

## Original Articles

# Soundscape analysis and acoustic monitoring document impacts of natural gas exploration on biodiversity in a tropical forest



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## ABSTRACT

Natural resource extraction is increasing rapidly in tropical forests, but we lag behind in understanding the impacts of these disturbances on biodiversity. In high diversity tropical habitats, acoustic monitoring is an efficient tool for sampling a large proportion of the fauna across varied spatial and temporal scales. We used passive acoustic monitoring in a pre-montane forest in Peru to investigate how soundscape composition and richness of acoustic frequencies varied with distance from a natural gas exploratory well and with operational phase (construction and drilling). We also evaluated how anuran and avian species richness and vocal activity varied with distance and between phases. Soundscape analyses showed that acoustic frequency similarity was greatest among sites closer to ( $\leq 250$  m) and farther from ( $\geq 500$  m) the platform. Soundscapes revealed more frequencies were used during construction and showed a weak trend of increasing frequency richness with increasing distance from the disturbance. Avian species richness and detections increased with distance from the platform, but anuran richness and detections declined with distance. Operational phase did not play a significant role in overall richness or activity patterns of either group. Among birds, insectivore detections increased with distance from the platform, and nectarivores were detected more frequently during the drilling phase. Results demonstrate that acoustic monitoring and soundscape analyses are useful tools for evaluating the impact of development activity on the vocalizing community, and should be implemented as a best practice in monitoring biodiversity and for guiding specific mitigation strategies.

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## 1. Introduction

Oil and gas fulfilled over 55% of the world's energy demand in 2012 (IEA, 2014), and energy consumption globally is predicted to increase by 56% between 2010 and 2040 (EIA, 2013), presumably with direct repercussions for biodiversity. Given the sheer diversity of landscapes affected by hydrocarbon exploration and extraction, quantifying impacts of these operations on biodiversity has proven difficult (Butt et al., 2013; Deichmann and Alonso 2013). While major spills produce clear visible impacts, and studies are often

conducted in the aftermath to quantify the effects (e.g. Junoy et al., 2005; Piatt et al., 1990; White et al., 2012), impacts on biodiversity resulting from the overall process of oil and gas exploration and extraction have been little studied, particularly in tropical habitats.

The Western Amazon is under particularly heavy pressure from exploration and extraction of hydrocarbons (Finer et al., 2015), and potential direct and indirect threats to biodiversity from these operations have been previously reviewed (Finer et al., 2008). Expected impacts in tropical forests include avoidance or changes in activity patterns in animal species disturbed by human activity (Klein, 1993; Knopff et al., 2014), and edge effects that modify the spatial distribution of some species after trees are cleared to make room for infrastructure (Broadbent et al., 2008). Sounds produced by construction machinery, camp maintenance and drilling may also mask acoustic signals of vocalizing species, potentially moti-

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vating individuals to alter acoustic activity (Sun and Narins, 2005) or relocate (Francis et al., 2010; Slabbekoorn and Ripmeester, 2008). Anthropogenic disturbance can directly and indirectly affect a variety of behaviors essential to fitness and survival of species including defense, courtship, mating and reproduction (Barber et al., 2010; Kight and Swaddle, 2011; Slabbekoorn et al., 2010; Weilgart, 2007).

While national governments often require some form of environmental assessment and impact evaluation prior to hydrocarbon development, these studies often do not use rigorous protocols and the data are rarely published. The scientific research that has been published shows varying levels of impacts that differ across taxonomic groups. For example, in northern Peru, a study of ocelot and large primate behavior during natural gas seismic exploration activities revealed no change in ocelot activity patterns (Kolowski and Alonso, 2010) nor in the number of primate groups during the disturbance, although the number of individuals per group was reduced (Kolowski and Alonso, 2012). In central Peru, primate encounter rate did not change significantly in the area surrounding a natural gas pipeline before, during and after its construction (Gregory et al. in press). In Ecuador, fewer species of understory insectivorous birds relative to other bird groups were found in plots closer to petroleum operation roads (Canaday and Rivadeneyra, 2001), and elsewhere in Ecuador, there was lower anuran occupancy and abundance in canopy bromeliad tanks closer to roads in an oil concession (McCracken and Forstner, 2014).

These studies are pioneers in the issue of oil and gas impacts on biodiversity in tropical forests, but overall represent a very small effort, particularly given the large scope of hydrocarbon activities in the Western Amazon. Why are there so few studies? Many operations take place in extremely remote areas where access is all but impossible without significant logistical support. When an area is accessible, it can take a long time and require significant funding for researchers to collect the robust data needed to respond to questions about impacts.

While traditional ecological monitoring has focused on direct observations of focal organisms or visual signs of their presence (e.g. Heyer et al., 1994; Wilson et al., 1996), passive acoustic monitoring (PAM) uses recorders placed in a study area to record vocalizations and detect the presence of species (Blumstein et al., 2011). Acoustic methods offer a cost effective way to autonomously collect large amounts of data, providing continuous, simultaneous and permanent records of vocal animals that can be revisited and reanalyzed to answer new questions or to apply new methods (Aide et al., 2013).

Passive acoustic monitoring has been used to evaluate impacts of oil and gas activities on specific focal species or taxonomic groups. In marine environments, it has been used along with visual methods to evaluate impacts of seismic exploration on whales and dolphins (Goold, 1996; Potter et al., 2007) and has recently been identified as a best practice for monitoring marine mammals during seismic activities (Nowacek et al., 2013). In the terrestrial realm, PAM has been employed to evaluate impacts of hydrocarbon operations on specific bird species in North America (Bayne et al., 2008; Francis et al., 2010) as well as elephants in Gabon (Wrege et al., 2010). While acoustic monitoring for focal species can be an indispensable tool to evaluate impacts, the results are limited to the group of interest. In tropical environments where species diversity is generally high, results regarding a single or even a few species are not likely to provide information that can be extrapolated to the community as a whole. This problem can be partially addressed by analyzing the soundscape (Pijanowski et al., 2011), which allows us to visualize all the frequencies that are dominant during certain times of the day or season, providing a framework to describe, compare and analyze acoustic information from many sites and many animal taxa simultaneously.

