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Original Article

Anuran communities increase aggregations of conspecific calls in response to aircraft noise

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Abstract

Noise pollution has been shown to affect wild animals in various ways, but little is known about its consequences at the community level. Investigating animals' overall vocal responses to noise across multiple sympatric species can reveal the complex nature of noise impacts but is challenging. In this study, we employed social network analysis (SNA) to evaluate how anuran communities and populations vary their calling behaviors in response to aircraft noise. SNA of anuran communities revealed that conspecific individuals increase the aggregation of their spectral (i.e., minimum frequency, maximum frequency, and dominant frequency), temporal (call duration, call rate, and call effort), and overall spectral–temporal features as an airplane passes through. SNA of populations also revealed that anurans could increase the interindividual similarity of multiple call characteristics in response to airplane noise. Furthermore, our network analysis of multiple species and multiple call traits revealed an effect of noise in species whose calling behavior did not change in previous separate analyses of each species and single traits. This study suggests that noise pollution may change the pattern of combined acoustic properties at the community level. Our findings highlight the importance of integrated methods and theories for understanding the ecological consequences of noise pollution in future studies.

Key words: acoustic similarity, anthropogenic noise, calling behavior, ecological consequences, social network analysis.

Human activities have driven unprecedented environmental changes. One major anthropogenic modification is the altered soundscapes globally, which is concomitant with increased noise intensity and the introduction of novel sources of sounds that vary from natural ones (Herbert-Read et al. 2017). Noise pollution is pervasive, even in protected areas (Buxton et al. 2017). Anthropogenic noise can seriously threaten ecological systems and is considered a potential cause of species decline and biodiversity loss (Bayne et al. 2008; Brumm and Horn 2019). For example, the sound produced by an airplane is the loudest source of noise (Smith 1989). An increasing number of airline businesses release increasing amounts of noise into various environments. Airplane noise may affect the survival and reproductive fitness of animals (Sun and Narins 2005; Klett-Mingo et al. 2016). In recent decades, noise pollution has become a global concern and has gained increasing attention among biologists and resource managers (Shannon et al. 2016; Jerem and Mathews 2021).

Understanding the effects of noise on wild animals can aid in biological conservation. Anthropogenic noise has been found to induce complex biological responses and influence wildlife in many ways (Shannon et al. 2016). Noise pollution can directly affect the behavior of many animals, such as mating (Bent et al. 2018; Senzaki et al. 2018; Duarte et al. 2019), foraging (Wale et al. 2013; Luo et al. 2015; Mason et al. 2016; Song et al. 2020), vigilance (Wale et al. 2013; Zhou et al. 2019), and territorial defence (Luther and Derryberry 2012). Human-generated noise can also influence multiple physiological responses that correlate with the stress response, immune regulation, hearing damage, cardiovascular health, DNA integrity, and gene expression (Kight and Swaddle 2011; Shannon et al. 2016). In addition, anthropogenic noise may affect the survival and reproduction of wildlife (Bee and Swanson 2007; Samarra et al. 2009; Schmidt et al. 2014; Nedelec et al. 2017; Dorado-Correa et al. 2018; Brumm et al. 2021). Although noise-induced pressure has been shown to influence different aspects of behavior, physiology, and fitness, recent investigations highlight several trends and knowledge gaps in fieldwork (Shannon et al. 2016; Jerem and Mathews 2021). One of the gaps is that most studies focus on individual organisms, with minimal research into effects on communities (Bruintjes and Radford 2013; Senzaki et al. 2020; Kok et al. 2023).

Animals often adjust their calling behaviors to adapt to environmental noise. For example, some birds advance their dawn chorus to avoid noisier periods (Gil et al. 2015; Alquezar et al. 2020). Frequency shifts in response to environmental noise are also well-known in many species. Some frogs, birds, and mammals emit lower or higher acoustic frequencies in more urbanized areas (e.g., Russo and Jones 1999;

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Luther and Derryberry 2012; Walters et al. 2019). Moreover, the temporal properties of some species modify their acoustic signals to cope with noise interference (Sierro et al. 2017; Wolfenden et al. 2019). Many researchers have investigated vocal adjustments at the level of single characteristics or individuals, but some difficulties remain in quantifying how multiple acoustic features are modified across groups of species (Potvin et al. 2019). Analyzing call properties at the community level is challenging but can reveal the complex nature of noise or other environmental impacts (Potvin et al. 2019).

Social network analysis (SNA) is a useful toolbox based on graph theory and has been increasingly used to describe complex interactions in animal communities (Farine and Whitehead 2015). This method employs data metrics to quantify the associations between individuals (Croft et al. 2011, 2016) and thus describes the pattern of multiple combinatorial properties. The SNA toolbox has great potential to address various questions in behavioral ecology (Krause et al. 2007; Wey et al. 2008; Sih et al. 2009). Some researchers have employed it to describe the social behaviors of animals, such as conspecific and interspecific interactions (Lusseau 2003; Farine et al. 2012). Many species interact with others via vocal signals. SNA can also be used to quantify some shared vocal properties (Weiss et al. 2014; Potvin et al. 2019), but few studies have employed it to reveal the effects of environmental change on acoustic communication systems at the community level. Here, we focus on noise pollution and use the tool to examine whether anthropogenic noise influences the acoustic network structure of animal communities.

