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HOW WELL DO CONSISTENTLY MONITORED BREEDING BIRD SURVEY ROUTES REPRESENT THE ENVIRONMENTS OF THE CONTERMINOUS UNITED STATES?

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Abstract. We investigated the degree to which consistently monitored Breeding Bird Survey (BBS) routes represented environmental conditions across the United States. Using 388 models of individual species distributions, we identified eight environmental variables to which birds were particularly sensitive. The nonproportional sampling of these variables would therefore have relatively large impacts on large-scale studies using BBS data. We then used a sampling grid to compare the distribution of these variables in grid cells with and without consistently surveyed BBS routes. We made comparisons nationally, within BBS-defined physiographic regions, and within U.S. states. Not surprisingly, given the geographic variation in the intensity of route coverage, areas with BBS routes differed from those without at a national scale. In general, higher elevations and drier climates were poorly represented by BBS routes, and northeastern deciduous forests were overrepresented. In contrast, we found few large differences within most BBS-defined physiographic regions and within most states. However, there were a few large differences in a small number of regions and states, many of which had relatively few BBS routes. We conclude that the weighting factors supplied by the BBS will likely address most differences in sampling densities at a national scale. However, for studies not using these weights, studies investigating specific subsets of the BBS data, and studies that include states with relatively few BBS routes, we strongly suggest resampling analyses to determine any bias incurred by uneven sampling and, if necessary, the subsequent development of study-specific weighting factors.

Key words: Breeding Bird Survey, elevation, northeastern deciduous forests, precipitation, predictive models, sampling, species abundance.

¿Cuán Bien Representan las Rutas Consistentemente Censadas por el Conteo de Aves Reproductivas los Ambientes de Estados Unidos?

Resumen. Investigamos el grado en que las rutas censadas anualmente por el Conteo de Aves Reproductivas (BBS, por sus siglas en inglés) representan las condiciones ambientales en los Estados Unidos. Utilizando 388 modelos de distribución individual de especies, identificamos ocho variables ambientales a las cuales las aves fueron particularmente sensibles. El muestreo no proporcional de estas variables podría tener un fuerte impacto sobre estudios a gran escala que utilizan los datos del BBS. Luego utilizamos una grilla de muestreo para comparar la distribución de estas variables en las celdas de la grilla con y sin rutas consistentemente monitoreadas por el BBS. Realizamos comparaciones a nivel nacional, dentro de las regiones fisiográficas definidas por el BBS y dentro de los estados. De manera no sorprendente, dada la variabilidad geográfica en la intensidad de cobertura de las rutas, las áreas con rutas del BBS difirieron de aquellas sin rutas a nivel nacional. En general, las elevaciones más altas y los climas más secos estuvieron pobremente representados por las rutas del BBS, y los bosques deciduos del noreste estuvieron sobre-representados. De manera contrastante, encontramos pocas diferencias dentro de las regiones fisiográficas definidas por el BBS y dentro de los estados. Sin embargo, hubo algunas diferencias considerables en un pequeño número de regiones y de estados, muchos de los cuales tenían relativamente pocas rutas del BBS. Concluimos que los factores de peso que el BBS provee probablemente dan cuenta de la mayoría de las diferencias en las densidades de muestreo a una escala nacional. Sin embargo, para los estudios que no utilizan estos pesos, los estudios que investigan subconjuntos específicos de datos del BBS y para los estudios que incluyen estados con relativamente pocas rutas del BBS, sugerimos con énfasis un análisis de re-muestreo para

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determinar cualquier sesgo que pueda presentarse debido al muestreo desigual, y si es necesario, el desarrollo subsiguiente de factores de peso específicos para el estudio.

INTRODUCTION

The Breeding Bird Survey (BBS) is an extensive roadside survey program organized by the U.S. Geological Survey (USGS) Biological Resources Division and the Canadian Wildlife Service. The goal of the BBS is to provide long-term data on population trends of bird species across the U.S. and Canada (Robbins et al. 1986). The program, which started in 1966, currently maintains in excess of 4000 survey routes, approximately 3000 of which are surveyed each summer. Routes are randomly located within 1° blocks of latitude and longitude and stratified by state or province. Routes are 40 km long and consist of 50 point-count stops at 0.8-km intervals. The BBS has provided invaluable information for the study and conservation of many bird species (Robbins et al. 1989, Sauer and Droege 1990, Brown et al. 1995, Villard et al. 1995, Curnutt et al. 1996, Flather and Sauer 1996, Sauer et al. 1996, Koenig 1998) and is the most extensive monitoring program for vertebrates in North America.

An important requirement of a monitoring program is that it adequately samples the range of species and areas it purports to cover (i.e., that its sample coverage is representative of its target inferential universe). Many potential biases in the BBS have previously been investigated, including the effects of the diurnal nature of the survey (Robbins et al. 1986), observer biases (Faanes and Bystrak 1981), and biases introduced by roadside sampling (Droege 1990, Hanowski and Niemi 1995, Keller and Scallan 1999). However, the extent to which the environments surrounding the individual routes represent the area considered sampled for birds has not previously been investigated, except in the context of roadside sampling bias. A recent peer review of the BBS found this to be a critical issue that remained to be addressed (O'Connor et al. 2000).

