Long-Term Monitoring of Bat Activity and Species Richness Reveals Changes in Northwest Ohio Bat Communities

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ABSTRACT. Bat populations are declining worldwide because of threats such as white-nose syndrome and habitat loss. Multiple-year studies are advantageous for looking at population trends over time and determining the extent of declines. While numerous multiple-year studies have been conducted for bats, they are limited in regional and local coverage. This study compiled the results of 282 walking surveys across 10 years of acoustic bat recording data collected in 3 northwest Ohio parks from 2011 to 2021 to examine temporal trends in bat activity. Overall bat activity (all species combined, average per night) decreased from 2011 to 2018 but showed a slight positive trend from 2019 to 2021. Average activity per night for big brown (*Eptesicus fuscus*), northern long-eared (*Myotis septentrionalis*), and little brown bats (*Myotis lucifugus*) decreased significantly (75%, 95%, and 33% decreases from 2011 to 2021, respectively). Average activity per night of hoary (*Lasiurus cinereus*) and silver-haired bats (*Lasionycteris noctivagans*) increased significantly in activity until 2016 (169% and 163% increase from 2011 to 2016, respectively) before decreasing in activity to be closer to initial levels, although their general trend in activity was positive overall (92% and 32% increase from 2011 to 2021, respectively). These data show the advantages of monitoring bat activity over more years to make inferences about population trends. Significant decreases in activity for big brown, little brown, and northern long-eared bats from 2011 to 2021 suggest alterations in bat community structure. These results illustrate a decline in overall bat activity over the last decade. This study also provides an example of volunteer-collected long-term bat monitoring data.

Publication Date: January 2025 **https://doi.org/10.18061/ojs.v124i2.9356** **OHIO J SCI 124(2):23-35**

INTRODUCTION

Long-term monitoring is useful for effectively detecting shifts in species assemblages, because it improves statistical power for detecting population trends, provides a longer timeframe for inference, and is less prone to bias from a single year of unusual results (Pelton and van Manen 1996; Havstad and Herrick 2003). Using the same locations and procedures every year can mitigate variation between monitoring efforts and provide more accurate results for long-term research (Ingersoll et al. 2013). It is especially critical to monitor trends in bat populations since some bat species in the United States have declined in population by more than 90%, with the disease white-nose syndrome (WNS) the main cause of declines in the United States and Canada (Cheng et al. 2021; White-Nose Syndrome Response Team 2023). The fungal pathogen *Pseudogymnoascus destructans* (Pd) causes this disease, which causes hibernating bats to arouse from torpor and burn too much energy during their hibernation period, plus damage to their skin and wings, and other physiological issues such as dehydration (Blehert et al. 2009; Frick et al. 2010; Frick et al. 2016). Habitat destruction and degradation from human land use, energy development, climate change, and pollution are other major threats to bats (Frick et al. 2020). The combination of multiple threats can also exacerbate the danger to bats.

Threats also do not affect species equally. For instance, WNS most severely affects tri-colored (*Perimyotis subflavus*), little brown (*Myotis lucifugus*), and northern long-eared (*Myotis septentrionalis*) bats. Big brown bats (*Eptesicus fuscus*) are less impacted in both scope and severity, and Indiana bats (*Myotis sodalis*) are impacted over a large part of their range but less severely than most other species (Nocera et al. 2019; Cheng et al. 2021). Big brown bats develop much less frequent and severe lesions for white-nose syndrome than other susceptible species, such as

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little brown bats, even under the same hibernation conditions, which indicates big brown bats are less susceptible to the disease (Moore et al. 2017). Silver-haired (*Lasionycteris noctivagans*) and eastern red bats (*Lasiurus borealis*) have been found with Pd fungus on their skin, but they are not affected by the disease. This is likely mainly because they do not hibernate (ODNR 2020).

Habitat changes such as urbanization and deforestation also affect bats unequally. They disproportionately impact rare or threatened bat species and slower-flying species with low wing aspect ratios (Longcore and Rich 2004; Barber et al. 2011; Fuentes-Montemayor et al. 2013; Lacoeuilhe et al. 2014; Stone et al. 2015). Meanwhile, fast-flying generalist species that forage in open habitats are more tolerant of urbanization, albeit only to a degree (Longcore and Rich 2004; Barber et al. 2011; Fuentes-Montemayor et al. 2013; Lacoeuilhe et al. 2014; Stone et al. 2015). The unequal effects of both disease and habitat changes may lead to an increase in abundance of some species while others decrease (O'Keefe et al. 2019).

Previous bat monitoring studies mainly involved mark-recapture or count data, but acoustic surveys have become more common in recent years and are now one of the most common methods of providing a relative measure of population size (Kloepper et al. 2016; Salinas-Ramos et al. 2020). Using a crew of volunteers has reliably been used to gather long-term bat acoustic data in the past (Buckman-Sewald et al. 2014; Faure-Lacroix et al. 2020; Simonis et al. 2020; Tuneu-Corral et al. 2020).

