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Electronic Supplementary Material

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 Title:

Effects of bird community dynamics on the seasonal distribution of cultural ecosystem services

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Appendix S1: Supplemental Methods

Predictor variable: data collection and preliminary analysis

Environmental variables included local and landscape building density, land cover diversity, tree cover, vegetation structural diversity, estimated annual productivity, and elevation. Annual productivity and elevation were extracted at the center point of each study site. The remaining variables were extracted at various buffer sizes (100 m, 200 m, 300 m, 400 m, 500 m, 750 m, 1000 m) around the center of each study site to test for differences in the effect of landscape extent on bird communities. We used univariate regression and Akaike's Information Criterion (AICc; Burnham and Anderson 2002) to determine at which scale each environmental variable had the strongest relationship with bird CES indicator variables.

Digitized building footprints from county governments were used to locate each building (Graves et al. 2017a). Building density at local scales (100 – 200 m) has a significant effect on breeding bird occupancy within the study area (Lumpkin and Pearson 2013). We use 100-m radii in this study because preliminary data analyses revealed stronger univariate relationships between bird species richness and building density at 100 m than 200 m. We also tested for effects of building density within 1000 m of the study site center, since birds may be responding to broader scale habitat variables.

Discrete-return LIDAR data were collected in winter 2005 (NCDEM 2006) for the entirety of the study area. Vegetation height was measured from LIDAR first returns by subtracting the elevation of a bare-earth digital terrain model, derived from the same LIDAR data set, from the elevation of each return (Graves et al. 2017a). We excluded returns within digitized building footprints. Vegetation height was used to calculate vegetation structural diversity and tree cover as described in the Main Text.

Maps of predictor variables

Input layers were created for each predictor variable in order to project landscape CES supply

using the *predict* function in the *raster* package for R. All input layers were standardized to z-

scores based on the mean and variance of the training dataset (n=56) and referenced to the same

projection (Albers Equal Area) and 100-m grid cell. The 100-m grid cell was chosen to

correspond with the 100-m National Elevation Dataset digital elevation model (available from

the U.S. Geological Survey: https://catalog.data.gov/dataset/100-meter-resolution-elevation-of-

the-conterminous-united-states-direct-download). The NED DEM layer was also used to extract

the elevation predictor layer.

We created maps of tree cover and vegetation diversity within each 100-m pixel and used a

moving window analysis to calculate the landcover diversity (SIDI) within 200 m and local and

neighborhood building density for each 100-m pixel. Building footprints were obtained from

county government GIS offices and converted to point locations. Local building density

(building units per hectare) was quantified using the point-density tool with a 100-m circular

moving window in ArcMap 10.4, with the output raster specified as a 100-m grid matching the

NED DEM, and points/ha as the output value. Similarly, neighborhood building density was

quantified using the point-density tool with a 1-km circular moving window, with the output

raster specified as a 100-m grid matching the NED DEM, and points/ha as the output value.

We used 30-m raster data from the 2014 National Crop Data Layer (CDL; USDA NASS 2014)

to create maps of landcover diversity within 200 m of each 100-m grid cell using a moving

window analysis in GIS. We first reclassified the CDL to six land-cover categories

(grassland/herb, shrubland, cropland, forest, developed and other/water). Land-cover diversity

was calculated as the Simpson's diversity index ($SIDI = 1 - \sum_{i=1}^{m} P_i^2$) using six land-cover

categories (grassland/herb, shrubland, cropland, forest, developed and other/water) within 200 m of each cell center.

Forest canopy cover maps were created using the proportion of LIDAR returns within each 100-m grid cell within the subcanopy or canopy layers (i.e., >2.0 m above ground). Discrete-return LIDAR data were collected in winter 2005 (NCDEM 2006) for the entirety of the study area during winter. Vegetation height was measured from LIDAR first returns by subtracting the elevation of a bare-earth digital terrain model, derived from the same LIDAR data set, from the elevation of each return. Only first returns were used, and we excluded returns within digitized building footprints. Vegetation structural diversity was calculated using the Shannon Evenness index ($E_H = \frac{-\sum_{i=1}^{S} p_i \ln p_i}{\ln S}$) using the proportion ($p_i$) of LIDAR returns in each of four vegetation strata (i.e., herb, shrub, subcanopy, and canopy layers) for each 100-m grid cell.