The degree to which a set of BBS routes represents environmental variation is likely to be scale dependent. The number of available observers in each state determines the density of BBS routes, so more populated states have more BBS routes (Droege 1990). Because human population density is not independent of environmental conditions (Bartlett et al. 2000), it is likely that different environments are sampled with different intensities by the BBS, in effect weighting the bird populations from different environments differentially. On the other hand, because BBS routes are located randomly within 1° blocks of latitude and longitude (Droege 1990), sampling is likely to be more representative of the environmental conditions over areas comparable in extent to degree blocks (roughly 8000–11 000 km^2). As previously noted, the location of routes within degree blocks is not entirely random. Routes are located along roads and are known to under-sample some systems such as wetlands and alpine zones.

The BBS provides weighting factors for routes based on the state stratification to account for the differential sampling densities (Sauer et al. 2003). Although many analyses that use BBS data are conducted within states or provinces (Igl and Johnson 1997, Schmidt 2003), several others are conducted over larger areas. Many of these larger-scale analyses use the weights provided by the BBS to account for the differential sampling densities (e.g., Peterjohn et al. 1995). Because not all routes are surveyed each year, often these analyses also weight routes by the frequency with which they are surveyed (Geissler and Sauer 1990, Peterjohn et al. 1995). If routes are representative of environments at a state level, these weighting factors should produce a representative sample of the environments across a given area. However, because some routes are run so infrequently as to be excluded from analyses and because many studies using BBS data do not apply one or both of the weighting factors (e.g., Curnutt et al. 1996, O'Connor et al. 1996, Peterson 2001), even if routes do represent statewide environments, they may not adequately represent the environments of a given area of interest.

The possibility of differential representation of avian habitats within the BBS has significant ramifications for studies using BBS data. Consider a species for which core habitat is sampled to a lesser degree than is more marginal habitat. If the species is in decline, the marginal habitat will experience more drastic decreases in population levels as the remaining birds move into core habitat and buffer changes in population levels there (Wilcove and Terborgh 1984, O'Connor and Fuller 1985). Thus trend analyses for such a species would tend to overestimate the magnitude of declines. A similar argument holds for increases. Conversely, if the core habitat of a species is sampled more intensively than the marginal habitat, both declines and increases will be underestimated.

Our objective was to investigate the degree to which a set of consistently surveyed BBS routes represented the environmental conditions over three different spatial extents within the conterminous United States. We use the phrase ''consistently surveyed'' to indicate that our study did not involve a random sample of the BBS routes but rather a subsample of consistently covered routes. We conducted our assessment at the scale of the conterminous U.S., at the scale of BBS-defined physiographic regions (Bystrak 1981), and at the scale of individual states. We examined the problem with a database used previously in a number of national models of avian species richness (O'Connor et al. 1996, 1999, O'Connor and Jones 1997). Although this analysis would ideally address the entire extent of the BBS, including Canada, we restricted our analyses to the conterminous U.S. for the sake of consistency in environmental datasets.

We used a set of 388 individual species models to identify a subset of 195 environmental variables whose unequal representation by BBS routes would likely have significant effects on the outcome of large-scale avian studies. These variables were the most influential variables in the individual species models. Thus, they were those most likely to affect large-scale analyses of individual species abundances if they were disproportionately sampled by the BBS. We compared the representation of the selected variables at sites with and without consistently monitored BBS routes at a national and at two regional scales. By analyzing only those environmental variables that were most likely to affect the prediction of individual species distributions, we avoided wholesale ''data mining'' that would likely exaggerate any estimate of the misrepresentation of environments by BBS routes.

METHODS

We analyzed all BBS routes that were visited at least seven times between 1981 and 1990. At least 7 years of data were needed to standardize for survey effort (i.e., to correct for the increase in the number of species detected as the number of annual surveys considered increased; RJO, unpubl. data). A 10-year period was chosen because examination of results from long-running BBS routes showed that the changes in species tallies increased systematically over the first 10 years, thereafter stabilizing (M. T. Jones et al., unpubl. data). In addition, routes with 7 to 9 years of data could be reliably adjusted to a 10-year total, but routes with fewer than 6 years of data could not. The 1981–1990 decade was chosen to best coincide with the environmental data at our disposal (Advanced Very High Resolution Radiometer [AVHRR] data from which land-cover classifications and land-cover pattern metrics were generated, and climate and weather data). These qualifications constrained our analyses to 1189 BBS routes. For a full description of the BBS protocol see Robbins et al. (1986).

We used a grid of 12 518 hexagonal cells, each approximately 640 km^2 in area, to sample environmental conditions at all three spatial extents (White et al. 1992). These cells, with center-to-center distances of about 27 km, encompassed most of the landscape directly surrounding the 40-km BBS routes. Hexagons with BBS routes were identified using the starting point of the routes. We analyzed remotely sensed environmental data known to be pertinent both to the study of avian habitats and to environmental change (Hunsaker et al. 1994, Flather and Sauer 1996, Freemark et al. 1995), including data on climate, topographic condition, land use, land cover, and landscape pattern. A detailed account of the data used in this study can be found in O'Connor et al. (1996). Briefly, climate variables included January and July temperatures (at 1-km resolution) and annual precipitation levels (modeled at 10-km resolution and resampled to 1 km) obtained from the Historical Climate Network (1996) database. For each hexagon, mean, maximum, and minimum temperatures and precipitation levels were computed across the 1-km^2 pixels. In addition, we calculated mean, maximum, and minimum seasonality (the difference between July and January temperatures). Topographic data for each hexagon included both elevation (mean, maximum, minimum, and range) from the USGS Digital Elevation Models (EROS Data Center 2000), and river lengths (calculated separately for large, perennial, intermittent, and braided rivers). Land-use variables (modeled at 1-km resolution but aggregated to hexagons) included road density (km of highway and km of secondary roads) and the proportion of federally owned land in each hexagon. Land-cover data consisted of the proportion of each hexagon occupied by each of 160 land-cover classes (159 classes defined by Loveland et al. [1991] and an additional urban class). Finally, we used 10 landscape-pattern metrics including mean patch size, land-cover type richness, fractal dimension, dominance, contagion, Simpson's diversity index, edge-type richness, sum of edge distances, and maximum edge length.