The main aim of the current study was to compile acoustic data from bats across multiple years to look at how bat activity has changed over time. The focus was on changes in activity levels of individual species, observed species richness (defined as number of species detected), and overall bat activity over a period of multiple years as collected during volunteer surveys. It was expected that overall bat activity would decrease from 2011 to 2021, as other acoustic studies have recorded contemporary declines in bat activity (Brooks 2011; Rodhouse et al. 2012), and that the 3 species most affected by WNS (tri-colored, little brown, and northern long-eared bats) would show a continuous reduction in activity during the survey period as seen in the national declines in their population. Evaluation of these trends will contribute to our understanding of the impacts that native bat populations face in this region.

METHODS

Study Area

The Oak Openings region of northwest Ohio is one area of important growing-season bat roosting and foraging habitat, but recent population trends have not been recorded in the region (Buckman-Sewald et al. 2014). WNS was first detected in the area in 2012 (ODNR 2020). The region has also experienced major habitat changes since 2009, with a 28% decrease in total area for forests, a 5% increase in residential and urban areas, a 159% increase in savanna, and a 215% increase in prairie and meadow (Martin and Root 2020). About 12% of the area is protected preserve, but the rest is open to development (Abella et al. 2001; Martin and Root 2020). These protected lands include multiple Metroparks. The largest of these parks is Oak Openings Preserve (1,200 ha), which consists of a wide variety of ecosystems including forest, upland prairie, and upland savanna and is surrounded by a mix of residential areas, cropland, Eurasian meadow, and prairie (Schetter and Root 2011; Martin and Root 2020). Secor Metropark (253 ha) consists mainly of swamp and floodplain forest and upland prairie and is bordered by a mix of forests, prairies, residential areas, and cropland. Lastly, Wildwood Metropark (199 ha) is composed primarily of upland deciduous and floodplain forest and upland prairie and is proximate to residential and dense urban areas.

Eight bat species can be found in the region: the big brown bat, little brown bat, northern long-eared bat, tri-colored bat, evening bat (*Nycticeius humeralis*), eastern red bat, hoary bat (*Lasiurus cinereus*), and silver-haired bat (Buckman-Sewald et al. 2014). Indiana bats may be found in the area and have had a few local recordings previously identified as them with automated recording ID, but their presence cannot be confirmed in the region because of the difficulty in distinguishing recordings of them from those of little brown bats (Buckman-Sewald et al. 2014). All 8 confirmed species are listed as of conservation concern in Ohio (Boyer et al. 2018). The northern long-eared bat is listed as endangered on the Endangered Species List and tri-colored bats have been recommended to be listed as endangered (USFWS 2022, 2023). The IUCN (International Union for Conservation of Nature) lists the little brown bat as endangered, the northern long-eared bat as near threatened, and tri-colored bats as vulnerable (Solari 2018a, b). In Ohio, the northern long-eared bat is listed as threatened and the evening bat is listed as of special interest due to lack of information (Boyer et al. 2018). Throughout their range, little brown, tri-colored, and northern long-eared bats are decreasing in abundance; eastern red, evening bat, and silver-haired bats are stable; population trends of hoary bats are unknown; and big brown bats are increasing (Arroyo-Cabrales et al. 2016; Gonzalez et al. 2016; Miller et al. 2016; Solari 2018a,b; Solari 2019a,b; Solari 2021). The most development-tolerant and open-foraging species are hoary, silver-haired, and big brown bats (Agosta 2002; Ford et al. 2005; Menzel et al. 2005; Hein et al. 2009; Loeb and O'Keefe 2011; Starbuck et al. 2014). Tri-colored, evening, and eastern red bats are more common in forested areas but often found in open areas, while little brown and northern long-eared bats are primarily found in forested areas (Ford et al. 2005; Menzel et al. 2005; Henderson et al. 2008; Hein et al. 2009; Farrow and Broders 2011; Loeb and O'Keefe 2011; Starbuck et al. 2014). The conservation status of bats in Ohio creates a critical need for these data. The current study compiled acoustic data collected by volunteers in the Oak Openings region since 2011 (Buckman-Sewald et al. 2014) to look at temporal changes in bat activity, defined as the number of bat recordings.

Acoustic Data Collection

Around 500 to 540 total volunteers conducted acoustic monitoring surveys from 2011 to 2021 in Oak Openings, Wildwood, and Secor Metroparks (Fig. 1). Every year, volunteers and researchers conducted surveys in each park during the third week of the summer months (June to August), and all surveys were conducted Monday to Wednesday, with each park typically surveyed 3 times a year. No surveys were conducted in 2014 because of a lack of coordinators and surveys were not completed in Wildwood in 2018 due to inclement weather. Surveys began 15 minutes after sunset. Volunteers walked 3 trails at each park and the same trails were walked each time. Volunteer groups of 2 or more moved steadily at a "slow pace" at 1 of 3 designated trails in the park (same set of 3 trails used in every survey) with an Anabat® SDII recording unit with an omnidirectional microphone (Titley Scientific®, Columbia, Missouri, USA) held about 4 to 5 feet above the ground. Anabat SDII sensitivity ratings were set to 7 to reduce background noise, 16 for audio division ratio, and 8 for data division ratio (Turner 2018; Simonis et al. 2020). A Garmin® GPS was attached to the monitors to collect continuous bat recording data and geolocations for 1 hour. Groups adhered to standard survey protocols, including contacting the researcher if recorders did not appear to be recording correctly and using red light headlamps. The same volunteers did not survey every year, but many repeat volunteers existed across years. There were no notable differences in how long it took volunteers to walk the same trails across sampling periods.

