the decision-making process (Pierson, 1998). Presently there is little agreement as to how to quantify habitat, the scale at which habitat characteristics should be measured (i.e., tree, stand or landscape), whether habitat characteristics should be examined separately or in a multivariate context, and the level of sampling effort

necessary to achieve a specified level of precision for the habitat characteristics measured. The purposes of this paper are: 1) to review the existing literature and identify habitat characteristics that appear to be best suited to the study of tree-roosting bats, and 2) to develop recommendations for estimating sampling effort that will achieve a high probability of detecting meaningful biological effect sizes.

## METHODS

We reviewed literature published between 1988 and 2001 for studies that examined habitat characteristics associated with roost site selection in tree-roosting bats. We specifically identified studies where habitat characteristics were measured at roosting sites and then compared to random or available conditions, or where habitat characteristics were compared among species. Finally, we identified 25 published studies that met desired habitat comparison requirements, and were used in calculating power analyses. These include (in alphabetical order): Barclay *et al.* (1988), Betts (1996, 1998), Boonman (2000), Brigham *et al.* (1997), Callahan *et al.* (1997), Campbell *et al.* (1996), Crampton and Barclay (1998), Cryan *et al.* (2001), Foster and Kurta (1999), Grindal (1999), Hutchinson and Lacki (2000), Lacki and Schwierjohann (2001), Lunney *et al.* (1995), Mattson *et al.* (1996), Menzel *et al.* (1998), Ormsbee and McComb (1998), Rabe *et al.* (1998), Sasse and Pekins (1996), Sedgeley and O'Donnell (1999*a*, 1999*b*), Vonhof (1996), Vonhof and Barclay (1996), Waldien *et al.* (2000), and Weller and Zabel (2001). For each paper we determined the number of habitat characteristics quantified, number of habitat characteristics found to be significant, whether nominal (i.e., categorical) habitat characteristics were examined, and whether habitat characteristics were tested using a multivariate approach, tested separately, or both.

Rather than rely on power curves based on a range of possible effect sizes to evaluate the sample size needed to detect a biologically significant effect size for a habitat characteristic (Steidl *et al.*, 1997), we used differences reported to be statistically significant in the published literature and, thus, interpreted as if they were biologically significant by the authors to estimate effects. For habitat characteristics where differences were reported across three or more studies, we calculated the mean estimated standardized effect size, i.e., the absolute value of the difference between means divided by the population

standard deviation, and 95% confidence intervals, based on the estimated or measured effects reported in the studies reviewed (Cohen, 1988). Standardized effect sizes are helpful in the planning phase of studies because they are unitless and can be compared among studies (Steidl and Thomas, 2001). We estimated the sample size of radio-tagged bats needed to achieve minimally acceptable power (i.e., 0.8; Steidl *et al.*, 1997), and a power level (0.95) where alpha and beta are equal and the chance of committing a Type I or Type II error equal (0.05), using upper and lower limits of the 95% confidence intervals associated with mean estimated standardized effect sizes for habitat characteristics and tables provided in Cohen (1988). For all comparisons we used tables assuming a two-tailed *t*-test and an $\alpha = 0.05$.

We combined habitat characteristics across studies that we thought measured like attributes and organized the variables into two categories: those associated with the roost tree and those measured at the stand or landscape scale. Habitat characteristics for study of tree-roosting bats were evaluated based on their frequency of success, i.e., % of time found significant, and the sample sizes of radio-tagged bats projected to achieve measured levels of precision with sufficient power for these characteristics.

## RESULTS

We identified 25 published studies from 1988 to 2001 that met desired habitat comparison requirements. The mean ($\pm$ SE) number of habitat characteristics measured per study was $8.0 \pm 1.1$, with $4.2 \pm 0.7$ habitat characteristics found on average to be significant. Ten (40%) of the studies also measured nominal habitat characteristics. Thirteen (52%) of the studies used a multivariate approach to evaluate habitat characteristics, with the mean number of habitat characteristics examined being $9.2 \pm 1.8$. In these papers, $4.2 \pm 1.0$ habitat characteristics were found to be significant on average. Logistic regression was the most common multivariate approach used in evaluating habitat characteristics.

