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A New Approach for Analyzing Bird Densities from Variable Circular-Plot Counts[1]

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ABSTRACT: An approach for calculating bird densities from variable circular-plot counts is described. The approach differs from previous methods in that data from several surveys are pooled and detection distances are adjusted as if all distances were recorded by a single observer under a given set of field conditions. Adjustments for covariates that affect detection distances such as observer, weather, time of day, and vegetation type are made using coefficients calculated by multiple linear regression. The effective area surveyed under standard conditions is calculated from the pooled data set and then used to determine the effective area surveyed at each sampling station under the actual conditions when the station was sampled. The method was validated in two field studies where the density of birds could be determined by independent methods. Computer software for entering and analyzing data by this method is described.

VARIABLE CIRCULAR-PLOT (VCP) counts, also known as variable area surveys or point transects (Buckland et al. 1993), are widely used to estimate the size and trend of forest bird populations (Ramsey and Scott 1979, 1981, Reynolds et al. 1980, DeSante 1981, 1986, Scott et al. 1986). In Hawai'i, where precipitous terrain and dense vegetation make it impractical or impossible to use line transects or other methods, management decisions that may determine where and how species are saved from extinction are based on results of VCP counts. Bird surveys of native forests are conducted at least once every 5 yr on each of the main islands, and several key conservation areas are surveyed annually or even monthly. Considering the time and effort spent conducting surveys and the high cost of management actions that are based upon survey results, it is important that appropriate methods are used to analyze and compare survey data.

VCP counts are a modification of line transect sampling (Buckland et al. 1993). Sampling locations (stations) are systematically spaced along a transect, and the distance to each bird heard or seen by an observer at each station is recorded during a 5- to 8-min sampling period (Reynolds et al. 1980, Scott et al. 1981). A frequency distribution of detection distances for each species is used to develop a detection curve, *g(r),* which gives the probability of detecting a bird at distance r from the observer. A key assumption of the method is that $g(0) = 1$ (i.e., birds at and very near the station are always detected). A primary purpose of counting for 5–8 min is to increase the probability that this assumption is met and to maintain a high probability of detecting a bird close (e.g., <5–10 m) to the station.

The basis of the various methods used to calculate bird densities from VCP counts is the calculation of the effective area surveyed for a particular species at each station. The effective area surveyed is the area for which, if all birds were detected within the area and none beyond, the expected number of birds detected would be the same as the actual count recorded at the station (Buckland et al. 1993). Effective area is calculated from the detection function, taking into account the fact that area increases with the square of distance (Reynolds et al. 1980). Bird density can be calculated as the number of birds detected at a station (including those outside the effective area) divided by the effective area.

An important problem with VCP counts for most species is that it is rarely possible in a single survey to obtain a sample large enough

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for a precise estimate of effective area. Burnham et al. (1980) recommended that studies be designed to detect a minimum of 40 individuals, and Buckland et al. (1993:302) recommended 60–80 detections as a practical minimum. For surveys in oak-pine woodlands of central California, Verner (1985) reported that 533 hr of point-count sampling would be needed to obtain 40 detections for species with the lowest counts. The species of most interest are often those that are uncommon or rare and for which it is difficult or impossible to attain adequate sample size. Furthermore, numerous factors such as different observers, weather, vegetation near the station, and time of day are known to influence the detectability of birds (e.g., Robbins 1981, McCracken 1994). If the effect of these factors is accounted for by taking a subset of the data and calculating an effective area for each subset, sample size is decreased even further. For most surveys, it is impossible to account for the various factors that affect detectability of birds and still maintain adequate sample sizes, even for some common species.

DESCRIPTION OF THE METHOD

In this paper, I describe a new approach for analyzing VCP count data that makes it possible to adjust for the various factors that affect detection distances while maintaining adequate sample size. The method is applied on a species-by-species basis. The approach is a modification of Ramsey et al.'s (1987) method, whereby effective area is treated as a scale parameter for detection areas, and the logarithm of effective area is a link to covariates such as observer, weather, and time of day. Detection distances from many different surveys are pooled and transformed to areas, and multiple linear regression is used to determine the effect of each covariate on detection area. Regression coefficients are used to adjust all detection distances in the pooled data set to a set of standard conditions (e.g., one particular observer in dense forest at 0900 hours when there is no wind or rain), and the effective area surveyed under the standard conditions is calculated using the program DISTANCE (Laake et al. 1994). The density at each station during each survey is calculated by dividing the number of birds detected by the adjusted effective area, after adjusting for observer, weather, and other covariates at the time when that particular station was sampled. The overall density for the species for each survey is then calculated from the density estimates for each station.