ANALYSES

First, we determined for which of the 195 environmental variables unequal sampling would have the greatest impact on large-scale analyses using BBS data. We did this by identifying the most influential variables in each of 388 statistical models built to predict individual species' distributions. The models were regression trees built using subsets of the environmental variables as predictors and a probability of presence based on BBS route data as the response (Mathsoft 1997, O'Connor et al. 1999, Hahn and O'Connor 2002, Matthews 2003). The species used in these analyses were those for which the data collected at the 1189 routes over the 10-year period allowed us to build reasonable regression-tree models (i.e., models, which after pruning with a cross-validation technique had at least two terminal nodes). This selection criterion may have prevented us from identifying some important environmental variables for rarer birds and birds that are generally poorly represented in the BBS data. However, the 388 models provided an adequate assessment for a wide range of species.

Regression tree analysis and its categorical equivalent, classification tree analysis, are flexible modeling techniques that allow for the investigation of a large number of explanatory variables. In addition, the analyses deftly model nonlinear relationships and interactions among variables, even when these cannot be specified *a priori* (Clark and Pregibon 1992, De'ath and Fabricius 2000). Classification and regression trees work by recursively partitioning data into smaller and more homogenous groups with respect to a response variable (Breiman et al. 1984, Clark and Pregibon 1992, Venables and Ripley 1994). Each split of the data is made by determining which explanatory variable and which point along that variable's ordered distribution divides the sample into two groups that are as homogenous as possible with respect to (in our case) the abundance of an individual species. Splits are made until all subdivided groups of data are homogeneous with respect to the response variable, or until some stopping criteria are met. Models are then "pruned" back to a meaningful size using one of several methods (Miller 1994). We used a 10-fold cross-validation pruning technique to reduce trees (Venables and Ripley 1994).

The variable used in the first (or "root") split in a regression tree model is often the most influential variable (i.e., the one that accounts for the most deviance in the data). We used the first split in each of the 388 models to determine which variables had the greatest influence on individual species distributions. Of the 388 models, there were 143 unique variables that performed the first splits. We approximated the derivative of each species' probability of presence with respect to this root predictor variable as the difference in the mean probability of presence in the two groups of data generated by the split divided by the difference in the mean predictor value in each data subset, i.e.,

$$\frac{dA}{dP} = \frac{A_l - A_r}{P_l - P_r}, \qquad (1)$$

where A_l and A_r are the mean abundances in the left and right subsets from the (binary) root split in the tree model. P_l and P_r are the corresponding mean values of the predictor variable for that split and dA/dP is the derivative of the rate of change of abundance with change in the predictor (for a linear trend, this would be the slope of the regression equation). We then multiplied this derivative by the difference in the mean value for the predictor variable in all hexagons with (P_b) and without (P_n) BBS routes. This allowed us to estimate the extent to which the prediction of bird abundance would be in error given the representation of the root predictor variable in sampled BBS routes as follows:

$$A_b - A_n = \frac{dA}{dP}(P_b - P_n), \qquad (2)$$

where A_b and A_n represent the abundances of birds in sites, respectively, with and without

BBS routes. The larger the discrepancy in these values, the larger the potential error in prediction caused by the disproportionate sampling of environments by the BBS routes in our analysis. Thus, although a moderate error in estimated abundance can arise either because a species is particularly sensitive to the predictor variable (a large derivative) or because the predictor variable differs substantially between sites with and without BBS routes (large $P_b - P_n$), more substantial errors will only occur when both measures are large. Here we report only those root variables that produced an error in excess of 10% in at least one of the 388 models.

For our national-scale analysis, we computed the mean values for the subset of influential variables across the groups of hexagons respectively with and without BBS routes. We report the means as well as the between-group differences and the standard errors of those differences. We computed the standard error of the difference in two means as the square root of the sum of the variances of the two groups (Zar 1984). In addition, we performed *t*-tests (with Welch approximations for variables with unequal variances) for each of the selected environmental variables.

The between-group difference in means and its corresponding standard error was an inadequate measure for the two variables for which most of the values were zeros (e.g., the variables that represented the percentage of a hexagon covered by a particular land-cover type). For these variables we calculated the difference in the means for all nonzero values as well as the difference in the percentage of hexagons with and without BBS routes that had nonzero values.

These univariate analyses ignored possible correlations and interactions among the selected environmental variables. It is possible that any underrepresentation of the selected variables, in conjunction, could have a more substantial effect on analyses than that predicted by the univariate comparisons. In contrast, if the variables are correlated, the joint effects of their misrepresentation would not be much greater than any estimates provided by our univariate analyses. We used a multivariate analysis to investigate potential interactions among the selected variables. We used classification tree analysis to build a multivariate model that discriminated hexagons with BBS routes from those without BBS routes based on the selected environmental variables. The classification tree analysis facilitated the identification of any complex interactions among the explanatory variables without requiring the *a priori* specification of those interactions. Classification trees are also adept at handling correlated explanatory variables. Because only one variable enters the model at a given split, it is not possible for variables in the model to account for identical portions of the variance in the response variable. If the classification tree built to discriminate sites with BBS routes from those without had many variables and explained a relatively large proportion of the deviance in the data, we would conclude that there are potential interactions among variables and that the effects of differential representation might be larger than estimated by our univariate analyses. Conversely, if the tree model had relatively few variables and explained only a small proportion of the deviance in the data, we would conclude that there are no strong complex interactions among the variables.

