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Author(s)	Nakano, Yurika; Senzaki, Masayuki; Ishiyama, Nobuo; Yamanaka, Satoshi; Miura, Kazuki; Nakamura, Futoshi
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Short Communication

Noise pollution alters matrix permeability for dispersing anurans: Differential effects among land covers

Yurika Nakano^a, Masayuki Senzaki^{b,*}, Nobuo Ishiyama^a, Satoshi Yamanaka^c, Kazuki Miura^d, Futoshi Nakamura^a^a Graduate School of Agriculture, Hokkaido University, Kita 9, Nishi 9, Kita-ku, Sapporo, Hokkaido, 060-8589, Japan^b Center for Environmental Biology and Ecosystem Studies, National Institute for Environmental Studies, Onogawa 16-2, Tsukuba City, Ibaraki, 305-8506, Japan^c Hokkaido Research Center, Forestry and Forest Products Research Institute, Hitsujigaoka 7, Sapporo, 062-8516, Japan^d Graduate School of Environmental Science, Hokkaido University, Kita 10, Nishi 5, Kita-ku, Sapporo, Hokkaido 060-0810, Japan

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ABSTRACT

Successful dispersal or movement between patches in fragmented landscapes is key for the survival and population persistence of wildlife. Despite the growing interest in the impacts of anthropogenic noise, how noise alters the permeability of different types of land cover to animal movement in fragmented landscapes is underappreciated. Here, we experimentally quantified the movement distances of a frog species in three types of land cover common to fragmented landscapes (lawns with or without canopy cover and artificial bare land) under two acoustic manipulations (traffic noise vs. a silent control). The results showed that the effects of noise on frog movements varied among land covers: with movement being impeded on bare land and unaffected on lawns with and without a closed canopy. These results suggest that anthropogenic noise and land cover types can interactively affect the functional connectivity of these anurans and increase our understanding of the complex ecological consequences of urbanization. Our finding emphasizes that the impacts of noise on animal movement in fragmented landscapes should be evaluated with consideration of land cover types.

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1. Introduction

Habitat fragmentation has been expanding worldwide, and the importance of biodiversity conservation in fragmented landscapes is well appreciated (Haddad et al., 2015). In fragmented landscapes, many species breed in habitat patches and use the surrounding matrix for movement between patches (Daniel et al., 2010), which indicates that matrix permeability is key for the successful settlement of dispersing individuals in preferred patches as well as for long-term population persistence (Van Buskirk, 2012). Therefore, the exploration of factors affecting matrix permeability is a key aspect for biodiversity conservation in fragmented landscapes (Cline and Hunter, 2014; Van Buskirk, 2012).

Anthropogenic noise (hereafter, “noise”) is a widespread pollutant in fragmented landscapes and its spatial distribution has still been expanding (Buxton et al., 2017). During the last several decades, noise pollution has been linked to a wide range

* Corresponding author.

E-mail address: senzaki.masayuki@nies.go.jp (M. Senzaki).

of behavioural alterations and reduced habitat use across taxa (Bunkley et al., 2015; Francis et al., 2011, 2009; Injaian et al., 2018; Kleist et al., 2017; Senzaki et al., 2016). Recently, noise has also attracted attention as a potential driver of matrix permeability for animals (Shannon et al., 2016). For example, noise delays the movement of gravid female anurans travelling towards male advertisement calls in a forest landscape (Tennessen et al., 2014). However, noise may have complicating effects on animal movement in the matrix because several mechanisms (e.g., increasing vigilance levels, distraction, active avoidance) can operate simultaneously and their strengths may interact with matrices (Luo et al., 2015; Ware et al., 2015). For example, the noise impacts on vigilance, ultimately on movement, may be larger in more urbanized environments such as gardens than in natural environments such as forested corridors because animals' vulnerability to disturbance may be prominent in stressful environments (Boucek et al., 2017). Moreover, matrices in fragmented landscapes are mosaics of various land covers with different levels of resistance for animals (Shimazaki et al., 2017, 2016). Therefore, the effects of noise on animal movement may differ among land covers. However, to date, no study has demonstrated matrix-dependent movement in response to noise.