Data Analysis

Recording Identification. Automated BCID software (BCID, BCID version 9 2.7c) and manually examined sonograms in Analook (Buckman-Sewald et al. 2014) were used to identify recordings. Some species can be problematic to differentiate, particularly those in the *Myotis* genus (Obrist et al. 2004). However, the current study used an existing recording library developed by recordings of bats with visually confirmed species identification through mist netting and animals being brought to the local wildlife rehab center in 2010 to 2011 in the Oak Openings region (Sewald 2012; Buckman-Sewald et al. 2014) to ensure all results were as accurate as possible. All species were confirmed present and successfully identified in 2010 to 2011 except for the evening bat, which was able to be added to the recording library because of a recording from a mist-netted bat in the area in 2003 (Sewald 2012). A trained researcher (same for a single year and current researchers double-checked all identifications from previous years) made species identifications based on recording frequencies, slope, and shape. Only recordings with more than 4 clear pulses were identified, the rest were filtered out.

Model Fit. The current study collected total and mean bat recording per survey (i.e., relative bat activity) for each sample night, month, and year and used a linear mixed effects model with year as the independent variable and park as a random factor in JMP® (Version 11, SAS® Institute Inc., Cary, North Carolina) to estimate changes in overall bat activity and individual species activity over time. The independent variable was whatever factor was being measured in that test (ex: total activity or species richness). The default model options in JMP were used, which were standard least squares for personality, unbounded variance components, a minimal report for emphasis, and REML (restricted maximum likelihood mixed model) for the method. Model fit was assessed using R^2 values. A goodness of fit test was used to determine that distribution was normal. Alpha-levels were set at 0.05. A Bray-Curtis dissimilarity index was used to compare shifts in bat communities in study areas to compare changes over time. Restricted maximum likelihood mixed models were created for mean bat activity per survey combined for all species, observed species richness, and per survey means for individual species. Additionally, separate models were created for the 3 species WNS impacted most (little brown, northern long-eared, and tri-colored bats), the remaining species not affected by WNS, and for open and forested foraging guilds (Buckman-Sewald et al. 2014). Hoary, big brown, and silver-haired bats were in the open habitat foraging guild, whereas little brown, northern long-eared, tri-colored, evening, and eastern red bats were in the forested foraging guild (Agosta 2002; Owen et al. 2004; Ford et al. 2005; Henderson et al. 2008; Farrow and Broders 2011). The final open foraging guild and species not affected by WNS tests were run without the big brown bat, so that species' high abundance relative to others did not skew results.