Annual vegetation productivity was extracted from a smoothed and gap-filled MODIS Normalized Difference Vegetation Index (NDVI) dataset (Spruce et al. 2016). We calculated the 10-year (2004 – 2014) median of annual vegetation productivity for each study site and subsampled to a 100-m resolution.

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Table S1. List of species observed and their classification at 56 sites during April – August 2014 in the French Broad River Basin, NC. The most commonly occurring species (observed at 90% or more of the study sites) were Tufted Titmouse (100% of sites), Carolina Chickadee (98%), Northern Cardinal (96%), American Robin (93%), Blue Jay (93%), Eastern Towhee (93%), and Carolina Wren (91%). Migratory status was determined using Rodewald 2015; synanthrope status follows Johnston 2001; and infrequent species were classified as the least frequently recorded species for the French Broad River Basin in the eBird dataset (Sullivan et al. 2009).

Common Name	Code	Species name	Migratory status	Synanthrope status	Listed in NC Wildlife Action Plan	Infreq-uent species
Acadian flycatcher	ACFL	Empidonax virescens	neotropical	NA	0	1
American crow	AMCR	Corvus brachyrhynchos	resident	Tangential	0	0
American goldfinch	AMGO	Spinus tristis	resident	NA	0	0
American kestrel	AMKE	Falco sparverius	short-distance	Tangential	1	1
American redstart	AMRE	Setophaga ruticilla	neotropical	Tangential	0	0
American robin	AMRO	Turdus migratorius	resident	Casual	0	0
Baltimore oriole	BAOR	Icterus galbula	neotropical	NA	0	1
Barn swallow	BARS	Hirundo rustica	neotropical	Tangential	0	0
Black-and-white warbler	BAWW	Mniotilta varia	neotropical	NA	0	0
Bay-breasted warbler	BBWA	Setophaga castanea	neotropical	NA	0	1
Blue-gray gnatcatcher	BGGN	Polioptila caerulea	neotropical	NA	0	0
Brown-headed cowbird	BHCO	Molothrus ater	short-distance	Tangential	0	0
Blue-headed vireo	BHVI	Vireo solitarius	short-distance	NA	0	0
Blackburnian warbler	BLBW	Setophaga fusca	neotropical	NA	0	1
Blue grosbeak	BLGR	Passerina caerulea	neotropical	NA	0	1
Blue jay	BLJA	Cyanocitta cristata	resident	Tangential	0	0

