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研究課題名（和文）21st Century monitoring tools to make Okinawa a natural laboratory for ecology and evolution

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研究成果の概要（和文）：研究の目標は、沖縄本島に音声レコーダーを設置し、生物多様性の測定と人為的改変による変化を明らかにすることであった。概念実証では、サウンドスケープ指標を使用し、多様性の時空間変化と野鳥の自動識別に成功した。その後の解析では次の3つの目的に取り組んだ：1.生物音響学を私用したα多様性の推定、2.都会と農村部の音響β多様性の比較、3.沖縄全域の音声分布マッピング。研究を通し、生物音響の多様性は人間の妨害行動とともに減少することがわかり、都会は農村部に比べ、音響多様性が多大に異なることを明確にした。論文の出版だけでなく、イベントや博物館での展示を通して沖縄社会へ研究成果を発信した。

研究成果の学術的意義や社会的意義
My study began a natural history archive that is a record of Okinawa’s biodiversity. I demonstrated a proof of concept for acoustic monitoring, and addressed three ecological questions. My research was reported to society by publications, lectures, a museum exhibit, and several media appearances.

研究成果の概要（英文）：The overall goal of this project was to develop an acoustic monitoring program on Okinawa to measure biodiversity and test hypotheses about its response to anthropogenic disturbance. I installed recorders at 24 sites across the main island of Okinawa, maintained in collaboration with the Okinawa Environmental Observation Network (OKEON). In a proof of concept, I demonstrated my ability to compare biodiversity across time and space using soundscape indices, and to automatically detect bird species. Subsequent analyses have addressed the three principal aims of this grant: (1) to estimate alpha diversity using bioacoustics, (2) to compare acoustic beta diversity among urban and rural sites, and (3) to map the spatial distribution of sound across Okinawa. I show that acoustic diversity decreases with disturbance, and that urban sites are more different from each other than rural sites. Beyond publications, I used public events and museum exhibits to communicate my results to the public.

研究分野：Basic Biology

キーワード：Soundscape Ecology　Bioacoustics　Animal Behavior　Biodiversity　Evolutionary Biology　Sensory Ecology

１．研究開始当初の背景

Research background

Understanding the spatial distribution of biodiversity, as well as where and how human activity has the greatest impact on it, is essential for guiding conservation planning and achieving sustainability goals. The problem is that cataloguing and measuring biodiversity using conventional methods can be expensive: each survey requires a large amount of manpower from experts in the field. Acoustic monitoring is an emerging approach that allows these surveys to be conducted rapidly, regularly, and with a small staff. Many animals use sound to communicate, and these sounds can be an index of an ecosystem’s diversity across multiple trophic levels. Environmental recordings (soundscapes) include this information as a single electronic collection event, and can also include information on stressors such as anthropogenic noise.

２．研究の目的

Research Objectives, Purpose

Here, I aimed to build an acoustic monitoring system to estimate and track biodiversity on the island of Okinawa. Because its population density is distributed along a gradient from the urban south, to rural north with many rare endemic species, Okinawa is an ideal system in which to study the impact of human activity on biodiversity.I aimed to demonstrate the utility of acoustic monitoring in Okinawa by 1) using high-performance computing to compare the distribution of natural and anthropogenic sounds throughout the year, and 2) use machine learning to identify particular species and track their behavior across time and their distribution across space. Together, these represent new tools for monitoring biodiversity and can be used to test a number of ecological hypotheses.

３．研究の方法

Research Methods

I installed SongMeter SM4 acoustic monitors (Wildlife Acoustics, Maynard, MA, USA) at 24 sites across the island of Okinawa in spring of 2017. These sites coincide with arthropod collection sites that are part of the Okinawa Environmental Observation Network (OKEON). This project also includes weather monitoring and camera trap data sources, allowing for comparisons across many levels. Monitoring sites record audio in uncompressed .wav format for 10 minutes out of every 30 minutes, and are serviced in the field once every 14 days. In total, this has led to 100TB of natural sound recordings, which are archived on the OIST supercomputing cluster.