Authors tested an average of $6.7 \pm 1.2$ habitat characteristics in studies where measures were examined separately, with $4.3 \pm 1.0$ habitat characteristics found to be significant. Student's *t*-test and Wilcoxon nonparametric test were the most frequently used approaches when evaluating habitat characteristics independently.

Roost-tree diameter was the most frequently measured habitat characteristic, followed by roost-tree height, roost-tree canopy cover, roost height, and slope, respectively (Table 1). Habitat characteristics of the roost tree itself were measured far more often than stand or landscape characteristics; however, there was a total of 31 different habitat characteristics used to describe stand or landscape habitat features as opposed to only 23 habitat characteristics used to describe features of the roost tree (Table 1; Appendix). For stand or landscape characteristics, a significant difference was reported at least once for 61.3% ($n = 19$) of the habitat characteristics reported, whereas habitat characteristics measured at the roost tree were found significant in at least one instance for 82.6% ($n = 19$) of the measures reported.

Of the studies surveyed, 68% ($n = 17$) provided sufficient data for power analysis, i.e., mean, an estimate of variance, and sample size, of at least one or more habitat characteristic. Mean estimated standardized effect size of habitat characteristics ranged from 0.83 for stand basal area to 1.52 for tree/snag height (Table 2). A sample size of 11 radio-tagged bats was sufficient to achieve acceptable power, i.e., 0.80, for all habitat characteristics evaluated based on the upper limit of the 95% confidence intervals for estimated mean standardized effect sizes. In contrast, a sample size of 39 radio-tagged bats was sufficient in achieving the same level of power for only 50% of the habitat characteristics evaluated at the lower end of the 95% confidence interval. Habitat characteristics found to have low estimated effect sizes and, thus, are likely to be poor choices for modeling habitat conditions of tree-roosting bats included

TABLE 1. Quantitative habitat characteristics most frequently measured in studies of tree-roosting bats. The percentage of studies in which a habitat characteristic was found significant at $P < 0.05$ and the direction of the measured characteristic from random or available trees in the habitat are presented

| Habitat characteristic | No. studies measured | % different | Direction of difference |
|---|---|---|---|
| Roost-tree characteristics[a] | | | |
| Tree/snag diameter (cm) | 23 | 65.2 | Roost > random |
| Tree/snag height (m) | 21 | 52.4 | Roost > random |
| Tree/snag canopy cover (%) | 16 | 56.2 | Roost < random |
| Roost height (m) | 14 | 21.4 | Roost > random |
| Snag bark cover (%) | 9 | 22.2 | Roost > random |
| Roost aspect (°) | 7 | 14.3 | Roost ≠ random[c] |
| Distance to nearest tree (m) | 6 | 33.3 | Roost > random |
| Canopy height (m) | 5 | 20 | Roost > random |
| Distance to nearest tree > roost tree in height (m) | 5 | 80 | Roost > random |
| Height of nearest tree (m) | 5 | 0 | – |
| Difference between roost tree height and canopy height (m) | 4 | 50 | Roost < random |
| Distance to nearest available tree (m) | 4 | 25 | Roost < random |
| Branches remaining (%) | 3 | 33.3 | Roost > random |
| Stand/landscape characteristics[b] | | | |
| Slope (%) | 10 | 30 | Roost > random |
| Aspect (o ) | 8 | 0 | – |
| Mean stem diameter (cm) | 8 | 75 | Roost > random |
| Distance to forest edge (m) | 7 | 28.6 | Roost > random |
| Distance to open/lentic water (m) | 7 | 14.3 | Roost < random |
| Mean snag density (no. snags/ha) | 7 | 42.9 | Roost > random |
| Elevation (m) | 6 | 33.3 | Roost ≠ random |
| Mean stand density (no. trees/ha) | 5 | 60 | Roost ≠ random |
| Stand basal area (m²/ha) | 5 | 80 | Roost > random |
| Basal area of large diameter (≥ 25 cm) trees (m²/ha) | 5 | 80 | Roost > random |

[a] — Ten additional characteristics were measured in ≤ 2 studies
[b] — Twenty-one additional characteristics were measured in ≤ 2 studies
[c] — Direction of difference (≠) varied across studies

tree/snag canopy cover, mean snag density, and stand basal area. An explanation for poor performance of these habitat characteristics in our analysis probably lies in an inherently larger variation within the data collected to assess these measures, resulting in smaller estimated effect sizes.