The objective of this study was to experimentally evaluate whether the effects of noise on animal movement differ between land covers common to matrices in fragmented landscapes. We studied anurans because they exhibit cosmopolitan distributions but are declining globally due to various human activities including acoustic degradation, habitat loss and fragmentation, disease, over exploitation, and climate change (Cushman, 2006; Hof et al., 2011; Pittman et al., 2014). Anurans are commonly present in fragmented landscapes, and knowledge of the permeability of matrices to the movement of anurans is critical for their conservation because matrix permeability can affect gene flow between populations (Ishiyama et al., 2015; Van Buskirk, 2012). Furthermore, valid methods to quantify the relative permeability of different land cover types to anurans are available (Cline and Hunter, 2014). In this study, we established multiple experimental runways on three types of land covers (lawns with or without canopy cover and artificial bare land) in a fragmented landscape in northern Japan. We selected these land cover types based on their different qualities for dispersing anurans: the lawn with canopy was assumed to be most suitable for their dispersal because of its lowest risk of desiccation. The artificial bare land was assumed to be most unsuitable because of its highest risk of desiccation. The lawn without canopy was assumed to be a middle risk habitat. We then released frogs that were captured in breeding areas onto these runways under two acoustic manipulations (i.e., broadcast traffic noise vs. a silent control) and quantified how noise affected the movement distance of individual frogs per night on each land cover. We expected differential effects of noise on permeability of each land cover type because a high-quality matrix can compensate the influence of anthropogenic noise and vice versa. Thus, based on their dispersal suitability, we predicted that the noise impacts on the frog movement would be largest in the artificial bare land compared to the other land cover types.

2. Materials and methods

2.1. Model species and sampling

We used the Japanese tree frog *Hyla japonica*, which occurs throughout Japan and breeds in various shallow waterbodies (e.g., rice paddies) from April to July. After breeding, they disperse into surrounding habitats, such as forests. We collected a total of 76 individuals from rice paddies in two distinct areas (campus of Hokkaido University (1.3ha) and Minamino-sato agricultural area (18ha)) on the Ishikari Plain in central Hokkaido between late June and late July 2017. The two sampling sites were approximately 20 km apart. We measured the snout-vent length of each sample collected by hand for identification and the analysis (see the "statistical analysis").

2.2. Noise recording and playback files

We recorded vehicle noise at a roadway in our study area. Details of the noise recording and sound generation procedures are available elsewhere (Senzaki et al., 2018). Briefly, we created 1-min-long traffic noise files consisting of 28 vehicle pass-by events (23 passenger vehicles and five trucks), which corresponded to the average daily traffic level of major roads in our study region (Senzaki et al., 2018).

2.3. Experiment site and runways

The experiments were conducted at the Hokkaido Research Center of Forestry and Forest Products Research Institute (173.7ha). The institute is approximately 800 m away from the nearest busy road (prefectural road #82) and 13 km from the airport (Okadama airport), ensuring quiet condition throughout the experimental period (<45 dB; Y. Nakano personal data). The grounds of the institute include various land cover types. We established two experimental runways for each of the three land covers that the dispersing frogs might encounter: 1) lawn with closed canopy (hereafter, "canopy lawn"); 2) open lawn (0% cover); and 3) artificial bare land (hereafter, "bare land"). The ground cover in the first two treatments consisted of grasses from the family Poaceae. The canopy lawn was 100% covered by branches and leaves of conifer or broad-leaved trees at height of approximately 10 m. The most common artificial surface that dispersing frogs might encounter is a concrete/asphalt roadway. However, the use of this surface in our experiment was technically difficult. Thus, the bare land was generated by placing a dark-grey anti-weed sheet on an open lawn. This land cover type in the strict sense is different from a concrete/asphalt roadway, but its coloration, hard surface, lack of vegetation cover, and moisture condition at ground level are similar