Anurans depend heavily on acoustic communication and are sensitive to noise pollution. Many species have been found to modify their acoustic amplitude and spectral–temporal characteristics in response to noise (e.g., Kaiser and Hammers 2009; Parris et al. 2009; Halfwerk et al. 2016). Airplane noise is a typical example of noise pollution and may severely mask acoustic signals (Alquezar et al. 2020). Therefore, anuran communities around an airport constitute an excellent research system for exploring the effects of noise pollution on the vocal behavior of an animal community. The spot-legged tree frog (*Polypedates megacephalus*), Guenther's frog (*Hylarana guentheri*), pointed-tongued floating frog (*Occidozyga lima*), and ornamented pygmy frog (*Microhyla fissipes*) inhabit the surroundings of Haikou Meilan International Airport, Hainan. These species have different spectral–temporal call characteristics (i.e., minimum frequency, maximum frequency, dominant frequency, call duration, call rate, and call effort) and generate a dense multispecies chorus at night. A previous study explored how spectral–temporal characteristics vary with and without airplane noise (Zhao et al. 2021). However, it only investigates the effects of aircraft takeoff on separate call parameters from those of individual organisms. The responses of multiple traits to population/community metrics remain unclear.

In this study, we first used SNA to examine how anuran communities vary in acoustic spectral–temporal, spectral, and temporal networks in response to aircraft noise (multispecies network analysis). The spectral–temporal features (Group 1) included 3 spectral parameters (Group 2) and 3 temporal parameters (Group 3). These spectral, temporal, and spectral–temporal characteristics were grouped for statistical analysis. Second, we used SNA to examine the effects of aircraft noise on the spectral–temporal, spectral, and temporal networks of single species (single-species network analysis). Third, we analyzed the degree of dispersion (the coefficient of variation) of all call parameters in different species (the variability analysis of different parameters). These analyses allowed us to comprehensively evaluate the impact of airplane noise on the calling behaviors of sympatric anuran species. Species characterized by different call traits (e.g., frequency ranges) demonstrate different behavioral modifications in noise (Hu and Cardoso 2010). We thus hypothesized that the acoustic networks of frogs may change in response to aircraft takeoffs.

Materials and Methods

Study area and species

Our study site was located at a swamp close to Haikou Meilan International Airport, Hainan Province, China (19.94° N, 110.46° E). The study area was east of the runways (ca. 1 km) and consisted of a still-water pond and nearby marshes. The pond was consistently filled to more than half of its entire depth (water depth: 1–1.5 m; pond depth: <2 m), and marshes near the pond were filled with water and aquatic plants (herbaceous plants with a height of ~0.5 m). These environmental characteristics create very favorable conditions for the reproduction of several anuran species, including *H. guentheri*, which is a nycterohemeral species, whereas *P. megacephalus*, *O. lima*, and *M. fissipes* are nocturnal species. These frogs are the local dominant species (Zhao et al. 2021). According to our survey, they can breed at least from March to October on Hainan Island. In this study, these species were recorded between the 11 August and the 9 September 2020, during which all of them were in reproduction peaks. During sound recording, they generated a multispecies chorus at our study site. *Polypedates megacephalus* and *H. guentheri* produce calls with a dominant frequency of ~1.5 kHz, and the dominant frequency of *O. lima* and *M. fissipes* is ~3 kHz (Zhao et al. 2021). Airplane takeoffs can release high-intensity noise (Figure 1) into the calling sites of these frog species. Airplane noise has a broad frequency range (Figure 1) and severely overlaps with the acoustic signals of these frog species (Zhao et al. 2021).

Acoustic recording and measurement

All data for 6 acoustic parameters (i.e., the minimum frequency, maximum frequency, dominant frequency, call duration, call rate, and call effort) from the 4 anuran species were previously derived (Zhao et al. 2022). Acoustic data were collected only within a specific period (between 19:00 and 23:00 h on clear days) when all 4 sympatric anurans were actively called. After calling was initiated, a directional microphone (ME 66 + K6, Sennheiser, Germany) and a digital recorder (PMD 661, Marantz, Japan; sample rate, 44,100) were used to continuously record the calling of focal individuals before, during, and after airplane takeoff. The distance between the focal individual and the microphone was ~1 m in *H. guentheri* and *O. lima*. *Polypedates megacephalus* and *M. fissipes* were not sensitive to our approach and were recorded at a shorter distance (~0.5 m) to increase the signal–noise ratio. The takeoff intervals between airplanes were unpredictable; thus, the duration of each recording was variable. On average, the duration of each airplane was 281 s, of which the "before" and "after" recording categories were ~131 s and 90 s (not standardized), respectively, whereas the "during" category was 60 s (standardized). A single individual (the