DISCUSSION

Although not exhaustive, we do believe that our sample of available literature reflects the variety of habitat characteristics being examined and variability in the data collected across studies of tree-roosting bats. Further, we restricted our analysis to quantitative habitat characteristics only, so recommendations here cannot be applied to nominal measures of habitat characteristics. Regardless, we believe the results of this analysis can be used to aid in designing habitat studies of tree-roosting bats. For example, based on the findings presented (Tables 1 and 2), we could hypothesize that forest bats should typically choose roost trees larger in diameter, taller in height, lower in canopy cover, further from the nearest tree ≥ roost tree in height, and smaller in distance between roost-tree height and canopy height than random or available trees in the

TABLE 2. Mean estimated standardized effect sizes for quantitative habitat characteristics measured in studies of tree-roosting bats and associated sample sizes (shown in LCI and UCI columns) required to achieve indicated power levels. Based on α = 0.05, using two-sample *t*-test (Cohen, 1988). LCI and UCI: lower and upper ends of confidence interval, respectively

| Habitat characteristics | Effect size | | | Power level | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | | | | 0.8 | | 0.95 | | |
| | $n^{a}$ | Mean | 95% CI | LCI | UCI | LCI | UCI | |
| Roost-tree characteristics | | | | | | | | |
| Tree/snag diameter (cm) | 18 | 1.19 | 0.94–1.44 | 19 | 9 | 31 | 14 | |
| Tree/snag height (m) | 7 | 1.52 | 0.92–2.12 | 21 | 9 | 33 | 14 | |
| Tree/snag canopy cover (%) | 7 | 0.95 | 0.40–1.50 | 99 | 9 | 163 | 14 | |
| Distance to nearest tree ≥ roost tree in height (m) | 4 | 1.37 | 0.65–2.09 | 39 | 9 | 64 | 14 | |
| Roost height (m) | 3 | 1.1 | 0.79–1.41 | 27 | 9 | 43 | 14 | |
| Stand/landscape characteristics | | | | | | | | |
| Mean snag density (no. snags/ha) | 6 | 0.85 | 0.45–1.25 | 82 | 11 | 134 | 18 | |
| Mean stem diameter (cm) | 4 | 1.22 | -1.30–3.74 | – | 9 | – | 14 | |
| Stand basal area (m²/ha) | 4 | 0.83 | -0.10–1.77 | – | 9 | – | 14 | |

[a] — Indicates the number of comparisons in which sufficient data (i.e., mean, variance, and sample size) were provided to allow calculation of estimated standardized effect size

habitat. Further, forest bats should choose roost trees on steeper slopes, in stands greater in basal area, higher in snag density, and closer to open water relative to random stands in the landscape. We suggest that these variable combinations represent baseline models that could be tested across landscapes to identify patterns common to bat species. Anderson *et al.* (2001) have encouraged authors to develop biological theories for testing prior to undertaking empirical studies leading toward the development of predictive models. The results presented here provide a baseline from which biological theory on roost-site selection of tree-roosting bats could begin to be formulated.

It should be anticipated that some habitat characteristics will be more or less important to some bat species than others, and that species may respond differently to the same habitat characteristic; thus, reciprocal effects in models of habitat use for some characteristics are plausible among different bat species (e.g., elevation and stand density; Table 1). The difference in canopy closure observed between roost trees of northern bats (*Myotis septentrionalis*),

which select higher closure (Foster and Kurta, 1999; Lacki and Schwierjohann, 2001), and *M. sodalis*, which select more open canopies (Callahan *et al.*, 1997; Foster and Kurta, 1999), is a case in point. In turn, habitat characteristics important to foliage-roosting species, such as the lasiurine bats (e.g., Menzel *et al.*, 1998; Hutchinson and Lacki, 2000), cannot be expected to mimic those required of snag or cavity-roosting bats (Hayes, In press).