Soundscapes offer the potential to study biodiversity and community dynamics of vocal species in an ecosystem impacted by immediate threats such as logging, agricultural expansion, and energy development, as well as challenges with more latent impacts such as climate change. Here we aggregate acoustic recordings representing all sources of sound in an area of natural gas exploratory drilling platform in a Peruvian pre-montane forest to develop soundscapes for sites at different distances from anthropogenic activities. We use the soundscapes to investigate how frequency composition and richness vary with distance from the disturbance. We also evaluate how species richness and vocal activity of birds and anurans vary with distance from the platform and between two phases of operations. Finally, we examine whether response to natural gas exploration varies by avian feeding guild, with the expectation that insectivorous birds will respond more acutely to activities, based on previous studies showing understory avian insectivores to be particularly sensitive to anthropogenic disturbance (Canaday, 1996; Stratford and Stouffer, 1999).

## 2. Materials and methods

### 2.1. Study area

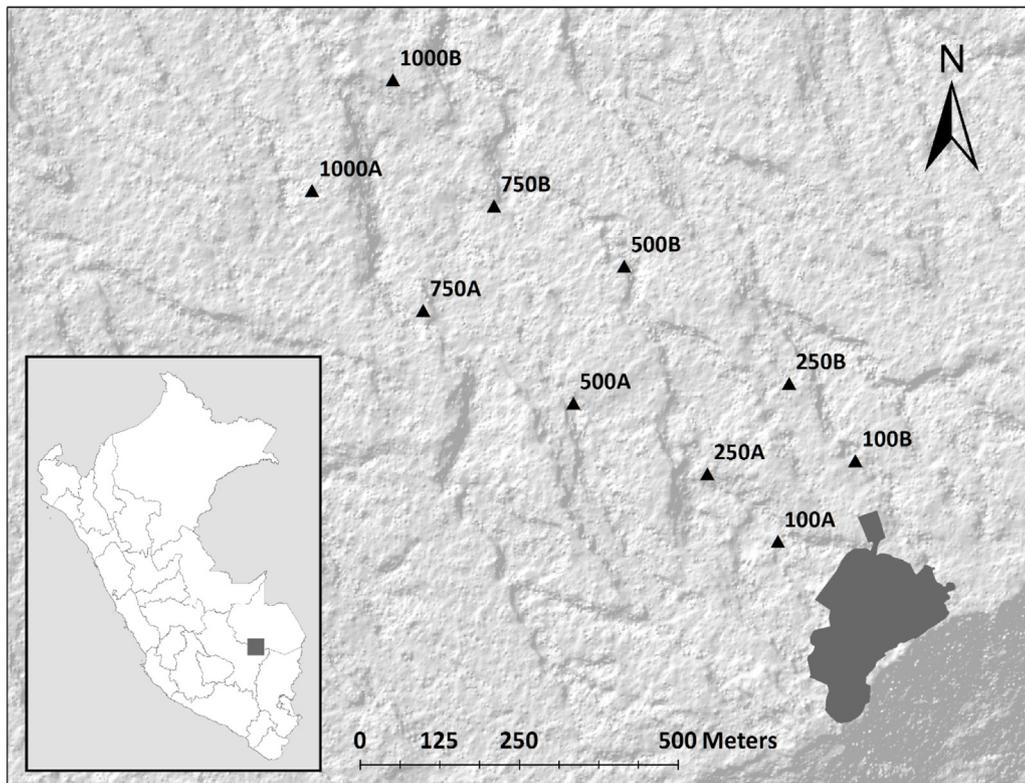
Our study site is located between the Colorado and Dahuene rivers in the Amarakeri Communal Reserve in the Department of Madre de Dios, Peru in a transition zone between the Andes Mountains and the lowland forests of Amazonia. The area, ranging in elevation from 820 to 1010 masl, is characterized by hilly pre-montane tropical moist forest and Peruvian Yungas. Locally there is exceptionally high plant species richness (I. Huamantupa, in prep). The area receives on average 6000 mm of rain annually (Condom et al., 2011). January is generally the wettest month (~1100 mm), and there is less precipitation from May through September, although no month of the year receives less than 300 mm of rain (<http://www.met.igp.gob.pe/clima/HTML/quincemil.html>).

The study was conducted in primary forest surrounding a new exploratory gas well platform. The study site can only reasonably be accessed by helicopter, which prevented data collection prior to disturbance. Clearing the area for the platform began in May 2014, construction was underway by July, and drilling of the exploratory well was initiated in December 2014. We conducted acoustic monitoring for all sound sources within the frequency range 50 Hz–20 kHz for 14 days in September–October (9/26–10/9) 2014 and for 17 days in January–February (1/29–2/13) 2015. The first sampling period coincided with the construction phase (CP) of platform operations while the second sampling period coincided with the drilling phase (DP). While it would have been ideal to obtain a true baseline for soundscape data before any activity began, we were not able to do so due to logistical constraints.

### 2.2. Data collection

To gather acoustic data we used 10 portable autonomous recorders (LG L70 cellular phones) protected inside a water-proof case (Grace Digital Eco Pod). The recorders were connected by a cable to the case and a microphone (Monoprice – Model 600200) was connected to the case externally.

During each sampling period we placed two recorders, approximately 200 m from one another, at five distances to the west of the platform (100, 250, 500, 750 and 1000 m; Fig. 1). Each recorder was attached with bungee cords to a tree trunk at 1.5 m above the ground, facing south and with the microphone pointing downward. We took photographs of the canopy above each recorder and used the HabitApp application (Version 1.1) to measure canopy cover. We also noted approximate slope, distance to nearest creek and



**Fig. 1.** Study area showing location of each of 10 automated recording units (triangles) relative to the natural gas exploratory well platform (gray form). The shading in the background represents the slope with darker hues indicating sharper slopes. The platform is located at the top of a peak in a topographically variable area. Stream headwaters are often, but not always, located along steep sloped areas to the north and west of the platform.

general structural characteristics of the understory surrounding each recorder.

All recorders were programmed to record in mono audio at a sampling rate of 44.1 kHz for 1 min at 10 min intervals (144 recordings each day) in uncompressed files (.wav format) using the ARBIMON touch application for the Android platform (Sieve Analytics). All data was stored and analyzed using the bioacoustic platform ARBIMON II and can be listened to and visualized at no cost (<https://arbimon.sieve-analytics.com/>).