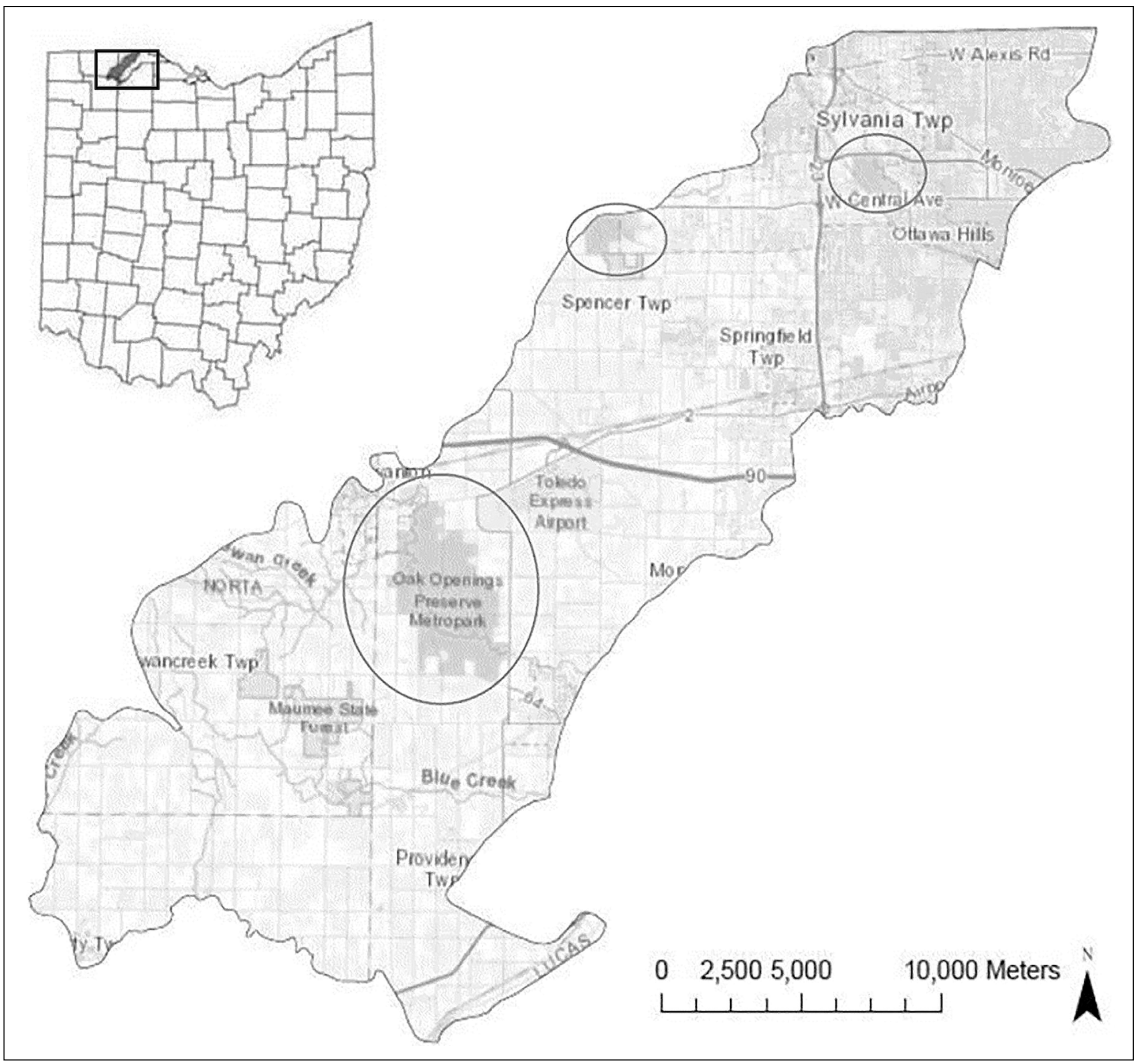

FIGURE 1. Parks where surveys occurred in the Oak Openings region of northwest Ohio, with boundaries as defined by Brewer and Venkat (2004) circled in black and overlaid on map of local roads (Martin and Root 2020). From left: Oak Openings, Secor, and Wildwood Metroparks.

RESULTS

A total of 5,787 recordings were made from 2011 to 2021 across 282 surveys, with a mean of 579 recordings per year (SE = 105.8722). Oak Openings had 2,570 recordings (mean of 257 per year, SE = 46.796), Secor had 1,669 (mean of 167, SE = 42.748), and Wildwood had 1,650 (mean of 183 per year, SE = 30.754, not surveyed in 2018). Of all recordings, 90% were identified to species (Table 1). However, the total number of recordings, regardless of if they could be identified to species, were used as a measure of relative bat activity.

The restricted maximum likelihood mixed model showed significant declines over time for mean bat activity ($p < 0.001$, $R^2 = 0.846$, N = 3 where N was the number of parks surveyed). Observed species richness did not change significantly over time ($p = 0.169$, $R^2 = 0.293$, N = 3, 95% CI of parameter estimates = 0.039 upper and -0.209 lower) and neither did evenness ($p = 0.401$, $R^2 = 0.079$, N = 3, 95% CI of parameter estimates = 0.029 upper and -0.012 lower) (Fig. 2). Big brown ($p < 0.001$, $R^2 = 0.854$, N = 3), northern long-eared ($p = 0.045$, $R^2 = 0.555$, N = 3), and little brown bats ($p = 0.044$, $R^2 = 0.620$, N = 3) significantly declined in activity over time as well (Fig. 3 A-C). Hoary ($p < 0.001$, $R^2 = 0.770$, N = 3) and silver-haired bats ($p = 0.009$, $R^2 = 0.676$, N = 3) both increased in activity over time and had activity peaks in 2015 and 2016 (Fig. 3 D-E). Activity did not change over time for eastern red ($p = 0.083$, $R^2 = 0.538$, N = 3), evening ($p = 0.059$, $R^2 = 0.657$, N = 3), or tri-colored bats ($p = 0.316$, $R^2 = 0.479$, N = 3) (Fig. 3 F-H). The open habitat guild ($p < 0.001$, $R^2 = 0.764$, N = 3) showed the same pattern as the 2 individual species included in it (Fig. 4 A). Significant changes over time did not exist for forested-guild species ($p = 0.136$, $R^2 = 0.652$, N = 3) (Fig. 4 B). This is likely driven by the lack of change in eastern red bat and evening bat activity, since these species made up the bulk of forest guild recordings. The species WNS affected most decreased in activity over time ($p = 0.001$, $R^2 = 0.670$, N = 3), while the species not affected by it had a positive trend ($p < 0.001$, $R^2 = 0.830$, N = 3) (Fig. 4 C-D). The generalized linear mixed effect models indicate that overall bat activity, the activity of some individual species, and the activity of certain groups of species did change over time (Table 2).

There was a 57% decrease in mean bat activity per survey between 2011 and 2021, although bat activity increased by 29% between 2019 and 2020 and 7% between 2020 and 2021. Community similarity changed over time for both totals combined from all parks and for individual parks (Table 3). The most dissimilar consecutive years were 2011 and 2012, closely followed by 2013. The large drop in activity in 2012 likely caused these dissimilarities. The most similar years were 2020 and 2021.