For our regional investigations, we analyzed the difference between hexagons with and without consistently monitored BBS routes within (1) 62 out of 64 BBS-defined physiographic regions and (2) 47 of the 48 conterminous U.S. states. We eliminated two regions and the state of Rhode Island, each with fewer than two consistently monitored BBS routes, from the analyses. Because the number of hexagons with and without BBS routes differed by physiographic region and by state, the power of any statistical analyses conducted in each of the various spatial units also varied. We report the mean differences in sites with and without BBS routes as well as the 95% confidence intervals on those differences. Although we had less statistical power for analyzing the differences among hexagons with and without BBS routes in the more sparsely sampled regions and states, we included them in our analyses because these areas are likely to be most susceptible to uneven sampling. As in the national-scale investigation, we used classification tree analysis to investigate any multivariate relationships within each physiographic region and state.

RESULTS

The percentage of the hexagons in each physiographic region that contained consistently monitored BBS routes from 1981–1990 varied with region and ranged from 0% to 40% (Fig.

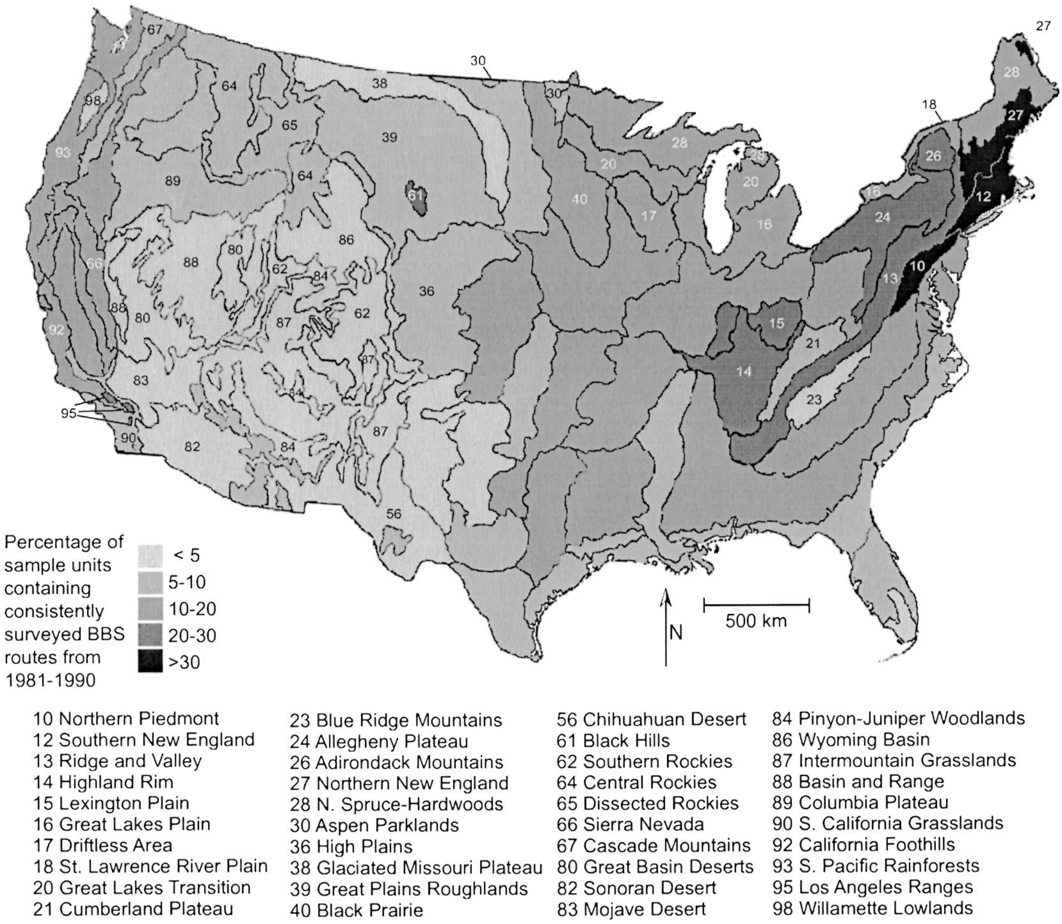

FIGURE 1. Map depicting the percentage of 640-km^2 hexagonal sampling units in each of 64 BBS-defined physiographic regions in the U.S. for which a consistently surveyed BBS route was in operation between 1981 and 1990. The names of physiographic regions are only provided for those regions mentioned in the text. See Sauer et al. (2003) for the identification of the regions not listed here.

1). The Willamette Lowlands was the only region that had no consistently monitored BBS routes in our sample. Habitats peculiar to that region were therefore unrepresented in the BBS sample under consideration. The northeastern U.S., particularly New England, had a high density of BBS routes, thus overrepresenting any habitats differentially present there. In contrast, most physiographic regions in the West (except those in California and coastal regions of Oregon and Washington) had low densities of survey routes. Two exceptions to this pattern in the West were the relatively small Black Hills and Los Angeles Ranges regions, which had high proportions of hexagons with BBS routes. The Southwest had particularly low densities of routes; fewer than 5% of the hexagons in each region contained a BBS route from our sample. The pattern of route density across the states was similar to that portrayed by the physiographic regions (Fig. 2). The percentage of hexagons with consistently monitored routes ranged from less than 1% in Nevada to 59% in Connecticut and Maryland.