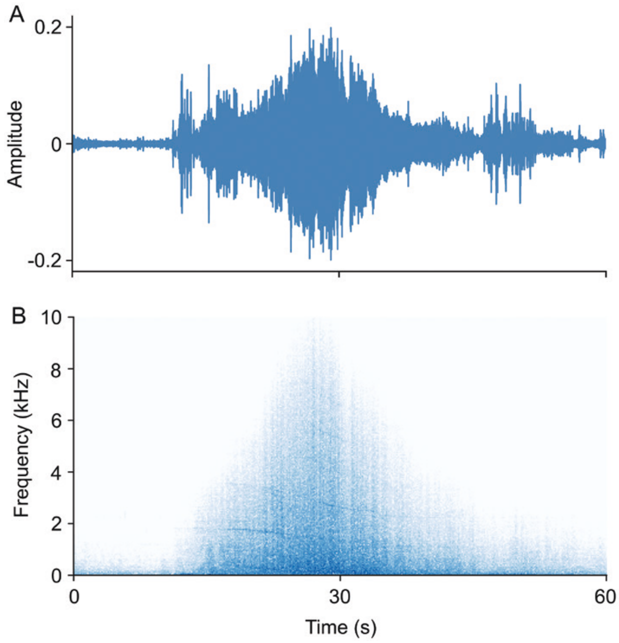

Figure 1 Waveform (A) and spectrogram (B) of aircraft noise. The recordings were made from the survey site.

"focal individual") was recorded at a time, and different species were recorded in turn. A total of 17 male *P. megacephalus*, 18 male *H. guentheri*, 19 male *O. lima*, and 18 male *M. fissipes* were recorded.

To evaluate the amplitude of aircraft noise, we measured the intensities of background noise (chorus and aircraft noise) and chorus noise during sound recordings. The amplitudes of the 2 sources were measured from a distance of ~1 m to the focal frog by a sound level meter (AWA 5661, Hangzhou Aihua Instruments Co., China). According to the logarithmic computation rule, ${}_{LA\ =\ 10\ \mathrm{log10}(10}{}^{(L}\mathrm{A + B}^{/10)}{}_{-\ 10}{}^{(L}\mathrm{B}^{/10)}{}_{)}$, where L_A, L_B, and L_{A+B} represent the sound pressure levels of aircraft noise, chorus noise, and overall background noise, respectively (Brumm and Zollinger 2011). The maximum background noise was ~83 dB when the focal frog was not calling, whereas the chorus noise was ~70 dB in the absence of flight takeoff. Consequently, the aircraft noise level during takeoff was ~82.8 dB after calibration.

All the parameters were measured via Adobe Audition software (version 3.0; Adobe Systems Inc., San Jose, CA, USA). To avoid observer-expectancy and interobserver biases, we assigned only 1 observer who was not familiar with the research background (but experienced with bioacoustics) to analyze all calls of each species. Frequencies features (i.e., the minimum and maximum frequencies as well as the dominant frequency) were measured using a power spectra method (FFT size, 512 points; window type, Blackmann–Harris), in which values were extracted at a decibel level relative to the peak amplitude. The peak value, minimum value, and maximum value corresponding to the decibel level were the dominant frequency, minimum frequency, and maximum frequency, respectively. To avoid the effects of noise masking and standardize frequency measurements, we used the same threshold (i.e., the decibel level relative to the peak amplitude in power spectra) to extract values of the same individual during the periods before, during, and after airplane takeoff. This method has been found to be impartial and reduces potential noise interference in the minimum and maximum frequency measurements (Zollinger et al. 2012; Brumm et al. 2017). Three temporal traits were included and defined as follows: call duration, the duration of the entire call; call rate, the number of calls per minute; and call effort, the number of call durations multiplied by the call rate. For each individual, the average number of calls per minute was calculated for 3 recording categories and used for later analyses. More details about the acoustic recording and measurement methods were included in our previous study (Zhao et al. 2021).

Data analysis

All analyses were conducted in R 4.1.0. Squared Mahalanobis distances between individuals were calculated independently for spectral–temporal (spectral: the minimum frequency, maximum frequency, and dominant frequency; temporal: call duration, call rate, and call effort), spectral, and temporal parameters using the *HDMD* package (McFerrin 2013) and were used as indicators of call similarity (Yoktan et al. 2011; Deng et al. 2021). The squared Mahalanobis distance is based on correlations between parameters, and a shorter distance implies a closer resemblance between call characteristics (McFerrin 2013). The inversely transformed squared Mahalanobis distance was used to generate a network for each period (before, during, and after the passing of an airplane) using the iGraph package (Csardi and Nepusz 2006). Consequently, a larger value represents greater call similarity between individuals.

We constructed multispecies networks using the inversely transformed squared Mahalanobis distance and calculated the assortativity by species for each period using the *assortnet* package (Farine 2014). Assortativity describes the correlation in the phenotype of connected individuals (Farine and Whitehead 2015). In this study, a positive assortment coefficient suggested that call similarity among individuals of the same species was greater than expected. To depict call similarity between individuals in networks, we constructed visualizations using the Fruchterman–Reingold algorithm in the iGraph package (Fruchterman and Reingold 1991; Csardi and Nepusz 2006), which essentially pulls nodes that are highly connected closer together. Nodes represent individual frogs in the visualized call characteristic networks, and edges represent call similarity, with a greater weight indicating greater similarity. To further determine whether the call characteristic networks of the 4 species were nonrandom, we compared the observed assortment coefficient with the coefficients calculated for 1,000 permutations of the network (Farine and Whitehead 2015). A network was considered structured if its observed assortment coefficient fell outside the 95% range of the random assortment coefficient distribution.