Table 1
Percentage of total activity comprised of each species for each year

	Year									
Species	**2011**	**2012**	**2013**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Big brown bat	59.57%	21.51%	56.68%	57.94%	38.25%	68.78%	35.58%	36.39%	54.14%	41.76%
Eastern red bat	8.80%	45.15%	14.27%	10.15%	19.68%	10.48%	25.96%	14.97%	11.88%	17.14%
Hoary bat	2.01%	1.65%	0.51%	6.18%	11.11%	0.87%	3.37%	3.06%	5.25%	10.99%
Silver-haired bat	2.93%	5.44%	2.24%	13.38%	15.87%	10.26%	14.90%	14.63%	12.43%	10.99%
Northern long-eared bat	3.16%	8.04%	0.31%	0.15%	0.16%	1.97%	0.48%	0.00%	0.00%	0.44%
Little brown bat	2.31%	13.95%	0.82%	0.74%	9.00%	0.87%	1.44%	3.40%	2.21%	4.40%
Tri-colored bat	1.70%	1.89%	0.41%	8.68%	11.59%	6.11%	17.79%	23.13%	9.67%	12.97%
Evening bat	2.24%	1.65%	0.31%	2.79%	1.90%	0.66%	0.48%	4.42%	4.42%	1.32%
Unknown	17.28%	0.71%	32.39%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Total recordings	1296	423	741	680	630	458	208	294	362	455

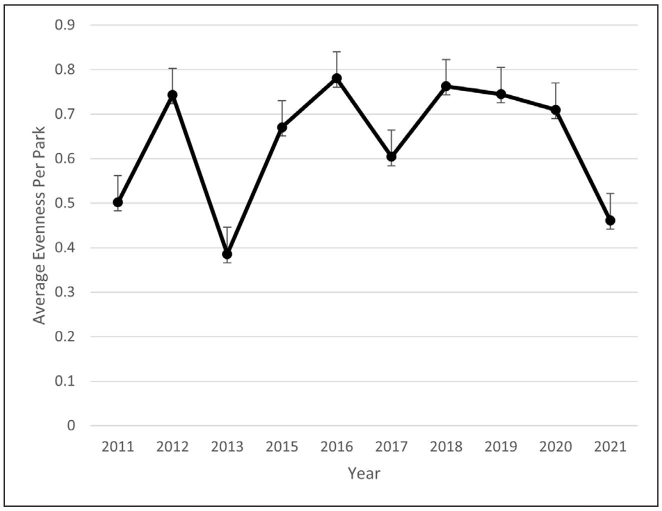

FIGURE 2. Long-term trend in average evenness per park per year from 2011 to 2021 in Secor, Oak Openings, and Wildwood Metroparks in northwest Ohio. Ninety-five percent confidence intervals for hourly data were used as error bars.

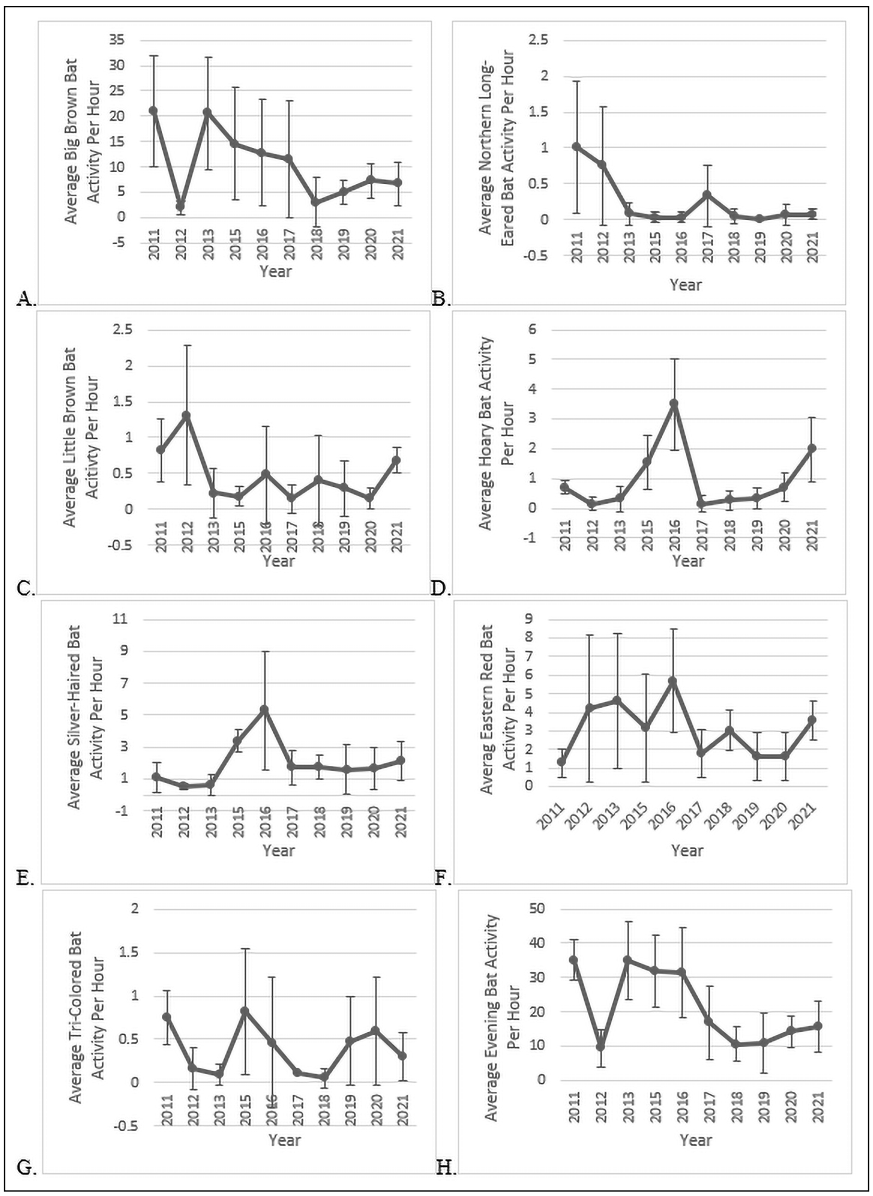

FIGURE 3. Long-term trends in mean recordings per hour-long survey from 2011 to 2021, measured in recordings per hour for A. big brown, B. northern long-eared, C. little brown, D. hoary, E. silver-haired, F. eastern red, G. tri-colored, and H. evening bat. Error bars are 95% confidence intervals for hourly data.