### 2.3. Analysis

#### 2.3.1. Soundscape

Soundscapes can be analyzed to provide visual representations of aggregated recordings, which reflect all sources of sound in an area (biotic, abiotic, and anthropogenic). We conducted a soundscape analysis using ARBIMON II, which provided an image of the regions (time x frequency) with the highest activity. ARBIMON II allows the user to define the time scale of aggregation, the frequency bin size, the minimum threshold for the amplitude of a peak (i.e. intensity of sound), and the minimum distance in frequency (Hz) between peaks. We aggregated recordings at the time scale of hour of day (24 h), and we used a frequency bin size of 86 Hz, an amplitude filtering parameter of 0.2, and the minimum distance between peaks was left at 0 Hz. To control for the different number of recordings collected at each site and each time interval, we normalized the soundscape analysis by dividing the number of peaks in each frequency by time class by the total number of recordings collected during each hourly interval.

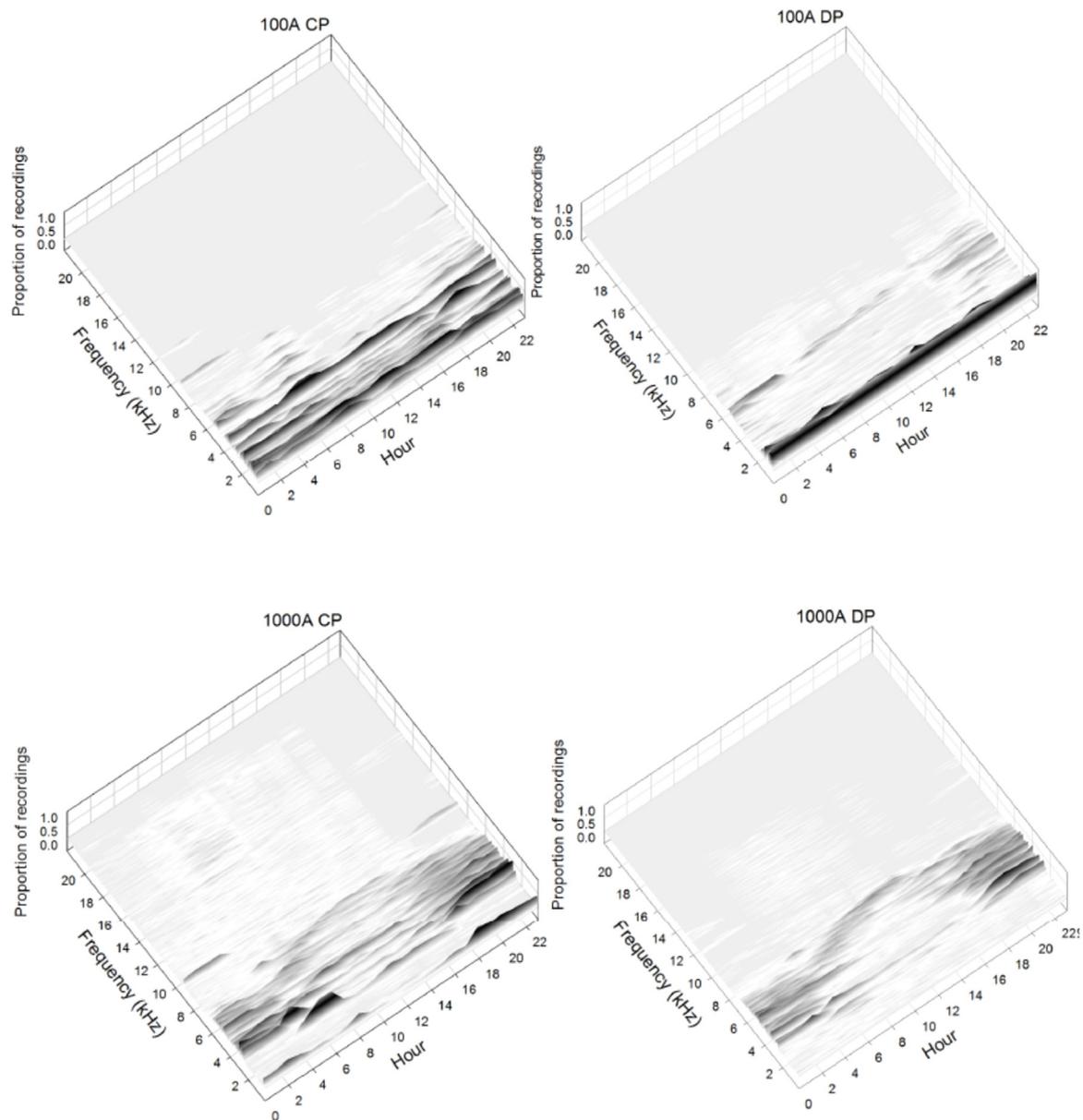
To compare the similarities of soundscapes among the sites for each time period (i.e. CP and DP), we employed a cluster analysis (Clarke, 1993). Clusters were calculated using Euclidean distance among sites, and the clustering method used was com-

plete distance. Statistically significant clusters were determined using approximate unbiased (au) and bootstrap probabilities (bp). Cluster analyses were done using the R package *pvclust* (Suzuki and Shimodaira, 2006).

To evaluate the richness of frequencies used in the soundscapes we compared the average number of frequency bins with activity >0 for each distance from the pipeline during each operational phase using a factorial ANOVA (R Version 3.2.0). In general, frequencies <2 kHz encompass most anthrophony, while frequencies between 2 and 8 kHz typically contain most of the biological activity (Kasten et al., 2012). We repeated the frequency bin analysis for three regions of the soundscape (<2 kHz, 2–8 kHz, >8 kHz) to evaluate whether variation in the complete soundscapes can be attributed to or explained by anthrophony, biophony or high frequencies. For analysis of the three regions, we used the number of frequency bins with >1% activity.