with those of a concrete/asphalt roadway (i.e., the bare land has dark-grey hard surface without vegetation cover and its water stress is expected to be higher than that of forest floor). Based on reference (Cline and Hunter, 2014), we constructed uni-directional runways by using silt-fence enclosures (length \times width \times height: 25 m \times 1.5 m \times 0.9 m). We placed funnels at 5, 10, 15, and 20 m from the release point (one of the short-sided edges) to prevent return movement (Fig. 1) (Cline and Hunter, 2014). We also covered the roofs of the runways using a low shading net (mesh-size: 1 mm), which prevents escape frogs but does not obstruct the view and light transmission. Finally, for noise playback, we set up two speakers (JBL CHARGE3: JBL, California, USA) connected to a player (WALKMAN NW-E080, Sony Corporation, Tokyo, Japan) on an edge of the runways on the ground at 7.5 and 17.5 m from the release point (Fig. 1). The speaker positions were decided to ensure even sound field in each runway because our previous study reported that sound attenuation at 7.5 m from the sound source was only 2.2 dB (Senzaki et al., 2016).

2.4. Experimental protocol

The experiments were conducted between 20:00 and 7:00 on seven nights in August 2017 (Appendix A1). Note that the experiment nights were randomly determined and were not always consecutive. The experiments were performed at night to coincide with peak activity levels in *H. japonica*. Each runway was used for six nights, half of which were allocated to the noise treatment (Appendix A1). Because we directly measured multiple environmental factors that can affect frog movement (see below), we conducted the experiments regardless of weather conditions (Appendix A1). Throughout the trials, traffic noise and no sound were repeatedly broadcast as the noise and control treatments, respectively. We used a unique noise file for each noise treatment and set the noise amplitude at 63 dB as the A-weighted equivalent continuous noise level during 1 min (i.e., LAeq [1 min]) in the centres of the runways. This sound level approximately corresponds to the average noise level in roadside waterbodies inhabited by native frogs (Senzaki et al., 2018). We released a group of 3–6 frogs with different snout-vent lengths at the release point of the runway at 20:00 and measured the movement distance of each frog from the release point at 7:00. Each group was randomly assigned to a given runway and subjected to different treatments 1–3 times, but not on successive nights.

2.5. Environmental factors

To consider potential factors affecting frog movement, we measured the daily temperature and humidity at the study site and the runway-specific soil moisture levels (except for the bare land because of the hard ground structure). Specifically, temperature and humidity were automatically recorded at 2-h intervals every day in an open space at our study site, and we obtained the daily averaged values for the experimental days.

2.6. Statistical analysis

We analysed how noise alters the permeabilities of different land cover types using generalized linear mixed models (GLMMs) with gamma error. The response variable was the individual movement distance per night. We first extracted candidate predictors that might affect frog movement: the land cover types (open lawn, canopy lawn, bare land), the interaction term between the noise treatment (noise or silence) and the land cover types, snout-vent length, temperature, humidity, date, and the number of frogs released in an experiment. We were simply interested in whether slope estimates of land cover types varied by the noise treatment and thus used the interaction term of the noise treatment and the land cover types. The last two predictors were used to control the effects of circannual rhythm and the individual interactions in groups. We scaled all predictors except for the land cover types and the interaction term. To control variances of individuals, runways, and sampling sites, we included the IDs of individuals, runways, and sampling sites as the random factors. We then constructed a global model including these and checked their multicollinearities using variance inflation factors (VIFs). As a result, humidity had the largest VIF value (2.157) (Appendix A2). Multicollinearity is especially problematic when ecological signals were weak. In such case, a VIF of 2 can cause nonsignificant parameter estimates in the model (Zuur et al., 2010). Thus, we reconstructed a model including variables other than humidity. Finally, we selected the best model based on Akaike's

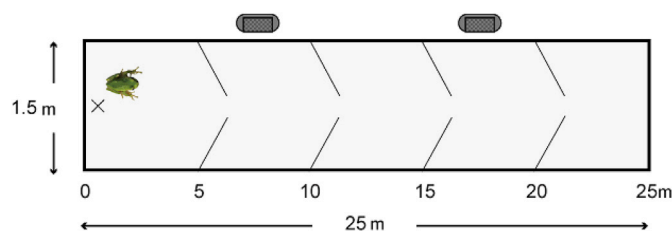


Fig. 1. Study sites and illustration of an experimental runway. X mark indicates the release location. Two speakers were set on an edge of the runways on the ground at 7.5 and 17.5 m from the release point.