Field methods and the assumptions involved in conducting VCP counts have been described previously (e.g., Reynolds et al. 1980, Kepler and Scott 1981, Ramsey and Scott 1981, Scott et al. 1986, Buckland et al. 1993, McCracken 1994) and are not repeated here. Accurate measurement of distances and correct identification of species is needed for reliable estimates of bird density. The importance of observer training and testing (Kepler and Scott 1981, Ramsey and Scott 1981) and recalibration of all observers before each survey cannot be overemphasized.

The first step in analyzing data collected during VCP counts is to enter the species' codes, detection distances, and associated data such as transect and station number, observer's initials, weather conditions, and time of day into a computer file in a standardized format. A separate file is created for each individual survey, which usually consists of data collected by one or more observers over the course of 1 or more days.

Multiple linear regression is used to develop a model that estimates the effective area surveyed at each station as a function of the variables that affect detectability. Data from many individual surveys of a particular study area are pooled to increase sample sizes for uncommon species. Pooling of data from many surveys is valid provided the purpose of pooling is to examine detectability and not directly to estimate density (Ramsey et al. 1987). To correct for the fact that detection areas increase with the square of distance, detection distances are transformed to areas, and multiple linear regression is used to fit the following model (Ramsey et al. 1987):

$$ln(\text{Area}) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots \beta_n X_n \quad (1)$$

where $X_1 \ldots X_n$ are covariates and $\beta_1 \ldots \beta_n$ are regression coefficients that represent the effect of each linearly independent covariate on $ln(\text{Area})$. Ramsey et al. (1987:4) suggested that "the effective area surveyed provides a natural link to the covariates, in the sense that time of day, temperature, etc. directly influence the amount of area that an observer is capable of effectively covering."

The regression coefficient for each covariate is used to adjust each detection distance to a set of standard, "reference" conditions. The reference conditions must be included in the pooled data set, so that predictions are not made outside the range of the data. For example, if detection distances during a series of surveys were recorded by four observers under different weather conditions and at different times, then distances might be adjusted as if all distances were recorded by observer 1 at 0900 hours when cloud cover was 0%, it was not raining, and wind speed was 1 on the Beaufort scale. When all distances are corrected to standard conditions, it is possible to calculate the effective area surveyed under standard conditions based on a relatively large sample size and then to use the same regression coefficients to adjust the effective area surveyed under standard conditions to the area surveyed under the actual conditions at each station when the survey was conducted.

I recommend choosing the observer with the most detections of a species as the reference observer, although the overall density estimate will be the same regardless of which observer is chosen as the reference observer. Some observers may not detect enough individuals of a species to calculate a good adjustment factor. Data for these observers can be dropped from the analysis or combined with those of the reference observer or another observer with similar detection distances before repeating the multiple regression.

For covariates such as observer or vegetation type that are recorded on a nominal scale, it is necessary to create a set of dummy variables that are coded as zero or one in the regression analysis. The number of dummy variables is always one less than the number of categories, because the values will always add to one and the value of one dummy variable can always be predicted from the others. For example, five observer variables would be created for data collected by six observers. If a particular distance was recorded by the reference observer, all five variables would be coded as zero, whereas for any other observer the corresponding dummy variable would be coded as one. The principle of parsimony leads to a regression model with as few variables as possible that adequately explain the data. I recommend retaining all dummy variables in the model unless the sample size for a particular variable is ≤ 15, in which case those data are combined with the reference condition. The decision whether or not to include other variables in the model should be based on the significance of t-tests on the individual regression coefficients. Variables that are nearly a linear combination of other variables (i.e., multicollinearity) should be dropped from the model.

By taking the exponent of both sides of equation 1, effective area can be expressed by the following equation:

$$\begin{aligned} \text{AREA} = \exp(\beta_0) \cdot \exp[\beta_1(x_1 - x_1{}^*)] \\ \cdot \exp[\beta_2(x_2 - x_2{}^*)] \ldots \\ \cdot \exp[\beta_n(x_n - x_n{}^*)] \quad (2) \end{aligned}$$

where $x_1, x_2, \ldots x_3$ are values of the covariates during a survey and $x_1^*, x_2^*, \ldots x_n^*$ are values of the reference conditions. One assumption of the model is that covariates affect area multiplicatively, as in the above equation (Ramsey et al. 1987:9). This assumption was found to be reasonable for observer and vegetational cover effects by Scott et al. (1986). The regression coefficient for each covariate retained in the model is used to adjust each detection distance (i.e., after transforming them to areas) to standard conditions. The program DISTANCE (Laake et al. 1994) is then used to calculate the effective area surveyed under standard conditions, based on the adjusted distances in the pooled data set. The intercept of the multiple linear regression is replaced by the estimate of effective area calculated by DISTANCE from the detection function for the species.