Blackpoll warbler	BLPW	Setophaga striata	neotropical	NA	0	1
Brown thrasher	BRTH	Toxostoma rufum	short-distance	NA	0	0
Black-throated blue warbler	BTBW	Setophaga caerulescens	neotropical	NA	0	0
Black-throated green warbler	BTNW	Setophaga virens	neotropical	NA	1	1
Broad-winged hawk	BWHA	Buteo platypterus	neotropical	NA	0	1
Carolina chickadee	CACH	Poecile carolinensis	resident	Tangential	0	0
Carolina wren	CARW	Thryothorus ludovicianus	resident	NA	0	0
Canada warbler	CAWA	Cardellina canadensis	neotropical	NA	1	1
Cedar waxwing	CEDW	Bombycilla cedrorum	resident	NA	0	0
Cerulean warbler	CERW	Setophaga cerulea	neotropical	NA	1	1
Chipping sparrow	CHSP	Spizella passerina	neotropical	Tangential	0	0
Chimney swift	CHSW	Chaetura pelagica	neotropical	Full	1	1
Cape May warbler	CMWA	Setophaga tigrina	neotropical	NA	0	1
Common grackle	COGR	Quiscalus quiscula	short distance	Tangential	0	0
Cooper's hawk	COHA	Accipiter cooperii	resident	NA	1	1
Common raven	CORA	Corvus corax	resident	Tangential	0	1
Common yellowthroat	COYE	Geothlypis trichas	short-distance	Tangential	0	1
Chestnut-sided warbler	CSWA	Setophaga pensylvanica	neotropical	NA	0	0
Dark-eyed junco	DEJU	Junco hyemalis	resident	Tangential	0	0
Downy woodpecker	DOWO	Picoides pubescens	resident	Tangential	0	0
Eastern bluebird	EABL	Sialia sialis	short-distance	Tangential	0	0
Eastern kingbird	EAKI	Tyrannus tyrannus	neotropical	NA	1	1
Eastern meadowlark	EAME	Sturnella magna	resident	Tangential	1	1
Eastern phoebe	EAPH	Sayornis phoebe	resident	NA	0	0
Eastern screech-owl	EASO	Megascops asio	resident	NA	0	1
Eastern towhee	EATO	Pipilo maculatus/erythr	short-distance	Tangential	0	0
Eastern wood-	EAWP	Contopus virens	neotropical	NA	0	0

pewee						
European starling	EUST	Sturnus vulgaris	resident	Full	0	0
Field sparrow	FISP	Spizella pusilla	short-distance	NA	1	1
Great crested flycatcher	GCFL	Myiarchus crinitus	neotropical	NA	0	1
Golden-crowned kinglet	GCKI	Regulus satrapa	short-distance	NA	0	0
Gray catbird	GRCA	Dumetella carolinensis	neotropical	Tangential	0	0
Hairy woodpecker	HAWO	Picoides villosus	resident	Tangential	1	1
Hermit thrush	HETH	Catharus guttatus	short-distance	NA	0	1
House finch	HOFI	Haemorhous mexicanus	resident	NA	0	0
Hooded warbler	HOWA	Setophaga citrina	neotropical	NA	1	1
House wren	HOWR	Troglodytes aedon	neotropical	Tangential	0	1
Indigo bunting	INBU	Passerina cyanea	neotropical	NA	0	0
Kentucky warbler	KEWA	Geothlypis formosa	neotropical	NA	1	1
Louisiana waterthrush	LOWA	Parkesia motacilla	neotropical	NA	0	1
Mourning dove	MODO	Zenaida macroura	resident	Tangential	0	0
Northern bobwhite	NOBO	Colinus virginianus	resident	Casual	0	1
Northern cardinal	NOCA	Cardinalis cardinalis	resident	Tangential	0	0
Northern flicker	NOFL	Colaptes auratus	short-distance	Tangential	0	0
Northern mockingbird	NOMO	Mimus polyglottos	resident	Tangential	0	0
Northern parula	NOPA	Setophaga americana	neotropical	NA	0	0
Northern pintail	NOPI	Anas acuta	short-distance	NA	0	1
Northern rough-winged swallow	NRWS	Stelgidopteryx serripennis	neotropical	Tangential	0	1
Ovenbird	OVEN	Seiurus aurocapilla	neotropical	NA	0	1
Palm warbler	PAWA	Setophaga palmarum	short-distance	NA	0	1
Pine warbler	PIWA	Setophaga pinus	short-distance	NA	0	1
Pileated woodpecker	PIWO	Dryocopus pileatus	resident	NA	0	0