information criterion for a small sample situation (AICc). We considered the predictors in the best model to be meaningful predictors at a 5% significance level (i.e., 95% confidence interval). We also calculated squared R values for all models with $\Delta AICc < 2$. Analyses were performed using “lme4” (v.1.1–5) and “MuMIn” (v.1.9.13) with R (v.3.4.1).

3. Results

The movement distance per night (average \pm SD) was 4.2 ± 6.0 m (range: 0–25 m) on the canopy lawn, 7.0 ± 6.0 m (range: 0.5–25 m) on the open lawn, and 6.8 ± 7.6 m (range: 0–24.5 m) on the bare land.

The best model included the land cover types, the interaction term of the noise treatment and the land cover types, temperature, and date (Table 1); movement distance was significantly longer in the open lawn than in the canopy lawn and marginally significantly longer in the bare land than in the canopy lawn (Table 2, Fig. 2). Presence of noise resulted in movement over a short distance in the bare land (Table 2, Fig. 2). Lower temperature and the progress of the experiment date resulted in movement over a short distance (Table 2).

4. Discussion

To the best of our knowledge, we provided the first experimental evidence that the effects of noise on animal movement may differ between land cover matrices. Different behavioural responses can have different consequences with respect to individual fitness and the associated species interactions (Creel and Christianson, 2009; Gallagher et al., 2017; Kuijper et al., 2013). Thus, the matrix-dependent noise impacts are particularly valuable not only for understanding the ecology of fragmented animal populations and the surrounding ecosystems but for the relevant conservation actions. For example, the impeded movement of our model species implies that noise can make crossing time longer on the bare land, suggesting that noise may increase vehicle collision mortality for individuals crossing the similar artificial open environments with heavy traffic such as paved roads. Thus, reducing noise levels on such grounds may be effective for reduction of collision mortality. Of course, our artificial bare land strictly differs from real concrete/asphalt roadways. Thus, follow-up work is needed to test whether increased noise on roadways leads to heightened collision mortality.

Although the detected impact of noise on dispersal distance for frogs on the bare land was consistent with our prediction, we did not detect the noise impacts on the other two matrices. These differential movement responses to noise could be interpreted as follows. First, the impeded movement on the bare land may be explained by an interaction between its moving costs for tree frogs and their stress-related behavioural alteration by noise; it is suggested that noise can be associated with increased stress levels and thereby can trigger tonic immobility in anurans (Tennessen et al., 2014). For tree frogs, the bare land is considered an unsuitable habitat for survival (Rothermel and Semlitsch, 2002), and hence the bare land itself would be a stressor. Thus, individuals travelling on such stressful environment might finally show the impeded movement due to the accumulated stress of artificial surface and noise.

Second, no detectable movement response to noise on canopy lawn also supported our prediction; this land cover type would be more suitable for settlement by the tree frogs in a fragmented landscape (i.e., slow movement) because of the similarity to the structure of their non-breeding habitat (i.e., forests) (Rothermel and Semlitsch, 2002). Thus, this response may be explained by outweighed benefits of this substrate than the costs of noise exposure. This explanation is also supported by the shortest movement distance on the canopy lawn relative to the other land cover types.

Finally, in contrast to our prediction, we found that the effect of noise on frog movement did not significantly differ between canopy and open lawns. For tree frogs, open lawn is considered to be unsuitable for long-term survival because of the increased risk of desiccation compared to canopy lawn (Rothermel and Semlitsch, 2002). However, this land cover type is one of common matrices that our model species can use and may be enough suitable for short-distance travelling as tested here (i.e., quick movement). Such moderate quality of open lawn could compensate the influence of anthropogenic noise as well as canopy lawn.