#### 2.3.2. Composition of the soundscape

Based on activity peaks identified in the soundscapes, a subset of the dawn and dusk choruses were selected to determine species richness and composition. We randomly sampled 30 recordings from each site during each phase to identify birds during the dawn chorus (05:00–08:00) and an additional 30 recordings during the dusk chorus (17:00–20:00) to identify anurans, for a total of 300 dawn and 300 dusk chorus recordings per phase. One experienced ornithologist (MCC) listened to all 300 dawn recordings and identified the bird species present in each recording, while one experienced herpetologist (JADC) listened to all 300 dusk recordings and identified the amphibian species. Species were identified using reference recordings of vocalizations witnessed and identified in the field by ornithological and herpetological teams. We also used sound databases for birds ([www.xeno-canto.org](http://www.xeno-canto.org)) and for anurans (Crocroft et al., 2000; Márquez et al., 2002) as references. We



**Fig. 2.** Soundscapes at sites 100A and 1000A during the construction (CP) and drilling (DP) phases of operations of a natural gas platform. Darker colors represent higher acoustic activity. Soundscapes were normalized by dividing the number of peaks in each of 256 distinct frequency bin by time class by the total number of recordings collected during each hourly interval. The z-axis represents the proportion of recordings with a peak of activity in a given frequency/time bin.

noted the number of recordings in the subset in which a species was detected and refer to these as detections (i.e. vocal activity).

We also determined the number of recordings in which anthrophony, defined as sounds produced by generators, tractors, helicopters and other machinery, was detected in the CP and the DP. We used a paired Wilcoxon signed rank test to analyze differences in overall anthrophony between the two phases. Given that operational activity during the day and night may have different impacts on diurnal and nocturnal vocalizing animals, we also analyzed differences in anthrophony detected between the two phases for the dawn and dusk recording subsets separately.

We used generalized linear models (GLM) to evaluate the effects of select predictor variables on avian and anuran species richness and also on detections in the subset of recordings from each site (30 per phase). We used the R (Version 3.2.1) package *glmulti* to select the best model based on the lowest AICc value from the following predictor variables: platform distance, operational phase, the interaction between platform distance and phase, canopy cover,

and distance from the nearest stream. Because not all sites were exactly the same distance from the platform, we used the actual distance (continuous variable) rather than a distance category in the GLMs. For response variables with more than one best model (within 2 AIC units of one another), we averaged the resultant models using the package *MuMIn* and determined predictor variable importance (the sum of Akaike weights over all models in which the term appears,  $\sum AICw$ ) based on the full averaged model.

We were also interested in potential changes in dietary guild structure within the avian community, with the expectation that distance from the platform would be a more important predictor of insectivore detection than for other guilds. Given the relative scarcity of information on the diet of Neotropical forest birds, we assigned species to one of four general dietary guilds using BirdForum (<http://www.birdforum.net/>) and the Handbook of the Birds of the World (<http://www.hbw.com/>) online databases. Birds were classified as insectivores if sources mentioned primarily invertebrate dietary items, as frugivores if sources indicated primarily

fruits, seeds and other vegetable matter, as nectarivores if sources indicated nectar as a primary item, and as omnivores if multiple cross-category diet items were indicated. We used  $\chi^2$  tests of independence to compare detections of different guilds between the CP and DP, and also between different distances from the platform within each phase. We also used the same GLM methods described above for each feeding guild, but with only the platform distance and phase predictor variables. For guild analyses, we included only species which were detected in at least five recordings.

### 3. Results

#### 3.1. Soundscape

We obtained 15,090 and 19,215 1-min recordings in 2014 and 2015 respectively. The soundscapes from both sampling periods (CP and DP) display some of the same general patterns. Most acoustic activity occurs below 8 kHz. There is a peak of activity throughout the night from approximately 18:00 until 06:00 with lower activity during the day (08:00–16:00; Fig. 2; Appendix A).

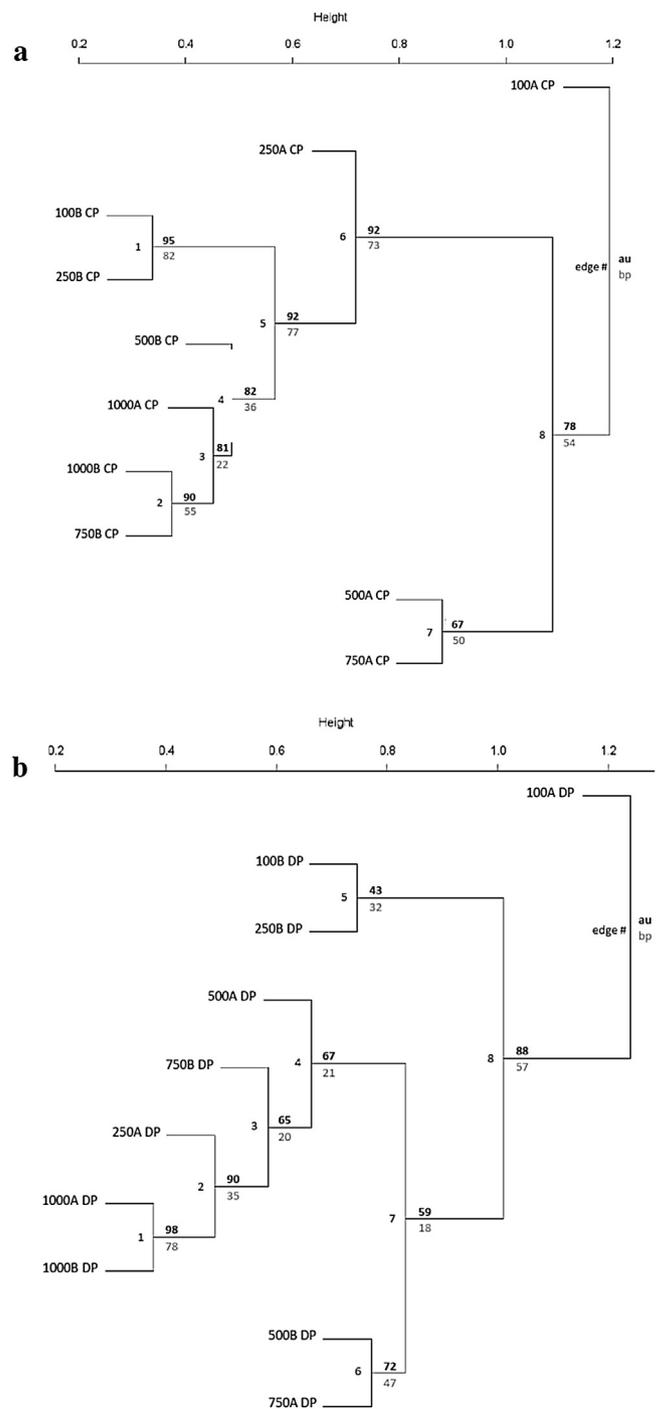
The cluster analysis of soundscapes recorded during the CP grouped sites into eight distinct clusters, one of which (100B and 250B) consisted of statistically similar frequencies (95%). Although the average distance (dissimilarity) among clusters was generally low (Fig. 3), sites farther from the source of disturbance ( $\geq 500$  m) clustered apart from those closer to the platform ( $\leq 250$  m; Fig. 3a). Site 100A is completely separated from all other sites, while 500A and 750A form another separate cluster. These three were the only sites that had three or more frequency bins with activity  $>0.4$  (i.e.  $>40\%$  of recordings contained a peak at that frequency), one of which was in the same frequency bin ( $\sim 3.2$  kHz).