It is well documented that tree-roosting bats switch roosts frequently (Lewis, 1995), and it is hypothesized that low roost-site fidelity of tree-roosting bats is in response, in part, to the ephemeral nature of tree roosts (Kurta *et al.*, 1993). Temporal shifts in energetic demands of tree-roosting bats, especially among pregnant, lactating, and post-lactating females, also is likely to be a contributing factor in roost switching over the course of the summer maternity season (Kurta *et al.*, 1996), rendering development of predictive habitat models difficult at best (Millspaugh *et al.*, 1998). Because of such anticipated variability in roost-site selection by bats, we recommend

that authors continue to explore other options for habitat characteristics, including characteristics little used in the studies reviewed here.

Prospective power analyses revealed that sample sizes of radio-tagged bats ranging from 11–39 would be sufficient to achieve some probability of detecting biologically significant effects for several of the variables tested. As was pointed out to one of us (MJL) by an anonymous reviewer (Lacki and Schwierjohann, 2001), the actual sample size upon which statistical inferences should be based in studies of tree-roosting bats is the number of bats fitted with radio-transmitters. This is because multiple bats can and do use the same roost tree and, therefore, individual roosts are not necessarily independent samples. Further, analysis of resource selection assumes that sampling of resource units is random and independent (Millspaugh *et al.*, 1998). Because roost trees are selected by the bats, and not the researcher, and that bats often use the same roost trees at various points in time, roost trees are not biologically or statistically independent. As such, the sample sizes reported here should reflect the number of bats radio-tagged for study and not the number of roost trees identified, because it is the bats that are presumed to be collected randomly and independently.

We also encourage researchers to consider planning when determining the sample size necessary for the number of random or available habitat plots or trees to be measured. Guidelines for determining sampling effort of random plots or trees exist (Ramsey *et al.*, 1994), with a recommendation of no more than 4:1 random to used samples, because of the limited increase in statistical power beyond this ratio relative to the expense of obtaining additional samples (Breslow and Day, 1980). The effect of scale also should not be overlooked. Although estimated sample sizes varied among the habitat characteristics examined (Table 2), there appeared to be greater variability in projected sample sizes associated with stand and landscape habitat characteristics than with measures used to describe the roost tree. Thus, the need for prior planning is even more critical when landscape-scale inferences are being examined.

Exactly how preexisting data should be used to calculate statistical power during the planning phase of studies remains a point of discussion (Steidl *et al.*, 1997; Thomas, 1997; Gerard *et al.*, 1998). To begin with, statistical significance does not always reflect biological significance (Tacha *et al.*, 1982; Yoccoz, 1991; Johnson, 1995), and use of preexisting data to measure the effect and variance can lead to biased estimates of power with low precision (Gerard *et al.*, 1998). Further, when analyses are based on actual data collected in the field, power becomes a random variable and the measures of power reported are 'estimates' of statistical power (Gerard *et al.*, 1998). Thomas (1997) recommended that when field data are used to estimate power, a sensitivity analysis should be performed that examines a range of Type II error levels.

Through an examination of Type II error levels at the upper and lower bounds of the confidence intervals of estimated standardized mean effect sizes, we provide a foundation for sensitivity analysis of power for studies planning to evaluate habitat characteristics of tree-roosting bats (Taylor and Muller, 1995; Thomas, 1997). By using data collected and previously analyzed across a series of studies, or a meta-analysis approach (Johnson, 2002), we believe that estimated standardized mean effect sizes can be calculated and used as a potential tool for estimating power or sample size for a given power level. This approach is in lieu of the development of a range of 'hypothetical' power curves; curves that represent a wide range of possibilities and are based

on limited forethought of the potential biological effect sizes in question. We believe this latter approach can be troublesome, especially for researchers who have limited experience with the species of bat or geographic region they intend to study.