DISCUSSION

Overall bat activity decreased from 2011 to 2021 and big brown, northern long-eared, and little brown bats especially declined in activity during this period. The change in activity of individual species over time indicates that community composition has changed since 2011. This includes significant declines in activity for most of the species WNS impacts. While consistent WNS prevalence data do not exist in the region, it is likely the primary cause for the observed declines in northern long-eared and little brown bats based on previous research (Reynolds et al. 2016; Thalken et al. 2018). Northern long-eared and little brown bats have suffered large declines throughout their range due to WNS, with declines up to 95% in some areas (Ford et al. 2011; Francl et al. 2012; Ingersol et al. 2013; Jachowski et al. 2014; Reynolds et al. 2016).

The other species in the region affected by WNS, tri-colored bats, experienced declines in activity, but not enough to be statistically significant. They did have slightly lower initial activity compared to the other species and is the most likely to be found in open areas (Broders and Forbes 2004; Starbuck et al. 2014). Either of these above factors could have impacted the slower decline, or effects of WNS on this species may have been slightly slower. Ford et al. (2011) also noted lower declines in tri-colored bats than other WNS affected species, which in that case was likely because of lower initial activity.

Multiple individual species had major declines in 2012, but the dip in activity was especially prevalent for big brown bats. WNS was first detected in the area in 2012, but large-scale declines from WNS are generally recorded 2 to 4 years after the disease is detected in a population and big brown bats do not typically experience high mortality rates from

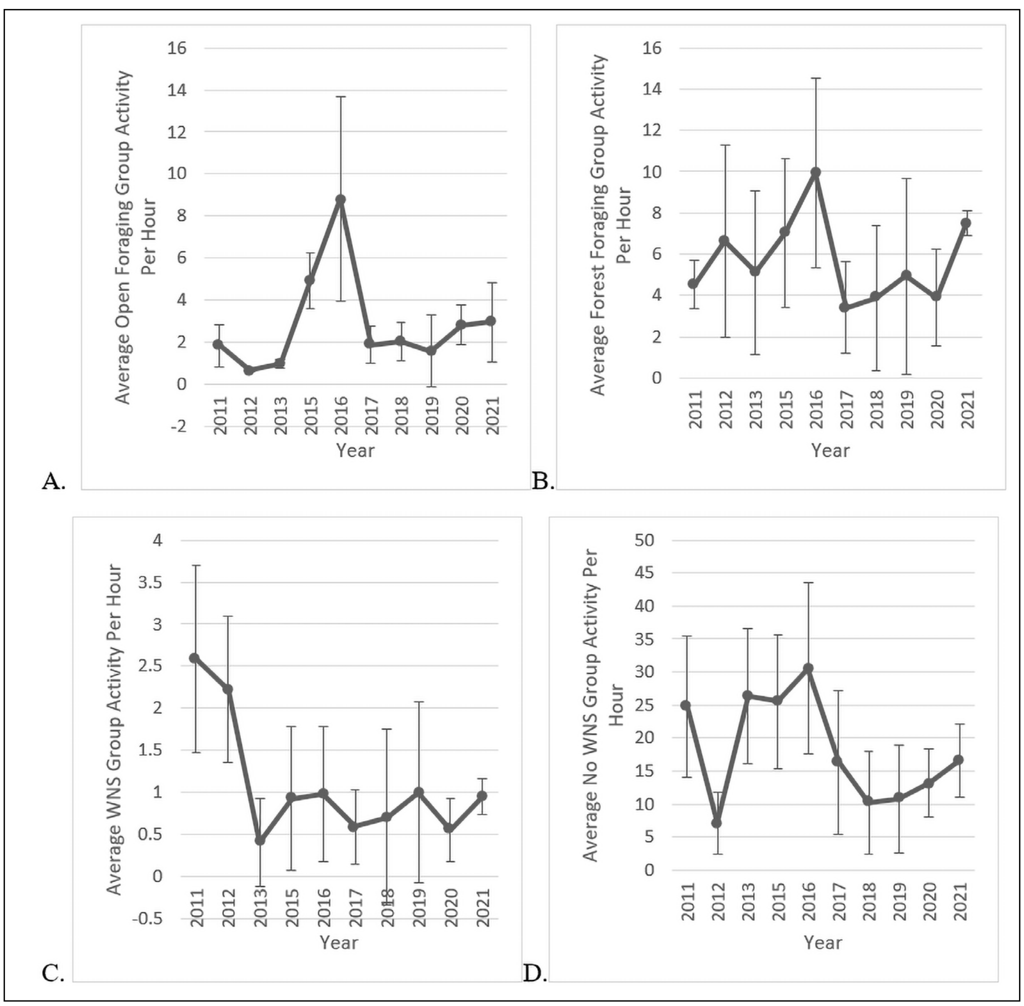

FIGURE 4. Long-term trends in mean recordings per hour from 2011 to 2021 for A. open guild activity minus big brown bat, B. forested guild, C. species impacted most by WNS, and D. species not impacted by WNS. Error bars are 95% confidence intervals for hourly data.