Our derivative analysis using the 388 individual species models identified eight environmental variables that produced at least a 10% error in predicted probability of presence in at least one model as a result of the difference in their representation in hexagons with and without BBS routes (Table 1). Models for 41 species were susceptible to this potential error of at least

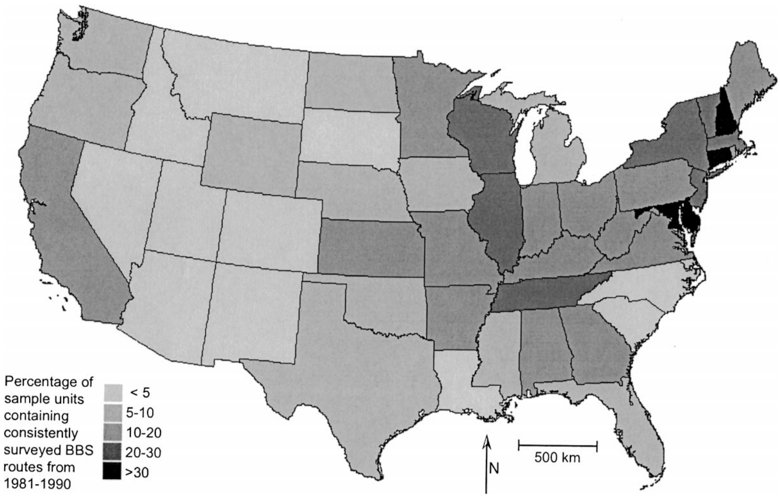

FIGURE 2. Map depicting the percentage of 640-km^2 hexagonal sampling units in each of 48 states for which a consistently surveyed BBS route was in operation between 1981 and 1990.

10%. All other variables we considered, therefore, either differed little between hexagons sampled and unsampled by the BBS or were variables to whose variation few species were sensitive. Our eight sensitive variables formed the first regression tree split, and therefore were likely the most influential, in 70 of the 388 models. These variables represented different measures (minimum, maximum, and mean) of precipitation and elevation, as well as two land-cover types: forage-hay-woodlot mosaic and northeastern deciduous forest (land-cover classes 52 and 93, respectively, from Loveland et al. 1991). Although only 11% of the species we examined were likely to be highly susceptible to differential sampling of these variables, because the distributions of many birds are associated with elevation and precipitation, analyses involving

TABLE 1. Differences in eight environmental variables measured in 640-km^2 hexagonal sampling grid cells with and without consistently surveyed BBS routes. Variance in mean values is presented as the SE of the difference between means of hexagons with and without BBS routes.

Environmental variable	Mean in hexagons with BBS routes	Mean in hexagons without BBS routes	Difference in means ± SE	P[a]
Climate				
Minimum precipitation (mm)	871	690	181 ± 11	<0.001
Maximum precipitation (mm)	1055	887	168 ± 16	<0.001
Mean precipitation (mm)	945	770	175 ± 12	<0.001
Topography				
Minimun elevation (m)	303	595	–292 ± 13	<0.001
Maximum elevation (m)	678	1063	–385 ± 22	<0.001
Mean elevation (m)	458	787	–329 ± 16	<0.001
Land cover				
Forage crops, hay, and woodlots (%)[b]	13.3[c]	11.0[c]	2.3 ± 0.8[c]	0.006
Northeastern deciduous forest (%)[d]	21.4[c]	15.0[c]	6.4 ± 1.5[c]	<0.001

[a] Results from *t*-tests (with Welch approximations for variables with unequal variances).
[b] Land-cover class 52 from Loveland et al. (1991).
[c] The means and the difference in the means presented for these variables were calculated for all nonzero values only.
[d] Land-cover class 93 from Loveland et al. (1991).

other species are likely to be susceptible to differential sampling to some degree.

Our national univariate analyses revealed large differences in these variables in hexagons with and without BBS routes (Table 1). BBS routes were more representative of areas receiving more precipitation (hexagons with BBS routes received on average 23% [175 mm] more precipitation per year) and of lower elevations (BBS hexagons had an average elevation 42% [329 m] lower than non-BBS hexagons). Given the high intensity of sampling in the Northeast in general, it is not surprising that more hexagons with BBS routes had northeastern deciduous forests (18% more hexagons) and of all the hexagons that had northeastern deciduous forests, those with BBS routes had 6% more of this forest type than those without BBS routes. Similarly, hexagons with BBS routes more often contained the mixed land-cover type consisting of forage crops, hay, and woodlots (21% more hexagons) than did hexagons without BBS routes.

In the national classification tree model we constructed to investigate possible interactions among the eight environmental variables, only two of the variables (minimum precipitation and the percentage of northeastern deciduous forests) were significant and together they explained only 7% of the total deviance in the data. This small proportion of the deviance predicted by their inclusion in the model shows that they have little classificatory power, despite the large differences highlighted in our univariate analyses (Table 1). The small number of variables included in the models also implies that the differences in hexagons with and without BBS routes were without any complex, non-linear interactions among the eight variables examined.