We chose to use data from published studies to reflect biologically significant effect sizes and variances under the supposition that the authors' of these papers deemed the effects to be biologically significant, because differences were interpreted to be biologically meaningful. We qualify analyses in this paper with the understanding that in each comparison that we evaluated, reality lies somewhere between biological and statistical significance; the larger the effect and/or the smaller the sampling variance the greater the likelihood that a 'difference' will be reported (Johnson, 1995; Hayes and Steidl, 1997). Conversely, studies for which no significant effect is observed are less likely to be published; thus, any evaluation based on published findings, including this one, has the potential for bias due to the method of sampling used (Dear and Begg, 1992). Ultimately, it is the responsibility of the researcher to decide if the observed effect is biologically significant given their understanding of the species of bat under study. Proper planning beforehand that produces a sampling design with sufficient power should minimize ambiguity in interpreting the outcome of the data collected. By no means do we imply that non-significant results are unimportant. They are more difficult to interpret, particularly when the study design used has low statistical power.

The results of our analysis, along with the synthesis provided in Hayes (In press), suggests that sufficient data exist to begin formulating biological theories that could be tested in empirical studies of tree-roosting bats. Regardless, we encourage researchers to provide the mean, an esti-mate of variance, and the sample size for each habitat characteristic measured in all published studies of tree-roosting bats. This alone will help in the design and analysis of future studies of tree-roosting bats. We support the use of pilot studies during the planning phase (Steidl *et al.*, 1997). Developing a priori hypotheses on how bats might respond to habitat characteristics, supplemented with estimates of effect size and variance from pilot study data, should provide useful comparisons with published data. Lastly, there can be no shortage of care taken to minimize sampling error in the field while studying tree-roosting bats. By minimizing error due to the collection technique, investigators should produce smaller estimates of variance via more efficient sampling protocols, and, ultimately, increased statistical power.

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APPENDIX

Supplemental list of quantitative variables to describe habitat characteristics of tree-roosting bats that were used in ≤ 2 studies. Significance met if $P \leq 0.05$

| Habitat characteristics | Significant | Direction of difference |
|---|---|---|
| Roost-tree characteristics | | |
| Canopy depth (m) | No | – |
| Distance to nearest vegetation (m) | Yes | Roost > random |
| Height of nearest tree as tall or taller than roost tree (m) | Yes | Roost > random |
| Number of cavities (*n*) | Yes | Roost > random |
| Percent bare trunk (bole — %) | No | – |
| Percent crown remaining (%) | Yes | Roost > random |
| Percent obstruction near roost entrance (%) | No | – |
| Percent of roost tree obscured by vegetation (%) | Yes | Roost < random |
| Trunk (bole) height (m) | Yes | Roost > random |
| Trunk (bole) surface area ($m^2$) | Yes | Roost > random |
| Stand characteristics | | |
| Basal area of snags ($m^2$/ha) | Yes | Roost > random |
| Density of available trees (no. trees/ha) | No | – |
| Density of conifer trees (no. trees/ha) | No | – |
| Density of deciduous trees (no. trees/ha) | No | – |
| Density of large diameter snags (no. snags/ha) | Yes | Roost > random |
| Downed log density (no. logs/ha) | Yes | Roost > random |
| Height of overstory (m) | No | – |
| Height of understory vegetation (m) | Yes | Roost < random |
| Mean stem diameter of trees ≥ 25 cm in diameter | No | – |
| Number of canopy layers (*n*) | No | – |
| Number of sapling (*n*) | No | – |
| Number of shrubs (*n*) | No | – |
| Number of stumps (no. stumps/ha) | No | – |
| Number of trees in overstory (*n*) | No | – |
| Percent understory cover (%) | Yes | Roost < random |
| Richness of understory (no. species) | Yes | Roost > random |
| Standard deviation of tree diameter (cm) | Yes | Roost > random |
| Stand height (m) | Yes | Roost > random |
| Landscape characteristics | | |
| Distance to capture site (m) | Yes | Roost < random |
| Distance to nearest roadway (m) | No | – |
| Distance to nearest stream channel (m) | Yes | Roost < random |