To investigate the variations in call similarities between conspecific individuals, we constructed networks for each species via the inversely transformed squared Mahalanobis distance and calculated the strength of each individual during each period. The strength is based on the sum of all of the edge weights connected to the focal individual (Farine and Whitehead 2015) and describes the similarity of the call characteristics between individuals. A greater strength represents greater call similarity. We further evaluated the variations in strength between the different periods via a Friedman test followed by pairwise comparisons (Wilcoxon signed-rank test). We also corrected the P values of all multiple comparisons using Holm's method.

We used the coefficient of variation (CV = (SD/mean) × 100%) to evaluate the variability in different acoustic characteristics across the 4 species. The CV describes the characteristics of vocalization in some anurans (Narins 2021). For each species, we calculated the coefficients of between-male variation in the minimum and maximum frequencies, dominant frequency, call rate, call duration, and call effort in 3 periods (before, during, and after the passing of an airplane). A high CV value indicates that a trait has high variability and is less stereotyped (Narins 2021). We accepted this rule and used it to evaluate how the dispersion degree of different parameters changed in response to aircraft noise. We employed a Wilcoxon rank sum test to compare the differences between the spectral and temporal CVs across all the species.

Results

Community call responses to aircraft noise

Our permutations of the spectral–temporal network for the 4 species revealed that the observed assortativities were significantly greater than those expected by chance in the 3 periods ($P_{\text{rand}} < 0.001$), suggesting that the call characteristic networks of these species did indeed aggregate nonrandomly. The assortativity of the spectral–temporal network in the "during" period was the highest among the 3 recorded periods (Supplementary Figure S1), which indicated a greater clustering of conspecific call traits (Figure 2A). Similarly, the multispecies call characteristic networks nonrandomly ($P_{\text{rand}} < 0.001$) exhibited a greater aggregation of conspecific spectral characteristics in response to airplane noise (Supplementary Figure S1; Figure 2B). Aircraft noise also caused an increase in assortment coefficients (Supplementary Figure S1) and the clustering of conspecific calls (Figure 2C) in temporal characteristic networks ($P_{\text{rand}} < 0.001$). Together, these results suggest that the call network of the frog community was more aggregated by chance when exposed to aircraft noise.

Underlying mechanisms of community call responses

SNA of the spectral–temporal, spectral, and temporal parameters suggested that *P. megacephalus* changed the interindividual similarity of all (spectral–temporal) characteristics (Friedman test: $\chi^2 = 6.125$, $df = 2$, $P = 0.046$) in response to airplane takeoff but not the spectral or temporal characteristics (Friedman test: $\chi_1^2 = 3.875$, $df_1 = 2$, $P_1 = 0.144$; $\chi_2^2 = 4.500$, $df_2 = 2$, $P_2 = 0.105$). However, further pairwise comparisons revealed no differences in spectral–temporal similarity between the periods before, during, and after aircraft takeoff (Wilcoxon signed rank test: $V = 112$, adjusted $P > 0.05$; Figure 3A). When the plane took off, the interindividual similarity of the spectral–temporal and spectral networks of *O. lima* significantly differed (Friedman test: $\chi_1^2 = 20.333$, $df_1 = 2$, $P_1 < 0.001$; $\chi_2^2 = 23.111$, $df_2 = 2$, $P_2 < 0.001$). Further analyses revealed that *O. lima* significantly increased the strength of its spectral–temporal and spectral networks in response to high-intensity noise (Wilcoxon signed rank test: adjusted $P < 0.05$ in all comparisons; Figure 3B). However, the strength of the temporal network of this species was not affected by aircraft (Friedman test: $\chi^2 = 3.111$, $df = 2$, $P = 0.211$). Furthermore, the spectral–temporal, spectral, and temporal networks of *M. fissipes* and *H. guentheri* did not vary significantly in terms of interindividual similarity in response to airplane takeoff (Friedman test: $df = 2$, $P > 0.05$ in all tests; Figure 3C, D). Taken together, aircraft noise affected the call network structure of *O. lima* (but not the other 3 species), and the similarity of its multiple call features significantly increased in response to the passing of airplanes.

The coefficients of between-male call variations revealed that spectral parameters (i.e., the minimum, maximum, and dominant frequencies) had lower CVs than did temporal parameters (i.e., call duration, call rate, and call effort) (Wilcoxon rank sum test: $W = 0$, $P < 0.001$; Figure 4). Therefore, the spectral traits of the 4 frog species were less variable than their temporal traits were. As shown in Figure 4, each species showed no common trend in the dispersion degrees of different call parameters when the aircrafts took off. Different species also presented no common trend in the degree of dispersion of the same trait in response to aircraft noise bursts.