Our univariate analyses for the 62 physiographic regions revealed few large differences between hexagons with and without BBS routes within each of the regions (Fig. 3). As one might predict based on the smaller amount of variability expected at smaller extents, differences between hexagons with and without BBS routes were generally smaller within physiographic regions than they were nationally (compare Fig. 3 and Table 1). However, a small number of physiographic regions showed large differences between hexagons with and without BBS routes (Fig. 3). The largest of these differences were in regions with relatively few BBS routes. The two largest differences in mean elevation were found in the Sierra Nevada and Sonoran Desert regions, in which BBS routes were on average 281 and 268 m lower in elevation, respectively, than areas without routes. The South Pacific Rainforests and the Central Rockies were the two regions with the largest differences in average precipitation. On average, sites with BBS routes in the South Pacific Rainforests received 235 mm less annual rainfall than sites without BBS routes. In the Central Rockies, sites with BBS routes received 203 mm less annual rainfall than sites without BBS routes. The most notable differences in land cover were in the Cumberland Plateau, Southern New England, and the Blue Ridge Mountains. Sites with BBS routes in the Cumberland Plateau contained on average <1% northeastern deciduous forest, 2% of that forest type found at sites without BBS routes (which on average, were composed of 10% northeastern deciduous forest). In contrast, sites in Southern New England and Northern New England, respectively, contained 2 and 1.5 times the area of this forest type than sites in these regions without routes.

Our univariate analyses for the 47 states also revealed only a relatively small number of states with substantial differences in areas with and without consistently monitored BBS routes (Fig. 4). In general, the states with the fewest BBS routes showed the largest differences. The largest differences in average elevation were in Colorado, where sites with BBS routes were 450 m lower than sites without routes, and in Nevada, New Mexico, and South Dakota, where sites with BBS routes were respectively on average 330, 309, and 260 m higher than sites without BBS routes. The differential representation in the latter three states was not statistically significant (95% CI include 0; Fig. 4), but we feel they are worthy of mention due to the extremely small samples sizes for these states. The largest differences in mean precipitation were in Nevada and California, in which sites with BBS routes respectively received 265 and 173 mm more annual precipitation on average than sites without BBS routes. The largest differences in land cover were seen in Michigan, where sites with BBS routes had roughly two times the area of mixed forage crops and woodlots found in sites without BBS routes, and in Massachusetts where sites with BBS routes had roughly 2.5

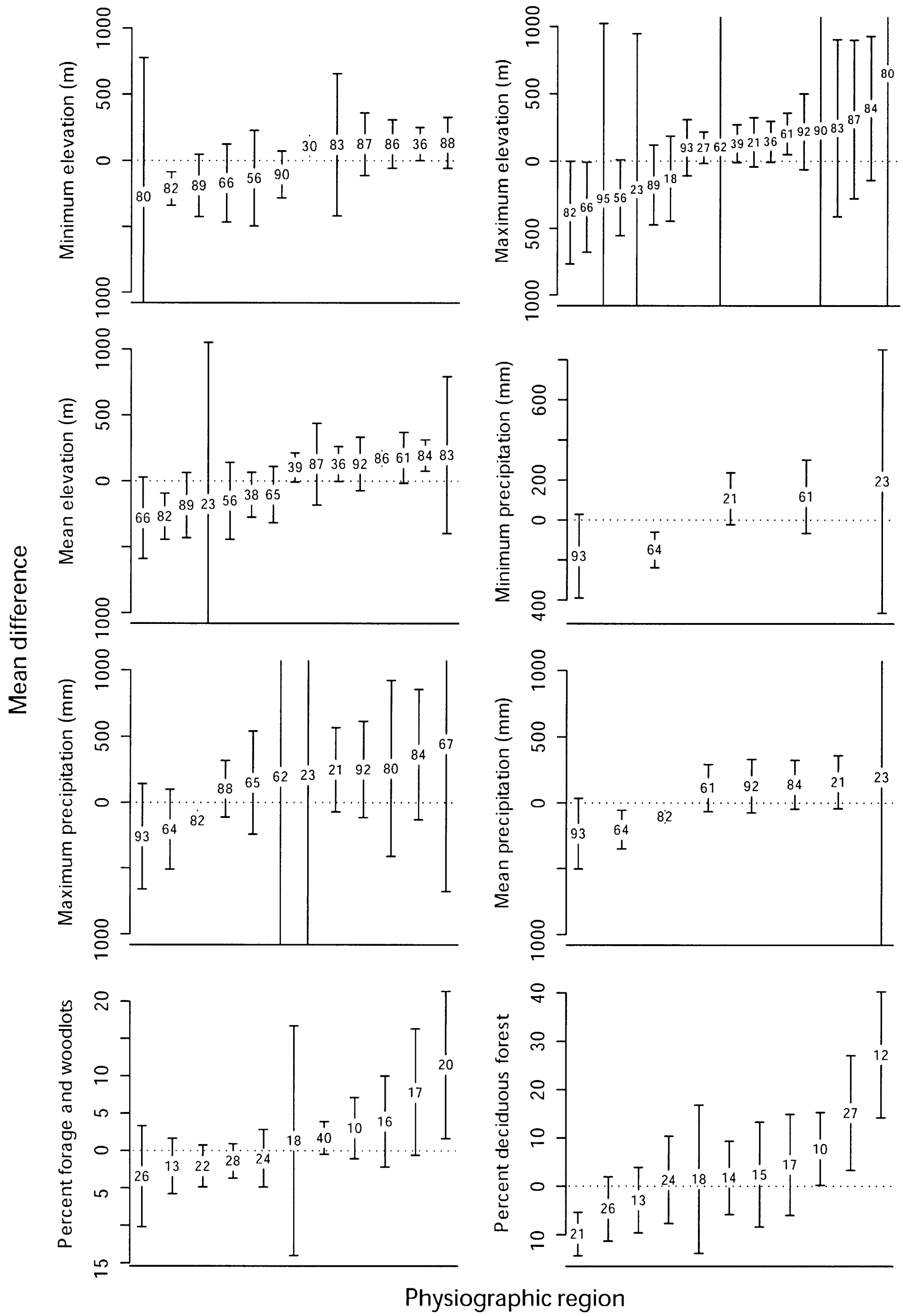

FIGURE 3. Plots of the mean difference in eight environmental variables in sites with and without consistently monitored BBS routes in 64 BBS-defined physiographic regions. The center of each bar (number corresponds to physiographic regions in Fig. 1) represents the mean difference; bars depict 95% CI. The horizontal dotted line marks zero mean differences; mean differences that do not overlap this line are statistically significant. Points above the zero-line indicate differences in which values at sites with BBS routes were greater than values at sites without BBS routes. Only absolute differences in excess of 100 m in elevation, 100 mm in precipitation, and 1% land cover are plotted.