To determine the effective area surveyed at each station, it is necessary to adjust the effective area calculated for standard conditions for the existing conditions (i.e., covariates) when that station was actually surveyed. The same regression coefficients used to adjust detection areas to standard conditions are used to adjust the effective area calculated by DISTANCE to the effective area surveyed at a particular station. For example, if the area surveyed by a particular observer was 20% larger than that surveyed by the reference observer (i.e., $b = 0.1823$, $\exp[0.1823] = 1.20$), the effective area surveyed under reference conditions would be increased by 20% at each station surveyed by that observer to adjust for the observer effect. Adjustments to effective area for other covariates in the final regression model would be made similarly for each station. For each species, density at each station is calculated by dividing the number of individuals detected (including individuals outside the effective area) by the effective area surveyed at that station. The mean and variance of density for each survey can be calculated from the densities for each station sampled during the survey.

EXAMPLE OF THE ANALYSIS METHOD

As an example of the analysis approach, I present data from annual surveys between 1980 and 1995 of the entire range of the Palila (*Loxioides bailleui*), an endangered Hawaiian honeycreeper found in high-elevation woodlands on Mauna Kea Volcano, island of Hawai'i. Palila were counted during 6-min counts each January or February at stations placed at 150-m intervals along 17 randomly placed transects following methods described by Scott et al. (1984) and Jacobi et al. (1996). The known distribution of Palila was stratified into four density strata based on the total number of Palila detected at each station during 16 yr of counts, vegetation boundaries, and elevation.

The initial multiple regression determined the effects of different observers, wind, and time of day on effective area. (Vegetation was similar throughout the Palila's range, and all surveys were conducted when there was no rain.) All detection distances were transformed to areas before analysis. I subtracted 9.0 (the reference time) from all observation times and 1.0 (the reference wind speed) from all wind speed values before running the regression. I selected JDJ as the reference observer because he participated in counts throughout the 16-yr period and his average detection area for Palila was midway among detection areas for all observers. Data for observers with ≤ 25 detections of Palila were pooled with those of the reference observer, resulting in 23 observers with >25 detections of Palila. I created 22 dummy variables for observer, all of which were coded as zero for the reference observer. For a detection by the ith observer, I coded the ith dummy variable as one, with all other dummy variables set to zero.

Wind speed did not significantly affect effective area (as determined by a t-test of the regression parameter divided by its standard error) and was dropped from the regression model ($t = 0.94$, $P = 0.35$). I repeated the multiple regression with detection area as the dependent variable and the 22 dummy observer variables and time as the independent variables. The regression coefficient for observer 1 was -0.33, indicating that the mean detection area for that observer was 72% as large ($e^{-0.33} = 0.72$) as that of the reference observer. The regression coefficient for observer 2 was 0.41; that observer's detection area was $e^{0.41} = 1.51$ or 151% as large as that of the reference observer. The regression coefficient for time of day (-0.16 ± 0.02, $t = -6.61$, $P = 0.0001$) indicates that for each hour past 0900 hours, detection area is 85% ($e^{-0.16} = 0.85$) of that at 0900 hours.

To adjust each detection area to the reference conditions, each area is adjusted by the appropriate adjustment factor for observer and time of day. The sign of the regression coefficient must be reversed to adjust areas to reference conditions. For example, if observer 1 detected a Palila at 1030 hours at 50 m (0.785 ha), the corrected distance would be:

$$0.785 \text{ ha} * e^{0.33} * e^{0.16 * 1.5}$$

$$= 1.388 \text{ ha} = 66.5 \text{ m}$$

This example shows that a detection distance of 50 m by observer 1 at 1030 hours is equivalent to a distance of 66.5 m by the reference observer at 0900 hours.