Discussion

Animals' calling responses to noise at the community and population levels

In this study, the noise-induced aggregation of acoustic signals has 2 possible explanations. Among the 4 anuran species, the acoustic, spectral, and temporal traits of each species vary significantly within a population (Zhao et al. 2021), resulting in individuals being affected differently by the same masking noise. For example, the dominant frequency of *H. guentheri* ranges from 11,00-2,000 Hz; however, airplanes produce high levels of low-frequency noise, which has the most energy below 3 kHz (Figure 1). The noise-masking effect may be due to the degree of overlap between the noise frequency and the call frequency (Francis and Barber 2013). Low-frequency calls may be more adjusted, whereas high-frequency calls are less varied (Hu and Cardoso 2010), resulting in limited signal variation between individuals. Thus, the reduced variation in specific spectral–temporal traits may cause an increase in the overall similarity of acoustic signals (the first explanation). Additionally, animals may modify whole-signal characteristics directly but not some specific traits in response to noise pollution (Hage et al. 2013, 2014). The higher clustering of acoustic signals may also be the outcome of entire spectral–temporal characteristics (the second explanation). In the present study, the CVs of the different parameters did not support the first possible explanation. Moreover, the results of the aggregated spectral and/or temporal characteristics of multiple species were not consistent with the findings of the specific spectral and/or temporal traits of a single species. Consequently, our results support the second possibility. Noise-evoked changes in call networks of anuran communities may be an overall performance of a multispecies chorus.

Anthropogenic noise affects the survival and reproduction of wildlife (Dominoni et al. 2020). For example, urban noise disturbs male–female communication in avian species that attract mates via low-frequency acoustic signals (Halfwerk et al. 2011). In *Dendropsophus microcephalus*, males significantly decrease chorus activity as well as daily chorus duration, which implies a shorter reproductive period (Kaiser et al. 2011; Zaffaroni-Caorsi et al. 2023). Noise pollution also influences interspecific interactions such as prey–predator relationships (Francis et al. 2009; Siemers and Schaub 2011; Halfwerk and van Oers 2020). In addition, noise pollution can reduce species richness and change community