In conclusion, we demonstrated the differential effects of noise on landscape permeability for the movement of an animal. These findings suggest that incorporating noise and matrix type in management plans could improve our understanding of animal movements and conservation efforts for anurans and other sensitive species. The expected expansion of urban areas and transportation networks will make the Earth's surface noisier because at least 25 million kilometres of new road are

Table 1

Results of model selection. Models with $\Delta AICc < 2$ are shown. “Land”, “Temp”, “Date” and “Size” indicate “land cover types”, “temperature”, “experimental date”, and “snout-vent length” respectively. “Land \times Noise” indicates the interaction term between land cover types and acoustic treatment.

Variables	df	AICc	$\Delta AICc$	Weight	R ²
Land + Land \times Noise + Temp + Date	12	597.30	0.00	0.10	0.20
Land + Land \times Noise + Temp + Date + Size	13	597.60	0.34	0.09	0.23
Land + Temp + Date	9	598.00	0.77	0.07	0.17
Land + Temp + Date + Size	10	598.20	0.90	0.06	0.20
Land + Temp + Size	9	598.50	1.28	0.05	0.18
Land + Size	8	598.80	1.52	0.05	0.16
Land + Land \times Noise + Temp + Size	12	599.10	1.85	0.04	0.21

Table 2
Parameter estimates and 95% confidence intervals of the best model.

Variable	Estimate	SE	95% confidence interval		P-value
			lower	upper	
Intercept	0.53	0.26	0.02	1.04	0.04
Open lawn	1.14	0.28	0.60	1.69	<0.001
Bare land	0.56	0.32	-0.06	1.18	0.08
Canopy lawn × noise (+)	0.16	0.21	-0.24	0.57	0.42
Open lawn × noise (+)	0.14	0.19	-0.24	0.52	0.46
Bare land × noise (+)	-0.49	0.17	-0.83	-0.15	<0.005
Temperature	0.26	0.11	0.05	0.47	0.02
Date	-0.26	0.11	-0.47	-0.05	0.01

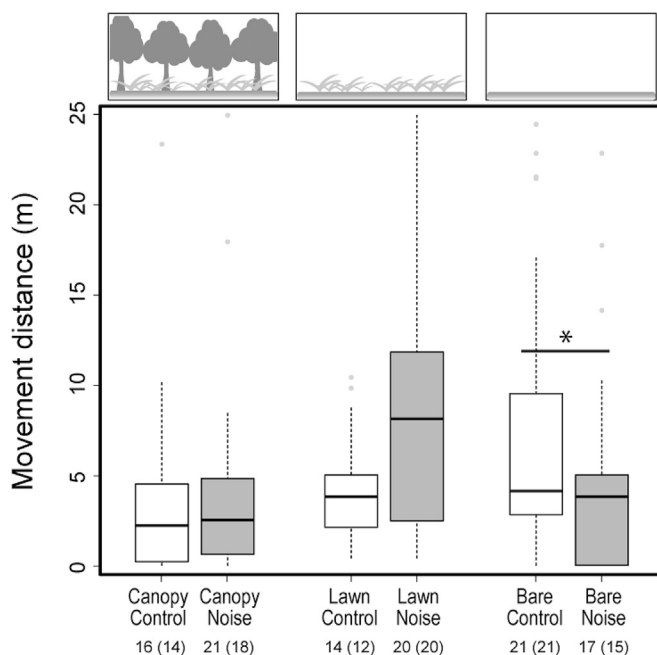


Fig. 2. Effects of treatments on movement distances. Asterisks indicate $P < 0.05$. The bottom figures indicate sample sizes (number of frogs analysed).

anticipated by 2050 (Laurance et al., 2014). Therefore, further studies on the interaction between noise and land covers are clearly needed to understand functional connectivity for wildlife, underpinning future biodiversity conservation in such noisy landscapes.

Competing interests

We have no competing interests.

Ethical statement

All experiments were conducted in accordance with the current laws of Japan and with relevant guidelines and regulations. Sampled individuals were released to the original habitats after the experiments.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gecco.2018.e00484>.

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