These data would take >16 years for a single person to listen to, assuming they did this 24 hours a day and 7 days a week. To analyze this kind of ecological big data, I used two approaches: first, I processed the raw audio into frequency bins representing different acoustic niches and analyzed the diversity of these frequency bins using a number of conventional ecological metrics (e.g., entropy, evenness). Second, I trained hidden Markov models to recognize different bird species. Using this approach, I was able to isolate individual species, or in some cases employ citizen scientists to identify clusters of similar recordings identified by the computer.

In particular, I used a set of scripts modified from those described from the R package *soundecology* by Villanueva-Rivera et al. (2018), and a parallelized version of *Matlab* scripts described in Lin et al. (2017). To perform unsupervised clustering and automated species identification, I used a cluster build of *Kaleidoscope* (Wildlife Acoustics, 2018).

Prior to analyzing the full dataset, I ran our analyses on data collected from 5 sites across a set of two-month trial periods in the summer of 2016 and another 5 sites in the winter of 2017. These allowed me to iterate and improve my methods on a dataset small enough to analyze in a single day with a personal computer. Subsequent analyses on the full dataset have been performed using OIST’s supercomputing cluster. A typical soundscape analysis utilizes 24 processor cores (i.e., one compute node) for a duration of 72 hours. These analyses were repeated for each site and analysis method after the first year complete year of recording.

４．研究成果

Proof of Concept

I began with a proof-of-concept demonstrating the utility of soundscape ecology for monitoring biodiversity (Ross, Friedman et al. 2018). I analyzed data collected from five sites across Okinawa over a one-month recording session in the summer of 2016. The results from this preliminary analysis showed several important findings. First was a demonstration of the feasibility of acoustic monitoring at remote field sites distributed across a broad geographic range (in this case, the length of Okinawa – approximately 100km from the southernmost site to the northernmost). Second, I found several challenges that needed to be addressed in studies using soundscape ecology methods to assess biodiversity, namely the prevalence of noisy insects, such as cicadas and katydids. Third, I demonstrated my ability to train machine learning models to reliably search sound libraries for individual species and detect their vocalizations. This allowed me to track the behavior of five bird species, and to assess their occupancy of five different habitats across Okinawa. Lastly, while there was considerable variability in the degree to which the five different soundscape indices we calculated reflected biological patterns, there was one clear pattern: the dawn chorus of bird songs at sunrise. Consequently, much of our subsequent work has focused on the intensity of the dawn chorus as a daily census of the local avifuana.

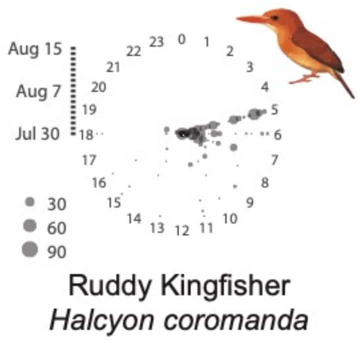

Fig. 1: Machine observations of a bird species on Okinawa

Subsequently, this grant facilitated the expansion of the acoustic monitoring program on Okinawa to encompass the whole island, with microphones recording at all 24 field sites in the core OKEON project. This new dataset was analyzed following the collection of two complete spring seasons, thus addressing directly the aims of the grant.

Aim 1: Alpha Diversity Estimation using Soundscapes

Many projects in soundscape ecology struggle to isolate and accurately quantify biological diversity without identifying the origin of each sound. To avoid this pitfall, I focused on a daily biological phenomenon: the dawn chorus of singing birds. I measured an acoustic diversity index (ADI) and normalized difference soundscape index (NDSI) for all recordings falling within the hour after sunrise. As expected, these metrics exhibited a yearly phenology, increasing from spring into summer, and decreasing in autumn into winter. However, soundscape indices were often saturated in the summer, which I had previously observed as a period of strong insect activity. To prevent the inclusion of insects in acoustic surveys, I focused on the interval in spring between March 1 and June 1, which is the approximate breeding season of many bird species on Okinawa. During this period, most sounds recorded in the morning are of an avian origin. This makes the dawn chorus a daily census of bird activity and a proxy for bird populations.