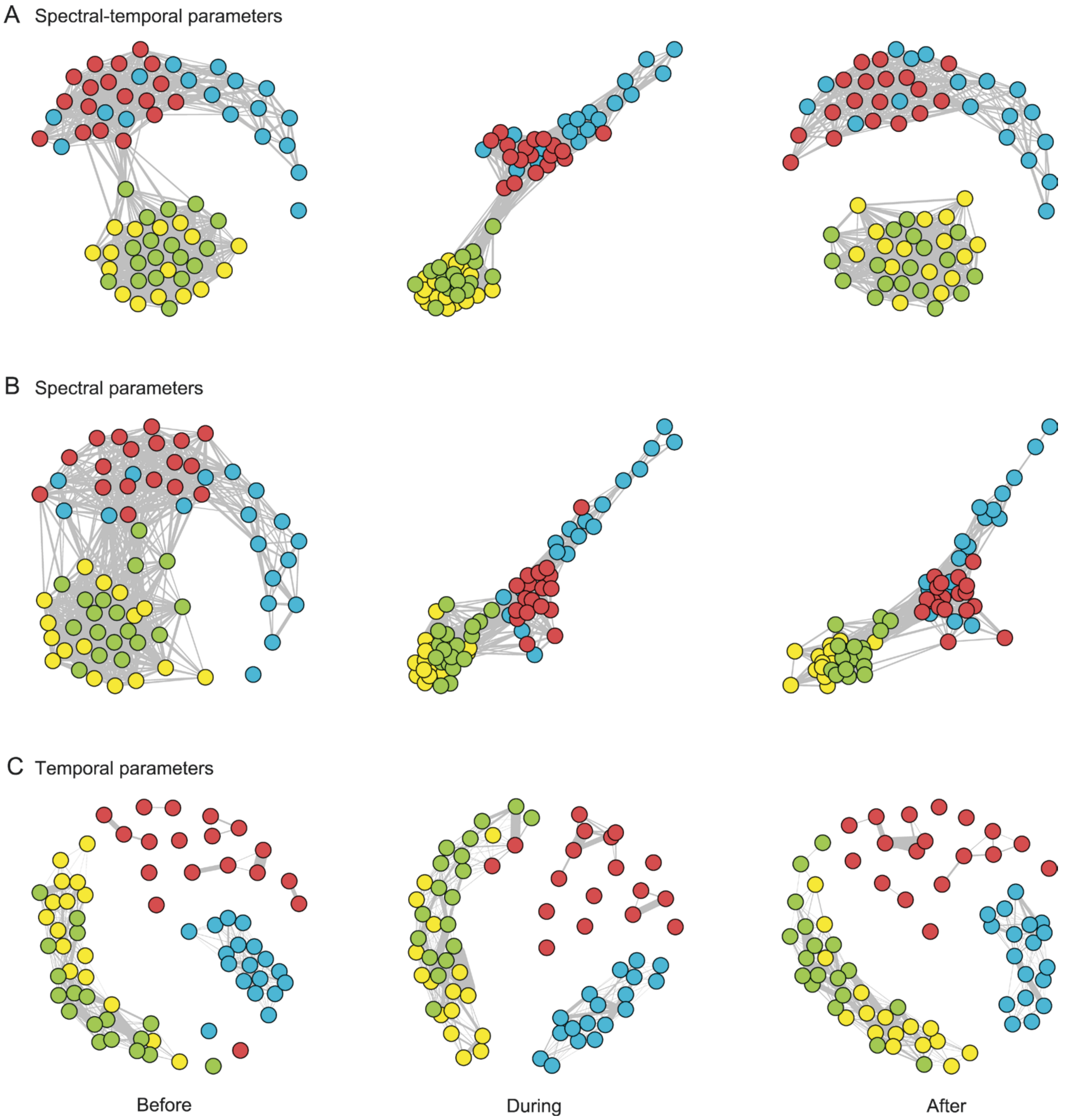

Figure 2 Call characteristic networks of 4 species from different periods based on the spectral–temporal parameters (A), spectral parameters (B), and temporal parameters (C). Nodes represent individuals, and each species is represented by a different color (yellow: *P. megacephalus*; green: *H. guentheri*; blue: *O. lima*; red: *M. fissipes*). The edge thickness highlights the similarity in the call characteristics between individuals. Strengths less than 0.05 were omitted for the sake of clarity. Visualizations were constructed using the Fuchterman–Reingold method of the *iGraph* package (Fruchterman and Reingold 1991; Csardi and Nepusz 2006).

composition and structure (Zaffaroni-Caorsi et al. 2023). Playback tests on anurans at the community level suggest that anthropogenic noise may reduce the number of individuals, even though species richness does not change (Grace and Noss 2018). Many animals adjust call traits to cope with noisy conditions; however, the alteration of a single parameter may not be enough because noise can influence multiple call traits. Anuran communities increase the overall similarity of conspecific calls in response to noise, which benefits the discrimination of conspecific signals over heterogeneous signals in noisy environments. The role of such adjustments in fitness, however, needs further research in the future. Research on more systems would reveal whether such performance is a general behavioral response because other communities (e.g., bird and other anuran communities) may also perform similar acoustic aggregation when exposed to noise pollution.

SNA of each species revealed that the network strength of *O. lima* and *P. megacephalus* was significantly affected by aircraft takeoff. Further pairwise comparisons revealed that *O. lima* increased the strength of its spectral–temporal