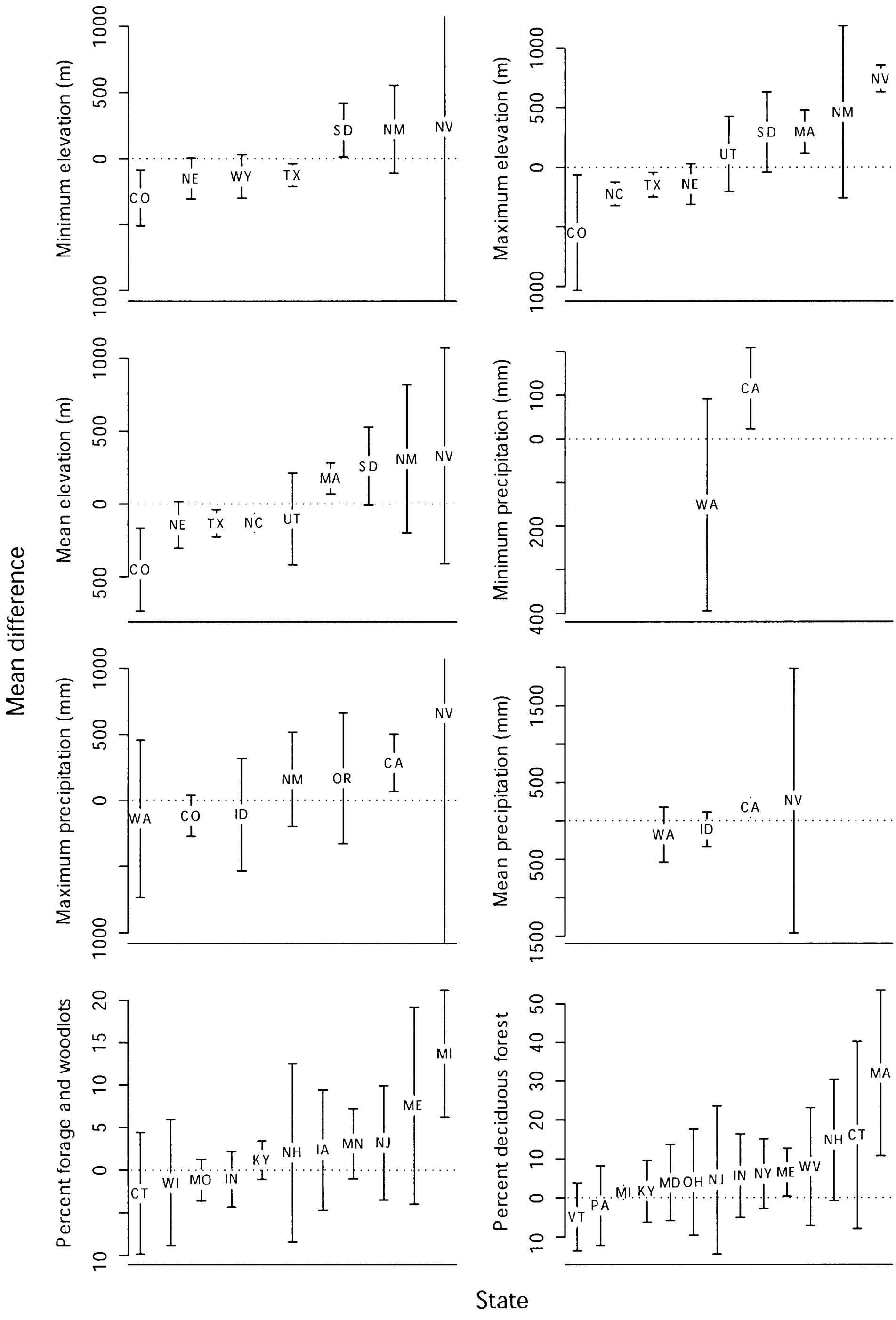

FIGURE 4. Plots of the mean difference in eight environmental variables in sites with and without consistently monitored BBS routes in the states of the conterminous U.S. The center of each bar (marked by the two-letter abbreviation for each state) represents the mean difference; bars depict the 95% CI. The horizontal dotted line marks zero mean differences; mean differences that do not overlap this line are statistically significant. Points above the zero-line indicate differences in which values at sites with BBS routes were greater than values at sites without BBS routes. Only absolute differences in excess of 100 m in elevation, 100 mm in precipitation, and 1% land cover are plotted.

times the area of northeastern deciduous forest found in sites without BBS routes.

None of the classification tree models built to investigate interactions among the eight environmental variables within any of the physiographic regions or states proved to be significant.