The effective area for Palila during standard conditions (all distances recorded by JDJ at 0900 hours) was calculated by the program DISTANCE. Distances were grouped into 12 intervals of 17-m width to lessen the effects of heaping (rounding to the nearest 5 m) and errors in estimating distances (Buckland et al. 1993:111). The detection function with the best fit to the standardized detection distances was a Fourier function with an effective detection radius of 64.0 m (effective area = 1.287 ha; $\chi^2 = 4.69$, df = 7, $P = 0.70$). For any station surveyed by JDJ at 0900 hours, Palila density could be calculated as the number of Palila detected divided by 1.287 ha. For other observers and times, it is necessary to adjust the standardized effective area for the conditions when the station was surveyed. As an example, if observer 2 surveyed a station at 0815 hours and detected two Palila, the adjusted effective area would be:

$$1.287 \text{ ha} * e^{0.41} * e^{-0.16 * -0.75} = 2.187 \text{ ha}$$

and the density estimate for that station would be 2/2.187 = 0.91 Palila per ha. For each year, mean Palila density within each stratum was calculated by simply summing the density estimates for each station and dividing by the number of stations. Total population size was calculated by multiplying the mean density estimate for each stratum by the area of the stratum and summing the population totals for the four strata.

FIELD TESTS

There are very few field situations where the true density of forest birds is known. I was able to compare density estimates calculated by the method described in this paper to reasonably accurate density estimates derived by independent methods for two study areas. The first study area was at Keauhou Ranch on the island of Hawai‘i, where the U.S. Forest Service conducted an intensive 5-yr study of forest bird ecology between November 1976 and January 1982 (Ralph and Fancy 1994*a,b,c*). Fifty-five surveys using the VCP method with 8-min counts were conducted beginning in July 1977. Surveys were usually conducted three times each month at 25 stations placed at 100-m intervals (see Ralph and Fancy 1994*b*). As a result of more than 62,000 net hours of banding effort and weekly searches of birds banded with colored bands on a 16-ha gridded study site, the majority of resident individuals were banded and closely monitored during the study. The most tractable species was the ‘Ōma‘o or Hawaiian Thrush (*Myadestes obscurus*), which showed strong site fidelity and was highly sedentary and vocal (Ralph and Fancy 1994*c*). Mean density of ‘Ōma‘o for the 55 surveys was 3.94 ± 0.16 birds per ha, corresponding to 63 ‘Ōma‘o on the 16-ha intensive study site. Adjustments were made only for the 16 different observers, because vegetation was similar at all sampling stations and weather and time data were unavailable. Effective area was calculated from 5000 (the maximum allowed by DISTANCE) detection distances that were randomly selected from 14,230 detections of ‘Ōma‘o. I independently calculated the number of banded ‘Ōma‘o on the study area from the first and last month that an individual was captured or sighted, assuming that the bird remained on the study site during the intervening period. The monthly average of 65.2 ± 3.3 ‘Ōma‘o determined by this method should be a good indicator of the number of ‘Ōma‘o present because all resident ‘Ōma‘o were banded and few unbanded individuals were observed. Furthermore, the median distance from the center of activity to all locations where an individual was captured or sighted was only 43.6 ± 2.5 m (Ralph and Fancy 1994*c*), indicating the sedentary nature of individuals on the study area. I also determined the number of ‘Ōma‘o on the study area from capture/recapture data of birds caught in nets during November–February each year using program JOLLYAGE (Pollock et al. 1990). The number of ‘Ōma‘o calculated by this method was 64 ± 18 for the 5-yr study (goodness of fit test, $\chi^2 = 2.15$, df = 2, $P = 0.34$). There is no difference ($P > 0.05$) among the density estimates (3.94 ± 0.16, 4.08 ± 0.21, 4.00 ± 1.13) calculated by the three independent methods.

The second field test occurred in an isolated stand of māmane (*Sophora chrysophylla* [Salisb.] Seem.) forest at Kanakaleonui, on the eastern slope of Mauna Kea (Fancy et al. 1997). Fieldwork at the site was conducted during 1 yr before and 2 yr after 31 translocated Palila were released at the site in March 1993. The Palila's range at Kanakaleonui was restricted by sharp habitat boundaries. The upper boundary of the study area was at tree line and the lower boundary was bordered by pasture. The northern and southern boundaries of the 2.74-km^2 forested stand were bordered by scrub vegetation and barren lava flows. Most of the Palila at Kanakaleonui were banded, and we were able to search the entire area intensively with 5–10 persons during five surveys when VCP counts were also conducted. The isolation of the study area and the dry, open habitat, coupled with the loud vocalizations and conspicuousness of the Palila, made it possible to determine the number of Palila in the area to within one to three individuals during searches. Before the translocation, we estimated that a maximum of eight Palila occurred at Kanakaleonui. During searches of the area between August 1993 and April 1995, we estimated from sightings of banded birds that 15–20 Palila remained in the area (Table 1). Estimates of Palila density from VCP surveys, after correcting for observer and time of day effects (weather effects did not contribute significantly to the regression model), differed from densities calculated from direct counts by only 1–19% (Table 1). The 95% confidence interval of all five density estimates by the VCP method included the estimate based on direct counts.