Eight clusters were also identified during the DP, one of which consisted of statistically similar frequency peaks and an overall lack of anthropogenic noise (1000A and 1000B, 98% similarity). While other clusters were not significant, certain trends were evident. For example, all sites  $\geq 500$  m were clustered together as in the CP, however this cluster also included site 250A (Fig. 3b). Sites 500 B and 750A shared a relatively high frequency of peaks at  $\sim 0.9$ , 1.3–1.8 and from 6.0–6.8 kHz, likely causing them to cluster separately from other distant sites. Both 100 m sites and 250 B had noticeably higher activity in lower frequencies in comparison with the other sites. The majority of these activity peaks in the lower frequencies are associated with anthropogenic noise, while those at the higher frequencies are likely associated with insects.

In terms of soundscape activity across all 256 86-Hz frequency bins, on average there were more frequency bins with activity farther from the platform during both the CP and DP (Fig. B1); however, distance was not a significant factor ( $F_{4,10} = 1.31, P = 0.33$ ). Phase was significant with more activity (i.e. more frequencies detected on average) in soundscapes during the CP ( $F_{1,10} = 18.52, P < 0.01$ ). For the region of the soundscape composed primarily of anthrophony ( $< 2$  kHz), the average number of frequencies with activity  $>1\%$  was significantly higher during DP than during CP ( $F_{1,10} = 25.48, P < 0.001$ , Fig. 4a). For the commonly recognized biophony region (2–8 kHz), there was no significant difference between phase ( $F_{1,10} = 0.056, P = 0.818$ ) or distance ( $F_{4,10} = 1.644, P = 0.238$ , Fig. 4b). Finally, for the high frequency region of the soundscape ( $> 8$  kHz), the CP had significantly higher activity overall than the DP ( $F_{1,10} = 8.497, P = 0.015$ ), with a trend during the CP of more high frequencies used at distances  $\geq 500$  m (Fig. 4c).

#### 3.2. Composition of the soundscape

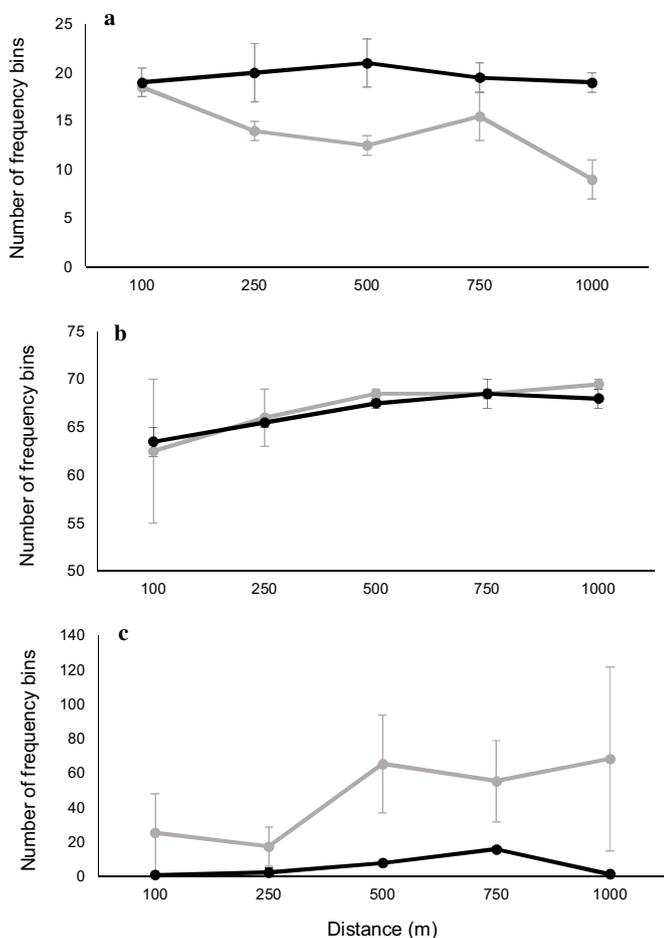
We documented clear anthrophony in recordings at sites closer to the platform (Fig. B2). Machinery sounds were not detected at



**Fig. 3.** Cluster analysis comparing soundscapes at 10 acoustic recording sites (a) during the construction phase and (b) during the drilling phase of a natural gas platform. Approximate unbiased (au) and bootstrap probabilities (bp) are reported for each node and represented in black and gray respectively. Probability values above 95 are considered significant.

sites farther than 250 m, so we constrained the analysis to sites  $\leq 250$  m from the platform. There was no significant difference overall between the number of recordings containing anthrophony in the CP and DP ( $V = 4, P = 0.875$ ). There also was no difference in the number of anthrophony detections separately in the dawn ( $V = 3.5, P = 0.713$ ) and dusk ( $V = 4, P = 0.789$ ) chorus subsets.