Table 2
Parameter estimates for each year (fixed effect, slope for following year) from 2011 to 2020 for each group

	Year									
Group [a]	**2011**	**2012**	**2013**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**95% CI [f]**
Total	13.9256	-11.8425	13.8130	10.5353	10.2760	-4.2796	-10.5152	-10.3536	-7.8351	± 6.5437
Big brown bat	10.6706	-8.2769	10.3565	4.3945	2.4972	1.3676	-9.0820	-6.3361	-3.0413	± 4.6712 (5.7079 in 2018)
Eastern red bat	-0.0294	0.9868	1.3368	-0.7021	2.4275	-1.4799	0.4370	-1.6280	-1.6651	± 1.7468 (2.1378 in 2018)
Hoary bat	-0.2713	-0.8237	-0.6680	0.5763	2.5208	-0.8311	-0.5931	-0.6459	-0.2751	± 0.7169 (0.4533 in 2018)
Silver-haired bat	-0.8332	-1.4493	-1.2938	1.4099	3.3359	-0.2197	-0.4357	-0.3679	-0.2948	± 1.3655 (1.6819 in 2018)
Northern long-eared bat	0.7627	0.5102	-0.1621	-0.2084	-0.2084	0.0879	-0.1924	-0.2454	-0.1721	± 0.3895 (0.5059 in 2018)
Little brown bat	0.4755	0.3527	0.8356	-0.2478	0.0059	-0.3274	-0.2555	-0.1052	-0.1792	± 0.4240 (0.5211 in 2018)
Tri-colored bat	0.3725	-0.2214	-0.2825	0.3266	0.0860	-0.2658	-0.2606	0.1045	0.2131	± 0.4100 (0.5045 in 2018)
Evening bat	-1.8211	1.1344	1.4845	0.07519	2.5752	-1.3322	0.4177	-1.4804	-1.5174	± 1.8032 (2.2091 in 2018)
Open foraging [b]	-1.0941	-2.2617	-1.9506	1.9975	5.8679	-1.0395	-0.9128	-1.0032	-0.5579	± 1.7654 (2.1883 in 2018)
Forest foraging [c]	0.4720	0.6518	-0.8760	-0.3260	3.9332	-2.5853	0.2422	-0.9927	-1.9564	± 2.5430 (3.1131 in 2018)
WNS [d]	1.5324	1.1693	-0.6474	-0.1270	-0.0714	-0.4603	-0.7463	-0.0529	-0.4974	± 0.6935 (0.8583 in 2018)
No WNS [e]	-3.9553	-2.6401	-2.0403	3.1951	10.0118	-3.0253	-0.4204	-1.6549	-2.2864	± 1.3362 (1.6427 in 2018)

[a] Groups used were total activity, big brown, eastern red, hoary, silver-haired, northern long-eared, little brown, tri-colored, and evening bats, open and forested foraging groups, and WNS and no WNS groups.

[b] The open habitat foraging guild consisted of hoary, big brown, and silver-haired bats.

[c] The forested foraging guild consisted of little brown, northern long-eared, tri-colored, evening, and eastern red bats.

[d] The WNS group consisted of little brown, northern long-eared, and tri-colored bats.

[e] The no WNS group included evening, eastern red, hoary, big brown, and silver-haired bats.

[f] The 95% confidence intervals, which were generated in JMP, are listed in the far-right column. Confidence intervals differed between years only when noted in parentheses. Occasionally different values for 95% confidence intervals existed in 2018 because only 2 parks were surveyed that year.

Table 3
Bray-Curtis dissimilarity index over time for 2011 to 2021 (each year compared to previous sampling year) across all 3 parks and for each individual park (Oak Openings, Secor, and Wildwood Metroparks)

	Years								
Park location	**2011 vs. 2012**	**2012 vs. 2013**	**2013 vs. 2015**	**2015 vs. 2016**	**2016 vs. 2017**	**2017 vs. 2018** [a]	**2018 vs. 2019** [a]	**2019 vs. 2020**	**2020 vs. 2021**
Oak Openings	67%	69%	41%	22%	31%	46%	18%	23%	28%
Secor	75%	82%	48%	27%	28%	64%	65%	48%	41%
Wildwood	48%	56%	63%	28%	42%	n/a	n/a	43%	38%
Total	62%	61%	39%	21%	31%	43%	22%	35%	15%

[a] Lack of Wildwood comparison for 2017 vs. 2018 and 2018 vs. 2019 was due to lack of Wildwood surveys in 2018.

it (Moore et al. 2017; ODNR 2020). WNS was recorded in surrounding states as early as 2010 and it is possible it was in Ohio before 2012 but not recorded (White-Nose Syndrome Response Team 2023). It is unclear if WNS was the main cause of decline or if other factors were involved; the answer will require more research. Activity increased from 2019 to 2021 but did not increase back to 2011 activity levels. It is unclear if the recent increase in mean total activity from 2019 to 2021 is because of year-to-year variation or an actual increase in bat abundance, but it could imply limited potential recovery after the decline of the past few years—as suggested by recent studies in the areas impacted by WNS (Nocera et al. 2019; Faure-Lacroix et al. 2020). Additional long-term monitoring will be needed to assess whether this is a temporary or permanent improvement for native bat species.