Rose-breasted grosbeak	RBGR	Pheucticus ludovicianus	neotropical	NA	1	1
Red-breasted nuthatch	RBNU	Sitta canadensis	resident	Tangential	0	1
Red-bellied woodpecker	RBWO	Melanerpes carolinus	resident	Tangential	0	0
Ruby-crowned kinglet	RCKI	Regulus calendula	short-distance	Tangential	0	1
Red-eyed vireo	REVI	Vireo olivaceus	neotropical	Tangential	0	0
Red-shouldered hawk	RSHA	Buteo lineatus	short-distance	NA	0	0
Red-tailed hawk	RTHA	Buteo jamaicensis	resident	Tangential	0	0
Ruby-throated hummingbird	RTHU	Archilochus colubris	neotropical	Tangential	0	0
Ruffed grouse	RUGR	Bonasa umbellus	resident	Casual	0	1
Red-winged blackbird	RWBL	Agelaius phoeniceus	short-distance	Tangential	0	0
Scarlet tanager	SCTA	Piranga olivacea	neotropical	NA	0	0
Song sparrow	SOSP	Melospiza melodia	resident	Tangential	0	0
Swainson's warbler	SWWA	Limnothlypis swainsonii	short-distance	NA	1	1
Tree swallow	TRES	Tachycineta bicolor	resident	Tangential	0	0
Tufted titmouse	TUTI	Baeolophus bicolor	resident	Tangential	0	0
Veery	VEER	Catharus fuscescens	neotropical	NA	0	1
White-breasted nuthatch	WBNU	Sitta carolinensis	resident	Tangential	0	0
White-eyed vireo	WEVI	Vireo griseus	short-distance	NA	0	1
Worm-eating warbler	WEWA	Helmitheros vermivorum	neotropical	NA	1	1
Wild turkey	WITU	Meleagris gallopavo	resident	Casual	0	0
Winter wren	WIWR	Aix sponsa	short-distance	Casual	0	0
Wood thrush	WOTH	Hylocichla mustelina	neotropical	NA	1	1
White-throated sparrow	WTSP	Zonotrichia albicollis	short-distance	Tangential	0	0
Yellow-billed cuckoo	YBCU	Coccyzus americanus	neotropical	Tangential	0	1
Yellow-bellied sapsucker	YBSA	Sphyrapicus varius	short-distance	NA	1	1
Yellow-rumped warbler	YRWA	Setophaga coronata	neotropical	NA	0	0

Yellow-throated vireo	YTVI	Vireo flavifrons	neotropical	NA	0	1
Yellow-throated warbler	YTWA	Setophaga dominica	neotropical	NA	0	1

Table S2. Temporal consistency of bird CES hotspots.

	Percent of landscape in each category				
Temporal consistency category	All bird species richness	Migratory species richness	Resident species richness	Synanthrope species richness	'Rare' species richness
Never classified as hotspot	66%	21%	63%	67%	23%
Hotspot during one time period	<1%	12%	8%	8%	12%
Hotspot during two time periods	2%	3%	3%	3%	20%
Always classified as hotspot	32%	63%	25%	23%	45%

Table S3. Overlap of projected hotspots of bird CES supply and public accessibility, measured as the percent of the bird CES hotspot contained within public accessibility categories, during three time periods from April to August.

Bird CES indicator	Time period	Percent of hotspot area		
		Highly accessible	Moderately accessible	Private or limited access
All species richness	Early spring	4%	5%	91%
	Late spring	4%	5%	91%
	Summer	4%	5%	91%
Migratory species richness	Early spring	6%	29%	65%
	Late spring	5%	26%	69%
	Summer	5%	31%	64%
Resident species richness	Early spring	4%	5%	91%
	Late spring	3%	3%	94%
	Summer	4%	4%	92%
Synanthrope species richness	Early spring	4%	4%	91%
	Late spring	4%	4%	92%
	Summer	4%	5%	91%
Rare species richness	Early spring	5%	28%	67%
	Late spring	5%	29%	66%
	Summer	5%	36%	59%