Fifty-five species of birds were detected in the dawn-chorus recordings subset during CP and 71 species during DP for a total of 81 bird species (Appendix C). For anurans, eight species were



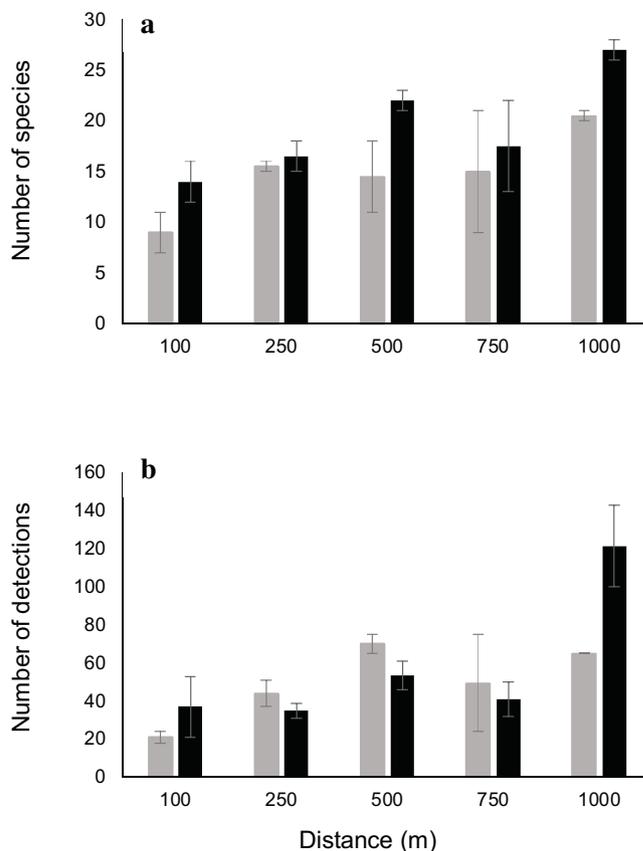
**Fig. 4.** Average number of frequency bins with activity >1% for three separate regions of soundscapes at 5 distances from a natural gas platform during construction (gray) and drilling (black) phases including (a) frequencies reflecting athrophony (<2 kHz), (b) biophony (2–8 kHz), and (c) high frequencies (>8 kHz). Error bars represent standard error.

detected in the dusk-chorus recordings subset during CP and 10 species during DP for a total of 12 species (Appendix D). Sample spectrograms showing the most common bird and amphibian species and noises can be found in Appendix E. Insects were present in virtually every recording during the morning and evening choruses, but they were not analyzed separately here due to limitations in identifying insect species and modeling their vocalizations.

### 3.2.1. Birds

The most common bird species based on the number of sites at which they were detected were *Microcerculus marginatus* (16 of 20 samples [10 sites × 2 phases]) and *Myrmeciza hemimelaena*, *Myrmoborus leucophrys* and *Liosceles thoracicus* were each detected in 14 of 20 samples. In terms of overall detection rate, *Myrmoborus leucophrys* was the most acoustically active species (detected in >15% of subsampled recordings) followed by *Chlorothraupis carmioli* (13.8%) and *Hypocnemis subflava* (13%).

Species richness and number of detections varied by distance and phase. More bird species were recorded on average during drilling (19.4 species/site) than during construction (14.9 species/site) at all distances, and there was a trend of higher average species richness farther from the platform during both sampling seasons (Fig. 5a). In terms of detections, there was slightly higher avian vocal activity during drilling (mean = 57.6 detections/site) than during construction (mean = 49.9 detections/site) sampling,



**Fig. 5.** Average avian (a) species richness and (b) number of detections in recordings at each distance for construction (gray) and drilling (black) phases. Error bars represent standard error.

but this was not true at all distances and appears to be driven primarily by more detections at 1000 m during drilling (Fig. 5b).

We fit GLMs for avian species richness using a Gaussian distribution. The best model for richness at a given site included operational phase, platform distance and distance to the nearest stream, although there were four models with  $\Delta AICc < 2$  (Table 1). Platform distance was the predictor of bird species richness with the most support, with richness increasing with distance. For detection data, we fit GLMs using the negative binomial distribution. Platform distance was the only variable included in the best model for predicting the number of recordings in which bird species were present (Table 1).

### 3.2.2. Anurans

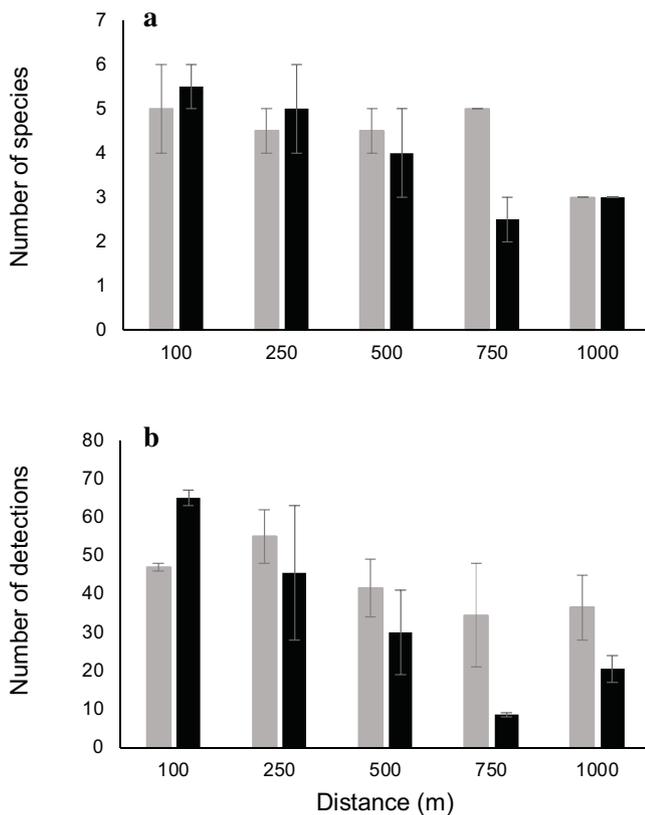
The most common anurans based on the number of sites at which they were detected were *Pristimantis cf. reichlei* (19 of 20 samples), *Pristimantis pluvialis* (14 of 20), and *Rhinella tacana* and an unidentified *Pristimantis* were both detected in 12 samples. In terms of overall detection rate, *Pristimantis cf. reichlei* was the most acoustically active species (detected in nearly 60% of subsampled recordings) followed by *Pristimantis pluvialis* (23.7%) and *Cochranella nola* (10.8%). Species richness and number of detections varied by distance and by phase.

Anuran species richness displayed a pattern different from birds, with average overall richness per site nearly equal in both the CP (4.4 species/site) and DP (4.0 species/site). The spatial trend showed higher average richness closer to the platform (Fig. 6a). Anurans demonstrated higher average detections during the construction phase (42.9 detections/site in CP, 33.9 detections/site in DP). In

**Table 1**

Results of fixed effects generalized linear models including significance levels of predictor variables incorporated in the best models for each response variable.