Big brown bats were the most common species of the 8, but showed a significant decline in mean activity over time. It was the only species not known to be heavily impacted by WNS that had significant declines in activity. Because big brown bats comprised most of the recordings, this may account for much of the decline in overall bat activity over time. Other studies have mostly recorded increases (Francl et al. 2012; Faure-Lacroix et al. 2020) or no change (Ford et al. 2011) in big brown bat activity after the detection of WNS. The only other study to see a decrease in big brown bat activity was also in Ohio, and recorded a decline in other cave-roosting bats (Simonis et al. 2020). There have been reports of big brown bats contracting WNS in Ohio (Simonis et al. 2020), but mortality rates have tended to be lower from this disease than in *Myotis* species and tri-colored bats in other studies (Moore et al. 2017), so it is unlikely that WNS is the main reason for the large decline in the current study. Continued monitoring is needed to determine if declines in big brown bat activity are due to natural fluctuations in populations or if there is a larger cause harming this specific species.

The other open-foraging species—hoary and silver-haired bats—increased in mean activity over time overall, but peaked in activity in 2015 to 2016. Frick et al. (2017) reported declines in hoary bat activity in the Midwest because of wind energy development, but hoary bat activity in the Oak Openings region of northwest Ohio appear to be minimally affected by this. Changes in activity over time were very similar for hoary and silver-haired bats, likely because they have very similar habitat preferences and niches (Owen et al. 2004). These open-foraging species have minimal niche overlap with the species that are negatively impacted by WNS; however, these open-foraging species heavily overlap in niche with the big brown bat, which is also a development-tolerant species that forages in open areas (Ford et al. 2005). Competitive release in an equivalent scenario has not been recorded because big brown bats have increased in activity in most other studies. Still other studies have recorded increases in silver-haired bat activity when northern long-eared and little brown bats decreased in activity, although these studies did not find significant increases in hoary bat activity (Ford et al. 2011; Faure-Lacroix et al. 2020). Increases in silver-haired and hoary bat activity in protected areas may also be related to increases in prairie and savanna habitats resulting from restoration efforts, because both species forage more in open areas (Owen et al. 2004; Martin and Root 2020). It also would be useful to see if any habitat changes, changes in insect activity, or other changes in the region occurred around 2015 to 2016 to cause the increase in activity of these species. Historic data on land use or insect activity from those years would be needed to obtain those data.

Total bat activity in the Oak Openings region of northwest Ohio has begun to increase since 2019, but there has not been a consistent trend of increasing activity in the specific species affected by WNS, which are tri-colored, little brown, and northern long-eared bats. Active efforts should be made to restore these threatened local species. Measures such as treating WNS in hibernacula when possible (Fletcher et al. 2020), providing heated bat houses (Wilcox and Willis 2016), preserving large dead trees for summer roosts (Thalken et al. 2018), and protecting riparian forested habitat and forest heterogeneity in the region, should be prioritized to help declining northern long-eared and little brown bat populations (Gorman et al. 2022). Further research, such as additional acoustic surveys combined with roost surveys or mark-recapture, can help determine specific habitat factors that contribute the most to declines and increases in overall and species-specific bat activity in northwest Ohio.

There are some limitations to the data in the current study. Since this study only occurred for 1 hour, and started 15 minutes after sunset, it had some sampling bias. For example, northern long-eared bats tend to be most active later in the night (Gorman et al. 2021). However, data collected at stationary points that were recorded the whole night during part of this time frame (2019 to 2021) found similar patterns in which species had the most and least activity, including that northern long-eared bats were the least commonly detected species (Russo-Petrick 2022). Other studies (Ford et al. 2011; Deeley et al. 2021) also found similar results in what species were declining in activity, although they did record an increase in big brown bat activity, unlike the current study. It is also worth noting that declines in activity may not completely reflect actual population trends, especially as bat activity tends to be very variable over time and some of the increases in activity observed after previous declines indicate unusually fast rebounds. However, unless future mist netting or hibernacula studies can be conducted, acoustic data currently provides the best measure of bat populations available for this region. Additionally, even if recorded activity does not exactly reflect population changes, it can still give a general idea of what species are more and less active over the 10-year period.

Conclusions

The results of this current study indicate changes in bat activity and community composition in the past 10 years. Managers should focus on increasing forest habitat for rare forest dwelling species (such as little brown and northern long-eared bats) and monitoring and assessing the impacts of management activities (such as habitat alteration) on bat activity. Additionally, annual studies in the Oak Openings region should continue and yearly volunteer survey programs should be implemented in other regions to allow the collection of additional data.

ACKNOWLEDGEMENTS

Bowling Green State University provided financial support and research materials. Toledo Metroparks gave permits for research and helped organize and recruit volunteers for bat monitoring events. Data from 2011 to 2018 were collected and processed by J. Sewald, C. Whorton, G. Janos, B. Adams, C. Nordal, Jennifer Hollen, T. Turner, A. Martin, and J. Schoen. Thank you to current Root lab members for support and assistance: B. Kron, S. Rair, and K. Ware. The authors would also like to thank all volunteers who collected data from 2011 to 2020.

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