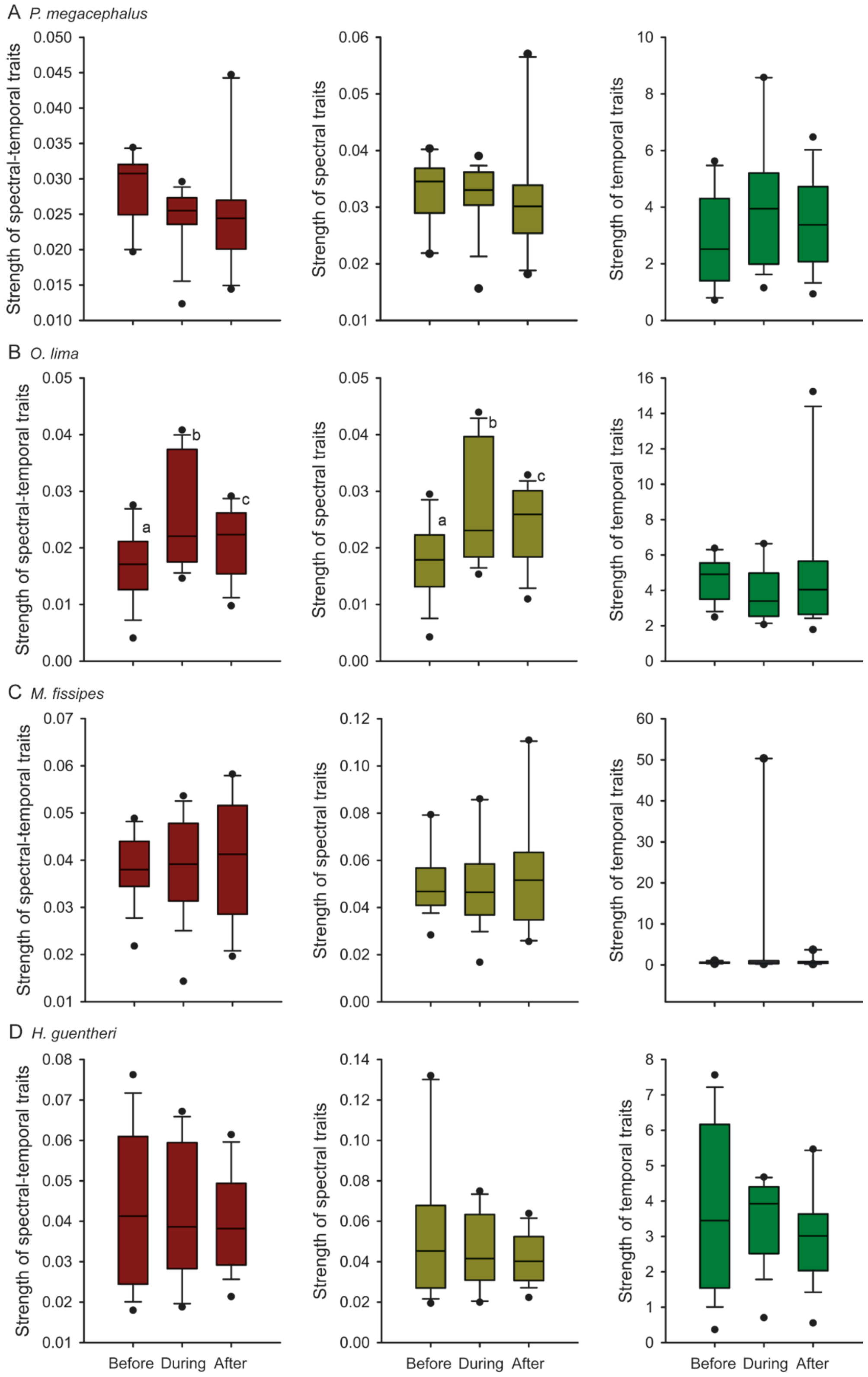

Figure 3 Variations in the association strengths of *P. megacephalus* (A), *O. lima* (B), *M. fissipes* (C), and *H. guentheri* (D) before, during, and after plane takeoff. Superscripts that do not share the same letter represent a significant difference ($P < 0.05$).

and spectral characteristics in response to aircraft noise. *P. megacephalus*, however, did not increase its overall network strength. *O. lima* did not adjust all its individual traits in a noisy period (Zhao et al. 2021). The plasticity of all the acoustic traits may help this species cope with aircraft noise. SNA at the population level also suggests that animals may increase interindividual call similarity to decrease noise interference. Moreover, the spectral–temporal, spectral, and temporal networks of *M. fissipes* and *H. guentheri* did not change in response to aircraft noise. Previous studies that independently

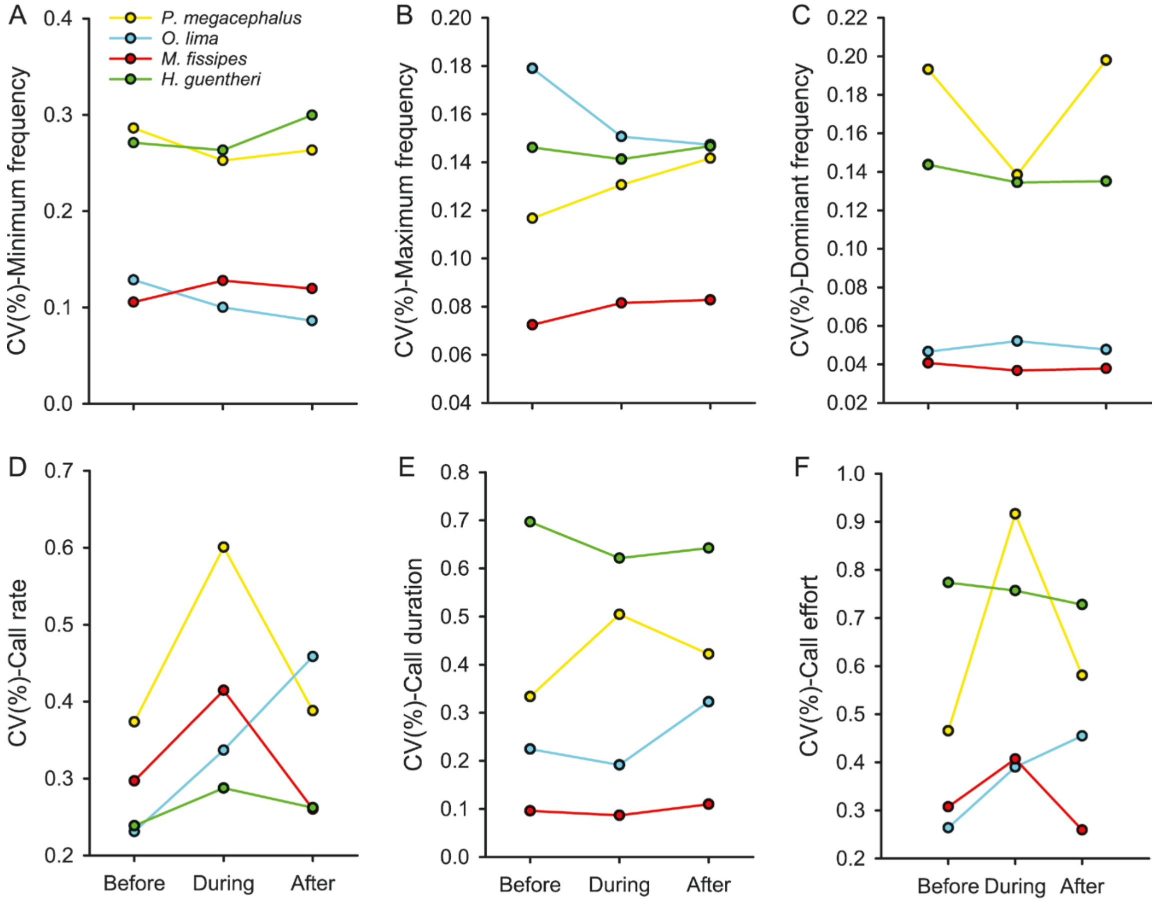

Figure 4 The between-male variability of the minimum frequency (A), maximum frequency (B), dominant frequency (C), call rate (D), call duration (E), and call effort (F) in the 3 periods for 4 frog species.