Figure S1. Maps of standard error of projected bird CES for total, migratory, resident, synanthrope, and infrequent species richness (left to right in each row). Standard error did not change across time periods.
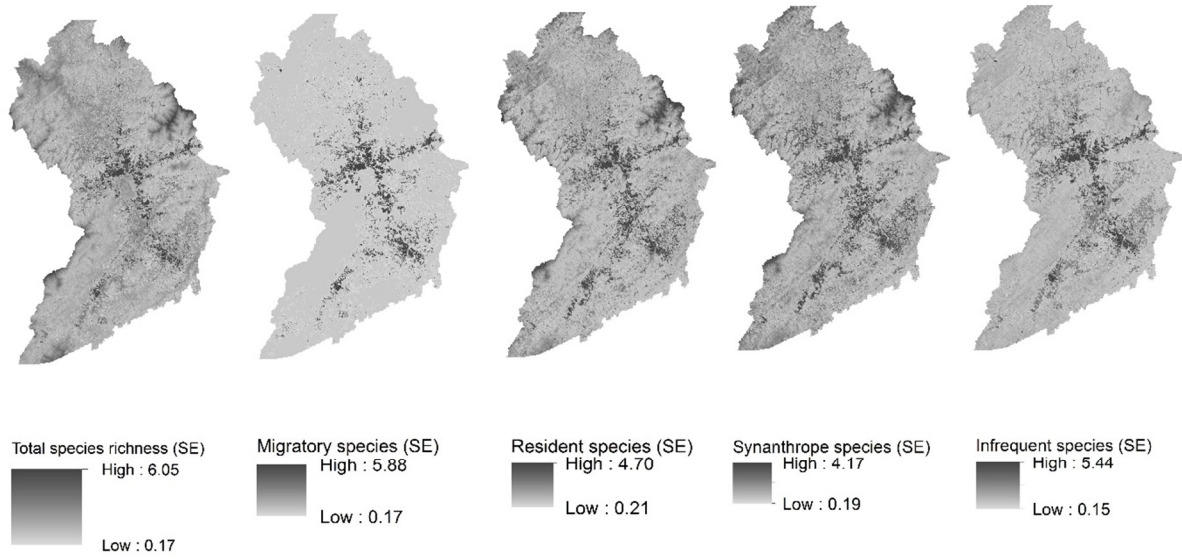
Figure S2. Distribution of publicly accessible areas classified by three levels of access (high, moderate, and limited) within the study area.
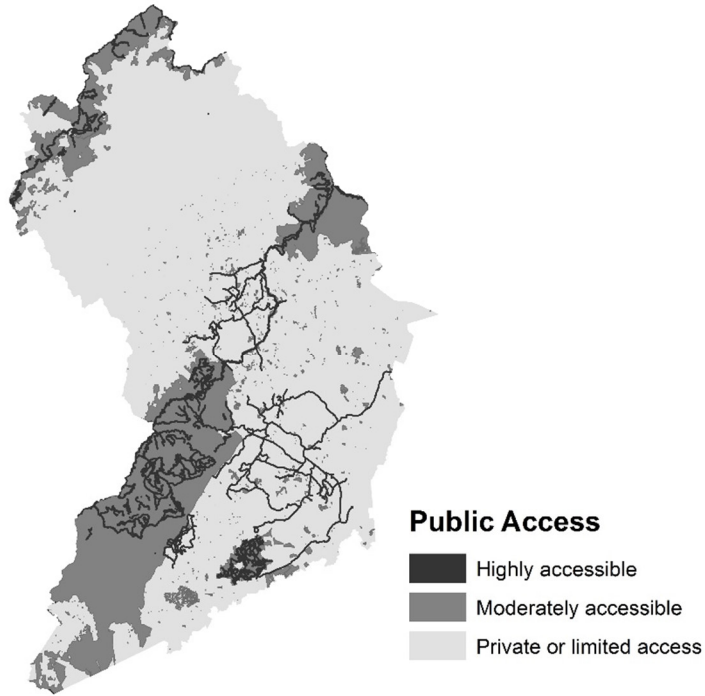
Figure S3. Locations of eBird observations during early spring, late spring, and summer from the years 2009 – 2014.