DISCUSSION

Verner (1985) discussed the numerous sources of bias involved in counts of birds and concluded that accurate estimation of bird densities is rarely possible and often unnecessary. Numerous studies have described biases caused by undercounting or misidentifying birds (Bart and Schoultz 1984, Bart 1985), failure to detect birds near the station (Verner 1985), movement of birds (Burnham et al. 1980), and other violations of the assumptions of plot counts (Verner 1985, Buckland et al. 1993, McCracken 1994). Verner (1985:292) recommended that we "seriously address the real challenge of finding efficient ways to obtain reasonably accurate density estimates of birds."

For some species, I believe that problems with small sample size or violations of important assumptions make it impossible to obtain accurate density estimates, but for many bird species it is now possible to adjust for factors affecting detectability and estimate density with reasonable accuracy. The work of Buckland et al. (1993) and the program DISTANCE (Laake et al. 1994), in particular, have advanced the science of bird counting considerably. In a recent review and simulation study, McCracken (1994:177) concluded that "Variable area density estimates are reliable when a sufficient number of birds are detected, critical assumptions are valid, and extreme conditions are absent. Furthermore, the variable area survey is robust to many of the factors that Verner (1985) and Dawson (1981) questioned." The method described here overcomes the problem of small sample size for most species. The method makes it possible to pool data from numerous surveys conducted over a period of years by different observers and during different counting conditions, and yet still adjust for factors that affect bird detectability. In addition to the two field validation tests described above, I found that the method provided reasonable estimates of density for several other studies where bird density could be approximated by some other method. I do not believe that this method, or any other method for that matter, gives reliable density estimates for very common (e.g., >8 birds per station)

TABLE 1

COMPARISON OF PALILA DENSITY (BIRDS PER KM^2) AT KANAKALEONUI, HAWAI'I, AS DETERMINED BY VARIABLE CIRCULAR-PLOT SURVEYS AND INTENSIVE SEARCHES OF THE STUDY SITE

SURVEY DATE	STATIONS SAMPLED	PALILA DETECTED	DENSITY BY VCP METHOD		DENSITY BY SEARCH METHOD[a]	% DIFFERENCE
			MEAN	SEM		
July 1992	41	3	2.59	1.46	2.9	10.7
December 1992	40	3	2.86	1.59	2.9	1.4
July 1993	40	7	8.12	3.60	7.3	11.2
January 1994	41	7	7.54	2.94	6.6	14.2
April 1995	40	7	6.54	3.78	5.5	18.9

[a] Minimum number of Palila identified during intensive searches of Kanakaleonui, divided by 2.74 km^2.

species that move quickly through a counting area. Further validation of the method is needed in field situations where the true density of birds can be determined with great accuracy.

COMPUTER SOFTWARE

Three DOS-based computer programs for entering and analyzing data collected during VCP surveys can be requested by sending a formatted diskette to me. The program VCPDATA is a menu-driven program that includes modules for entering data in a consistent format, checking for errors, reformatting data entered in several different formats, and calculating the mean number of birds per station and percentage occurrence of each species at stations sampled during each survey. VCPDATA includes a module that will read a data file and command file and then create a SAS command file to conduct a multiple linear regression.

The program VCPSC reads a pooled data file containing data from several surveys and a file containing regression coefficients from the multiple linear regression, and adjusts detection distances as if all distances were recorded under the standard conditions specified in the command file. The program outputs a file that can be input into the program DISTANCE (Laake et al. 1994) to calculate the effective area surveyed under standard conditions.

The program VCPADJ uses the effective area surveyed under standard conditions, and the coefficients from the multiple linear regression, to determine the density of each species at each station during a survey. The program allows the user to assign stations to different strata, and the mean density or population size within each stratum can be calculated. Confidence intervals are determined by bootstrapping. The program also allows the user to enter the coefficient of variation in effective area surveyed, in which case the effective area surveyed is sampled from a random normal distribution rather than being used as a constant for all stations.

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