Response Variable	Best model	AICc	$\Delta$ AICc	Predictor variable	$\sum$ AICw
Avian detections	Distance from platform	178.24	0.00	Distance from platform	0.997
Amphibian detections	Distance from platform + Phase*Distance from platform	165.40	0.00	Distance from platform Phase*Distance from platform	0.997 0.744
Avian species richness	Phase + Distance from platform + Distance from stream	119.12	0.00	Phase Distance from platform Distance from stream	0.660 1.000 0.550
	Phase + Distance from platform	119.61	0.49	Phase*Distance from platform	0.340
	Distance from platform + Distance from stream + Phase*Distance from platform	120.57	1.45		
	Distance from platform + Phase*Distance from platform	120.80	1.68		
Amphibian species richness	Distance from platform	58.38	0.00	Distance from platform	1.000
	Distance from platform + Phase*Distance from platform	58.48	0.10	Phase*Distance from platform	0.490

**Fig. 6.** Average anuran (a) species richness and (b) number of detections in recordings at each distance for construction (gray) and drilling (black) phases. Error bars represent standard error.

general, anurans were detected in more recordings closer to the platform, but this difference was most pronounced during the DP (Fig. 6b).

For both anuran species richness and detection data, we fit GLMs using the Gaussian distribution. The best model for richness included platform distance, although there was one additional model within 0.1  $\Delta$ AICc which also included the interaction between phase and platform distance (Table 1). Platform distance was the predictor with greatest support for anuran richness, which decreased with distance. For detection data, the best model included platform distance and the interaction between operational phase and platform distance. Both these covariates were well supported, with detections decreasing with distance (Table 1).

### 3.2.3. Avian feeding guilds

We identified six species of frugivores, 26 insectivores, two nectarivores and 11 omnivores detected in more than five recordings. Among all avian detections, insectivorous species were detected most frequently (74.2%), followed by omnivores (15.7%), frugivores (6.9%) and nectarivores (3.1%). The composition of avian feeding guilds differed significantly between the two sampling phases ( $\chi^2 = 26.341$ ,  $df = 3$ ,  $P < 0.001$ ), and between distances during the DP ( $\chi^2 = 28.586$ ,  $df = 12$ ,  $P = 0.005$ ), but not during CP ( $\chi^2 = 15.988$ ,  $df = 12$ ,  $P = 0.1918$ ). Insectivores composed 81% and 68% of detections in the CP and DP respectively. Detections of nectarivores and omnivores doubled in the DP (nectarivores 4.6%, omnivores 20.1%) relative to CP (nectarivores 1.5%, omnivores 10.9%). While the proportion of frugivores detected was approximately equal across distances during the CP (6.6–8.4%, with the exception of no detections at 100 m), the proportion of frugivores detected varied more than any other group across distances during the DP (3.0–15.3%).

The GLMs for avian feeding guilds suggest that insectivores were most affected by platform distance, with detections increasing farther from the platform. Distance from the platform also had the most support for predicting omnivore detections. Phase was well supported for predicting detections of nectarivores in recordings. While distance was the only predictor included in the best model for frugivores, this covariate received only moderate support ( $\sum$  AICw = 0.38; Table 2).

## 4. Discussion

Soundscape analysis is a useful tool for evaluating impacts of natural gas development activities on the vocalizing animal community. In our study area, the visual representation of soundscapes clearly demonstrated the most vocally active hours of the day and we used that information to direct further acoustic monitoring analyses for birds and frogs. Soundscape analysis allowed us to visualize how and when noise from the platform penetrates the surrounding forest. Soundscape analysis also showed that similarity of acoustic frequencies, including those created by anthropogenic noise, was greater among sites closer to the platform ( $\leq 250$  m) and among those sites farther from the platform ( $\geq 500$  m), and also revealed a weak trend of an increased richness of sound frequencies utilized with increasing platform distance.

Additionally, analysis of the complete soundscapes revealed a difference between phases with more frequencies utilized overall during the CP. Further patterns were evident when the analysis was broken down into different components or regions of the soundscape. For example, there is a distinct difference in anthropony between phases. The DP is consistently “noisier” with sounds penetrating further into the forest than during the CP. On the other hand, there is no difference in general biophony (2–8 kHz) between the

**Table 2**  
Results of fixed effects generalized linear models including significance levels of predictor variables incorporated in the best models for each avian feeding guild.

Feeding guild	Best model(s)	AICc	$\Delta$ AICc	Predictor variable	$\sum$ AICw
Frugivores	Distance from platform	97.59	0	Distance from platform	0.38
Insectivores	Distance from platform	163.04	0	Distance from platform	1
Nectarivores	Phase	69.1	0	Phase	1
	Phase + Distance from platform	70.7	1.6	Distance from platform	0.27
Omnivores	Phase + Distance from platform	124.95	0	Phase	0.43
	Distance from platform + Phase*Distance from platform	125.08	0.13	Distance from platform	0.84
	Distance from platform	125.2	0.25	Phase*Distance from platform	0.25
	Phase	126.9	1.95		

two phases, although the subtle distance trend represented in the complete soundscapes is also reflected in these data. High frequencies (>8 kHz) seem to drive the overall pattern of more frequencies used during CP in our study area. This difference is likely due to high activity of cicadas and other diurnal insects during CP sampling relative to the DP, however, without prior studies in the area, it is impossible to know whether this reflects a typical annual cycle of insect activity, or if operations had some impact.

In fact, because the CP and DP occur during different times of the year, seasonality is generally difficult to tease apart from phase. Nonetheless, it is clear that overall more frequencies were used farther from the disturbance during both sampling periods. Another pattern observed during both periods was that sites closer to the platform were more similar to one another in frequency-use composition; likewise, sites farther from the platform were more similar to one another in frequencies used. While season may play a role in composition and behavior of species, maintenance of these frequency-use distance patterns in soundscapes in both phases suggests that these are not caused by natural seasonal animal behavior patterns or a response to stochastic environmental conditions, but rather by disturbance in the platform area.