investigated all call parameters (i.e., the minimum frequency, maximum frequency, dominant frequency, call duration, call rate, and call effort) of these species revealed different effects of aircraft noise on their spectral and temporal characteristics (Zhao et al. 2021). Among the 4 species, *P. megacephalus*, *H. guentheri*, and *M. fissipes* significantly modified their call structures or calling activities in response to noise generated from airplane takeoff, whereas *O. lima* did not alter any call characteristics (Table 1). Using the same data, however, we found an effect of aircraft noise on the overall acoustic traits of *O. lima*. These results suggest the necessity of integrated methods and theories, that is, those enabling the evaluation of whole traits at multiple species scales (e.g., SNA), for investigating the ecological consequences of noise pollution.

Most research into behavioral adaptations is predominantly based on separate parameters or individual taxa. Such tactics may limit our comprehensive understanding of noise pollution effects. Many anuran species are known to perform behavioral adjustments during exposure to various types of human-made noise, such as road traffic and aircraft noise (e.g., Sun and Narins 2005; Lengagne 2008; Roca et al. 2016; Caorsi et al. 2017). Like that on *O. lima*, however, research on some species that produce choruses also shows that different call characteristics are not affected by traffic noise. For example, the spectral and temporal features of *Boana leptolineata* and *Hyla arborea* do not change in response to traffic noise (Troïanowski et al. 2015; Caorsi et al. 2017). *Kurixalus chaseni* maintains its acoustic spectral–temporal parameters as well as amplitude during exposure to low-intensity traffic noise (Yi and Sheridan 2019). For these species, the impact of noise pollution may be concealed when different signal traits are examined separately. Therefore, this study provides important insights for future research.

The effects of airplane noise on animals' calling behaviors can vary over time (e.g., different periods every day) and space (e.g., the location relative to the airport). Four frog species generated multiple species choruses only at a pond and nearby marsh from 19:00-23:00 h. Thus, we evaluated the effects of plane noise on these species only within a specific period and in a specific location. In addition, we only measured acoustic changes after ~90 s of aircraft takeoff and did not analyze the time frame over which the spectral or temporal parameters may return to the "before" configuration. Manual digital recorders can record high-quality vocalizations in close range. Passive acoustic monitoring devices (PAMs) may not obtain high-quality acoustic data but have recording advantages over great temporal and spatial dimensions. Research using PAMs would further increase our understanding of how noise impacts anuran chorusing.

Conservation and management implications

Our findings may aid in estimating the ecological consequences of anthropogenic noise and have crucial implications for conservation and management. First, most research

Table 1. Changes in the call characteristics of the 4 frog species during airplane passage

Species	Minimum frequency	Maximum frequency	Dominant frequency	Call rate	Call duration	Call effort
P. megacephalus	↑	↑	↑	↓	—	↓
H. guentheri	↑	—	—	↓	—	—
O. lima	—	—	—	—	—	—
M. fissipes	—	—	—	↓		↓

Note: The signs "↑," "↓" and "—" indicate the increase, decrease and invariability of the acoustic parameters, respectively. All the results are summarized from Zhao et al. (2021).

has failed to investigate the acoustic responses of animals at the community level (Senzaki et al. 2020). We suggest that some species may not change all individual features at the population level (but may change overall characteristics at the community level). This implies that noise impacts on calling behaviors may be more general, and integrated efforts are necessary in future works. In addition, the species in this study have been found to change acoustic parameters such as call frequency and call effort (Zhao et al. 2021). These spectral and temporal traits can affect female preferences and male reproductive success in birds (Halfwerk et al. 2011) and anurans (Sun and Narins 2005; Schou et al. 2021). The fitness benefits of multiple acoustic changes may imply animal conservation because they are directly related to species richness and biological diversity.

Noise pollution is a global problem and can impose great pressure on wild animals. Anthropogenic noise potentially affects the calling behaviors of individuals, populations, and communities; however, our understanding of the effects of noise at the community level is limited (Kok et al. 2023). By introducing SNA methods, we reveal that the anuran community increases the aggregation (similarity) of conspecific call characteristics in response to aircraft noise. Consequently, anthropogenic noise can alter the patterns of acoustic-sharing networks between sympatric species that utilize calling for social communication. Some human-made noise, such as ship whistles and the passing of trucks, has low-frequency, high-amplitude, and short-term burst characteristics, which are very similar to the aircraft noise in the present study. Such noise can impose similar constraints on animals. Therefore, our results are not specific to airplane noise and may also apply to other kinds of noise pollution. These findings provide new insights into how animals are influenced by human-made noise as well as how they respond to noise pollution.

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Authors' Contributions

L.Z. and J.W. designed the research. L.Z., T.W., X.Z., and R.G. performed the experiments. L.Z., K.D., J.W., and J.C. analyzed the data and wrote the paper. All the authors read and approved the final version.

Conflict of Interest statement

We have no conflicts of interest.

Supplementary Material

Supplementary material can be found at https://academic.oup.com/cz.

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