I compared recordings from this period across the urban-rural gradient of sites in my study, and used GIS-derived environmental variables to predict the spatial distribution of acoustic alpha-diversity. Because many of the variables that describe each site are correlated, I estimated their axes of dissimilarity using a non-metric multidimensional scaling approach in the R package *vegan*. The principal axes were (1) the level of disturbance - ranging from intense cultivation, to urban parkland, to the near-wilderness of the Yanbaru forest (the distance to the nearest building and the proportion of bare-earth land-cover were the strongest predictors of this), and (2) the exposure of the site to the elements - ranging from salt-inundated coastal scrub to interior forests.

I found that acoustic diversity (ADI) was highest in regions that had the least human disturbance, in particular the absence of buildings and intensive agriculture (Fig. 1). The prevalence of animal sounds over human sounds (NDSI) exhibited a similar trend.

Aim 2: Beta Diversity in Urban vs. Rural Okinawa

I predicted that acoustic beta diversity (turnover in species composition between sites) should be highest between rural sites. My reasoning for this was that there should be many unique forest communities, but the city should always be dominated by invasive species. Unexpectedly, my results show the exact opposite. I tested this by measuring the pairwise distance in soundscape diversity between sites, as compared within each 33% quantile of disturbance (MDS1). I found that acoustic beta diversity was highest among the most disturbed sites, and lowest among the least disturbed (Fig. 3; Kruskal-Wallace $p < 0.001$). These unexpected results are perhaps more interesting than my initial predictions. The first line of Tolstoy's *Anna Karenina* reads: *"All happy families are alike; each unhappy family is unhappy in its own way"*. My observations reflect this principle. Healthy ecosystems on an island as small as Okinawa have many bird species in common. In contrast, it is disturbed sites that exhibit the greatest beta diversity, perhaps depending on the unique combination of ecological stressors that reduce its species pool. This "Anna Karenina principle" has been suggested before in ecology (Moore 2001), but seldom tested.

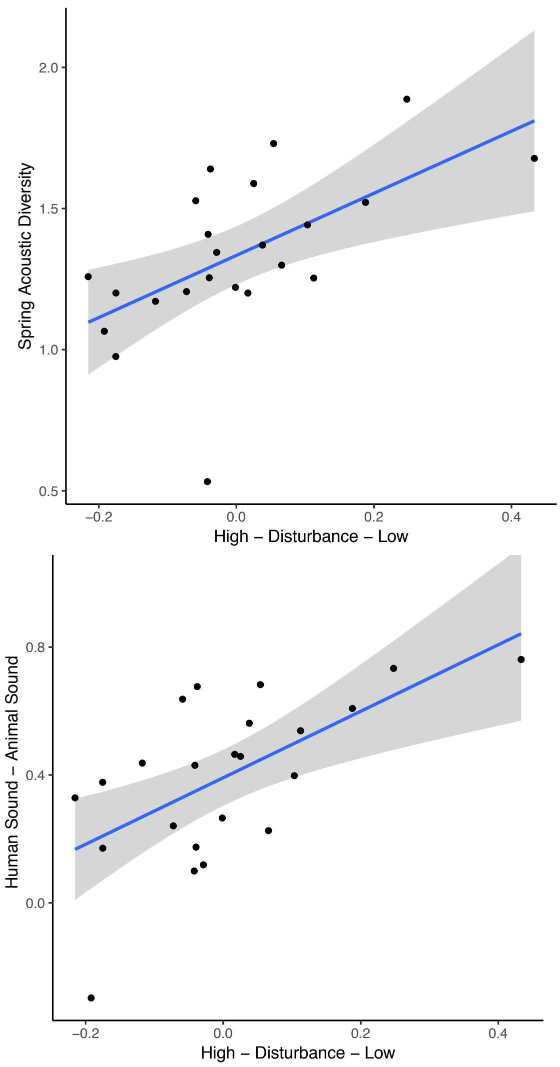

Fig. 2: Acoustic alpha diversity of the spring dawn chorus compared with environmental predictors. Each point represents a 2-month average from one site. Both linear regressions $p < 0.005$.