DISCUSSION

Our results indicate that the degree to which BBS routes consistently surveyed from 1981 to 1990 were representative of different environments varied with the spatial extent of the analysis. Our analysis of environmental derivatives indicated that a risk of relatively large bias in abundance estimates may arise in BBS studies involving a small set of environmental variables unevenly sampled nationally, notably elevation, precipitation, and two particular land-cover types. The magnitudes of these errors are likely to vary with each particular study, with studies covering large geographic areas (e.g., O'Connor et al. 1996, Curnutt et al. 1996, O'Connor and Jones 1997, Peterson 2001) being most susceptible. The lack of large differences within most physiographic regions and most states means that most large-scale analyses that employ BBS weighting factors to account for different state-level route densities (e.g., Sauer and Link 2002) and most statewide or regionwide analyses (e.g., Igl and Johnson 1997, Herkert 1997) will not be subject to large errors through differential environmental representation.

However, the results from our regional and state analyses indicate that some environments in a small number of states and physiographic regions are likely to be misrepresented by consistently monitored BBS routes. These differences were largest in the states and regions with fewer consistently monitored routes. Studies conducted in these states and regions run the risk of incurring bias related to the uneven sampling of environments. The predetermined BBS weighting schemes that can be applied to states will not account for these errors when these states are included in multistate analyses.

Because the BBS routes are stratified by state, the differences we found at the national scale as well as within physiographic regions largely reflect the fact that most regions span multiple states (Peterjohn et al. 1995). Differences within states, on the other hand, may reflect differences in the frequency with which individual routes are surveyed. Robbins et al. (1986) noted that routes closer to major human population centers are more likely to be surveyed in a given year than routes farther from population centers. Thus in some states, the locations of our consistently monitored BBS routes may be biased with respect to human population density. This bias is likely reflected in the within-state differences we found between areas with and without consistently surveyed routes.

There are at least two relatively simple ways in which future studies can guard against any potential bias related to uneven sampling of specific environments by particular sets of BBS routes. Both rarefaction and weighting can address the issue of unequal sampling across strata. The first of these techniques, rarefaction, involves removing samples from strata with more samples to produce a population that more evenly represents all strata. Rarefaction, or subsampling, can be used as a simple screen to determine whether the distribution of samples in the full dataset is biasing the results of an analysis. Although the rarefied data can be used in the final analysis, doing so results in a loss of data. Depending on the type of analyses being conducted, the second technique, the weighting of samples, can be used to address uneven sampling across strata and thus provide better representation of some environments. Determining the appropriate set of weights can be difficult. For studies that use data from a large portion of the BBS routes in a given area, the BBS-defined weighting factors will likely provide adequate weights for most areas, with the likely exception of those states for which we noted large differences in areas with and without consistently monitored BBS routes. For subsamples of BBS routes for which these weights may not apply, we suggest relatively simple analyses akin to some of those presented here to determine whether alternative weighting schemes are necessary. At the very least, these analyses can provide an estimate of the limitations or bounds that should be placed on the conclusions drawn from any given analysis.

There are also at least two ways in which the issue of underrepresentation of certain environments can be addressed with the design and application of the BBS. First, by increasing the route density in many of the western states, many of the underrepresented environments will likely be better covered (O'Connor et al. 2000). Second, more consistent monitoring of routes and environments farther from population centers might be achieved by encouraging the more regular monitoring of more infrequently visited routes. Although the BBS is clearly constrained by the volunteer nature of the program, both of these are potentially achievable goals.

There are several factors that will affect the degree to which any given set of BBS routes represents the area in question. As our analyses have revealed, the location and extent of the study region will influence the degree to which a given set of BBS routes evenly represents local environmental conditions. In addition, the timeframe over which a study is conducted is likely to influence conclusions about the representativeness of the BBS. The present analysis used only survey routes from 1981–1990, and it is quite possible that the distributions of BBS routes in earlier or in later years have been different. However, the sampling locations of BBS routes are constrained by the geographic and physiographic stratification built into the BBS design and this constraint, coupled with the limited magnitude of the differentials detected here, makes it unlikely that a huge mismatch between BBS and non-BBS sites can develop. The greatest potential for change is that the movement of people within the U.S. may alter the distribution of observers and therefore the intensity with which particular environments are sampled in the future. Present demographic trends, for example, show movements of people out of the central U.S. and into southeastern coastal regions and southwestern counties (Mageean and Bartlett 1999). Such movements may alter the distribution of available observers and eventually the distribution of BBS routes. These redistributions are however, open to remedy by a future adjustment of regional sampling intensities.

Moreover, it is well known that changes in the size of a sample grid can affect the estimation of the occurrence of a species (Greig-Smith 1952). At finer spatial resolution (grain), therefore, differentials in the representation of environmental conditions may differ yet again in magnitude. Roadside bias inherent in the BBS sampling design can result in differential representation of very local environments (Keller and Scallan 1999) in a way that would not be detected in our analysis. It follows that although our coarse-grained (640-km^2 hexagons) analysis demonstrated that the spatial extent of a given set of BBS data will likely affect the degree to which the set represents the environments in the region of interest, studies with large spatial extents need to be aware that their conclusions are also vulnerable to differentials in fine-grained environmental features.

In summary, given the BBS sampling design, it was no surprise that we found uneven coverage of environments at a national scale. The fact that our regional and statewide analyses generally revealed few instances of uneven coverage at these scales indicates that BBS-supplied weighting factors will likely account for most large-scale differences in sampling density. Our analyses do, however, raise concerns about the degree to which BBS routes are representative of the environments in a small number of states and regions with relatively few routes. At the very least, for studies using BBS data, we recommend investigating the distribution of the BBS routes used and performing a simple resampling exercise to determine the degree to which uneven sampling might affect the study results.

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