Acoustic community analyses revealed that while the bird community overall represents the distance pattern well, with fewer detections and lower species richness closer to the platform, the anuran amphibian community displayed the opposite pattern. While birds are a relatively mobile group of animals, tropical anurans (with the exception of toads) generally have small ranges and territory sizes. As such, birds may be able to respond more rapidly to perturbation than their amphibian counterparts (Allentoft and O'Brien, 2010). Furthermore, some anurans may in fact be attracted to the new habitat created in and around the platform (Urbina-Cardona et al., 2006). Platform construction can increase the availability of semi-permanent water sources through the purposeful construction of water retention structures and the inadvertent creation of water-filled depressions resulting from earth movements, and erosion prevention structures. Depending on the permanence of these new water sources, this may have only temporary effects on the anuran assemblage. Changes in avian and anuran communities could have repercussions for other taxonomic groups. For example, the loss of insectivorous birds near forest edges or in fragments may increase the rates of herbivory by insects (Peter et al., 2015)

It is not surprising that the edge effects, noise and other disturbances produced in the platform have differing effects on animals with varying natural histories (Kight and Swaddle, 2011; Laurance et al., 2011; Murcia, 1995). Even within taxonomic groups, we may expect to observe differences in responses to disturbance. Among four avian guilds, only insectivores were significantly influenced by distance from the disturbance with fewer detections closer to the platform. This supports other studies demonstrating that insectivorous birds are important indicators of disturbances (e.g. Canaday, 1996; Powell et al., 2015; Strattford and Stouffer, 1999).

While it is clear that insectivorous birds are negatively impacted by anthropogenic activities, the precise mechanism underlying the response has yet to be proven. Noise has been proposed as the primary factor causing extirpation of insectivorous birds (Canaday and Rivadeneyra, 2001), but experimental designs to address this hypothesis can be difficult to implement in the field. PAM has great potential to contribute additional data through documentation of both insectivore vocal activity and coincident noise variables.

The increase in overall detections of nectarivores during the drilling phase may simply be due to a change in season and plant phenology; however, detections were twice as high near the platform than at any other distance. At the edge, as in forest gaps, greater insolation favors colonization of plants utilized by nectarivores (Feinsinger et al., 1988). For this reason, nectarivores often frequent forest edges and can become more abundant at edges or gaps relative to other parts of the forest (Levey, 1988; Stouffer and Bierregaard, 1995), particularly generalist nectarivores (Feinsinger et al., 1988). In fact, frugivores can be found preferentially in gaps and edges as well, as they disperse seeds produced by many gap colonizing plants (Levey, 1988). Given the timing of operations, with the opening of the platform in May 2014, it is possible that we will see a continual presence of nectarivores closer to the edge, and even a further increase in frugivore detections as edge plants establish, although the relationship between frugivores and edges or gaps is as not well defined (Levey, 1988; Schemske and Brokaw, 1981). Nevertheless, it is also important to note that the detection pattern found for frugivorous and nectarivorous birds may in fact reflect patterns of landscape usage rather than residence, as these groups are more likely to track ephemeral resources across large distances and are less likely to hold stable territories than insectivorous birds (Stutchbury and Morton, 2001).

Insects made up a substantial proportion of the soundscape in our study area. This group is just as likely to be impacted at varying levels by anthropogenic activities as vertebrate groups, with some species attracted to the disturbance and others repelled (Lien and Yuan, 2003; Nichols et al., 2007). Insects form an important link in trophic chains – any change that influences them is likely to have reverberating effects on many other taxa, including both producers and consumers. However, because of difficulties identifying insect species in our recordings, insects were excluded from the subsample analyses for this paper.

While operational phase influenced the soundscape overall, particularly anthropony, it did not play a large role in models influencing avian or anuran species richness or detections, despite substantial differences in activities undertaken during the two. During construction, vegetation is cleared, workers use heavy machinery for earthworks and power tools for infrastructure assembly, helicopter flights bring materials and supplies, and general camp maintenance requires generators, water pumps and illumination. During drilling, the primary source of activity includes the drill rig and large generators and pumps required to operate the rig. Helicopter flights, camp maintenance and illumination are

also necessary during this time. The main differences between the CP and DP are the timing and intensity of the noise generated in the platform. During the CP, most noise is generated during the day. During the DP, the drill rig operates 24 h a day. During the CP, the machinery for earthworks moves around the platform completing construction on different areas within the 4 ha operation camp, resulting in different levels of noise intensity reaching into the forest each day. During the DP, most activity and noise are generated from the drill rig, which is stationary. The rig is generally louder (producing 90–120 dB) than any sustained activity during construction. Without data from the area prior to operations, it is difficult to determine why phase was not significant, but one speculation is that activities during the CP and up to October 2014 (first sampling) were sufficient to create a large gap and alter the habitat enough that the species most sensitive to disturbance may have already left the area, and those attracted to it may have already arrived. Increased noise and activity in the platform during the DP may have prevented sensitive species from returning, but did not appear to cause further significant changes in richness or detections. However, in order to support these hypotheses and to determine the permanence of any impacts on vocalizing species, it is essential that future studies include data collection prior to initiation of any anthropogenic activities, replication in different seasons, and repeated sampling over the long-term.

Findings from this study have implications for future natural gas exploration projects in similar habitat. In the planning stages of operations, soundscapes should be used to identify areas with particularly high acoustic diversity so efforts can be made to avoid these during development. To minimize impacts of operations, soundscapes should guide mitigation strategies. In the current case, bioacoustic activity was lowest during the day from approximately 08:00–17:00 h. Operational activities should take place during this time to minimize overlap with the hours in which animals are most active (18:00–06:00 h). Additionally, steps should be taken to muffle sounds from machinery in the platform and reduce the distance at which they can be heard into the surrounding forest. In terms of restoration, the results indicate that particular care should be taken to restore not only the area within the platform after activity has ceased, but also to ensure that monitoring and restoration of the understory plant community extends into the forest, at least up to 500 m where changes in avian and anuran assemblages are most evident.

While acoustic monitoring has already been declared a best practice in monitoring biodiversity during and after oil and gas operations in marine habitats (Nowacek et al., 2013), we recommend that it also be implemented as a best practice in the terrestrial realm. However, in addition to basic acoustic monitoring for focal species, soundscape monitoring specifically should be implemented as part of government-required Environmental Impact Assessments and monitoring plans to improve their usefulness and efficacy.

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## Appendices A–E. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.ecolind.2016.11.002>.

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