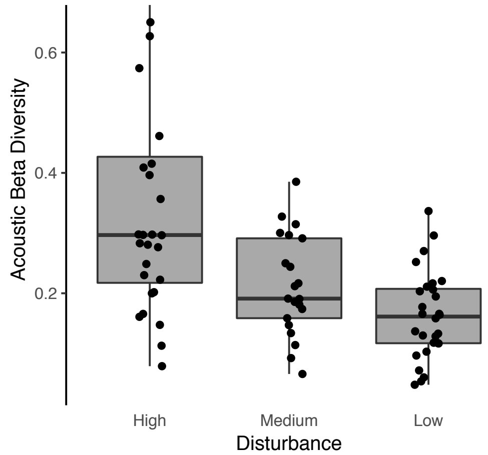

Fig. 3: Acoustic beta diversity of the spring dawn chorus compared with environmental predictors. Each point represents the Bray-Curtis distance between frequency bins at two sites of a category.

Aim 3: Mapping Sound Intensity on Okinawa
Previous approaches to mapping sound have focused on modeling point sources and the physics of sound attenuation in the environment. Such deterministic approaches can produce very high-resolution predictions, but they can be limited by the accuracy of point source reporting. This project takes an empirical approach instead: we measured sound and mapped its location. My goal is to produce a temporo-spatial model for soundscape indices and noise levels on the island of Okinawa. Unfortunately, validation of this model is not yet complete, though testing is underway using the R package *spTimer*. In the meantime, direct observations can be interpolated, such as in the Voronoi diagram in Fig. 4. I aim to complete these analyses by the end of 2019, following the collection of recordings from validation points across the island.

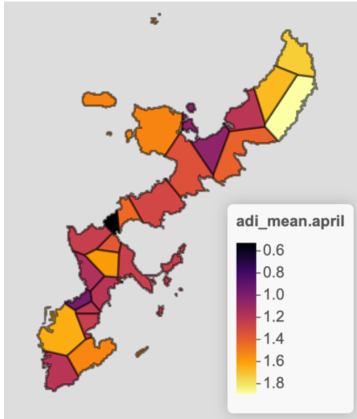

Fig. 4: Voronoi diagram mapping diversity of the dawn chorus across Okinawa.

５．主な発表論文等

〔雑誌論文〕（計　6　件）(* = peer-reviewed)

(1) *Friedman, N.R., V. Remes, E.P. Economo. A morphological integration perspective on the evolution of dimorphism among sexes and social insect castes. Integrative and Comparative Biology, 2019. doi:10.1093/icb/icz053
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(1) Friedman, N.R., E.T. Miller, J.R. Ball, H. Kasuga, V. Remes, E.P. Economo. Evolution of a multifunctional trait: shared effects of foraging ecology and thermoregulation on beak morphology with consequences for song evolution. Ecological Society of Japan, 2019.
(2) Ross, S.R.P.-J., N.R. Friedman, M. Yoshimura, I. Donahue, E.P. Economo. Urbanisation erodes acoustic diversity and stability in Okinawa. Ecological Society of Japan, 2019.
(3) Friedman, N.R., E.P. Economo. A morphological integration perspective on the evolution of dimorphism among sexes and social insect castes. Society for Integrative and Comparative Biology, 2019.
(4) Ross, S.R.P.-J., N.R. Friedman, M. Yoshimura, I. Donahue, E.P. Economo. Urbanisation erodes acoustic diversity and stability in Okinawa, Japan. Irish Ecological Association, 2019.

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(8) Ross, S.R.P.-J., N.R. Friedman, M. Yoshimura, I. Donahue, E.P. Economo. Using ecoacoustics to monitor ecological stability along an urbanization gradient. Ecological Society of America, 2018.
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〔図書〕（計　1　件）

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〔産業財産権〕
○出願状況（計　0　件）
○取得状況（計　0　件）

〔その他〕
ホームページ等

Soundscape exhibit at Okinawa Municipal Museum:
In this exhibit, we displayed museum specimens with QR codes. These QR codes can be scanned using a typical smartphone, and they link each specimen to the sounds that the living animal makes. Another display showed the distribution of different sounds across the island of Okinawa, which can be found at the website in the QR code at right.

６．研究組織

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