Research Article

Impacts of small-scale gold mining on birds and anurans near the Tambopata Natural Reserve, Peru, assessed using passive acoustic monitoring

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Abstract

Artisanal and small-scale gold mining (ASM) is becoming a significant cause of environmental degradation in tropical ecosystems. In this study, we conducted a rapid assessment on the impact of an ASM gold mine on the vocalizing avian and anuran communities in the buffer zone of the Tambopata National Reserve in Peru. We used seven audio recorders (three near an active mine, two in an abandoned mine, and two in an adjacent forest) to collect 2900 recordings to generate soundscapes and compare acoustic activity patterns of birds and anurans among sites. We identified 56 bird species during the morning chorus (05:00-07:00) and 9 anurans species in the evening chorus (18:00-20:00). Bird species richness was similar between the forest (28 bird species), the abandoned mine (25 species) and the active mine (24 species), but species richness of birds sensitive to disturbance was much lower in the active mine. In contrast, anuran species richness was highest in the active mine (5 species) and lowest in the forest (2 species). Results indicate that acoustic monitoring and soundscape analysis can be effective tools for evaluating the impact of mining activities on vocalizing species, and could become useful tools in rapid environmental impact assessments for mitigation and conservation strategies in ASM mining regions.

Key words: Soundscapes, passive acoustic monitoring, mining, Madre de Dios, biodiversity rapid assessment

Resumen

La extracción aurífera artesanal y en pequeña escala (ASM por sus siglas en inglés) se está convirtiendo en una causa importante de degradación ambiental en los ecosistemas tropicales. En este estudio, se llevo a cabo una evaluación rápida del impacto de una mina de oro artesanal en las comunidades de aves y de anuros en la Zona de Amortiguamiento de la Reserva Nacional de Tambopata en el Perú. Se usaron siete grabadoras de audio (tres cerca de una mina activa, dos en una mina abandonada, y dos en un bosque adyacente) para recoger 2900 grabaciones de paisajes sonoros y poder generar y comparar los patrones de actividad acústica entre sitios mediante la identificación de sus vocalizaciones. Se identificaron 56 especies de aves durante el coro de la mañana (5:00-7:00) y 9 especies de anuros en el coro de la noche (18:00-20:00). La riqueza de especies de aves fue similar entre el bosque (28 especies de aves), la mina abandonada (25 especies) y la mina activa (24 especies), pero la riqueza de especies de aves sensibles a la perturbación fue mucho menor en la mina activa. Por el contrario, la riqueza de especies de anuros fue mayor en la mina activa (5 especies) y más baja en el bosque (2 especies). Los resultados indican que el monitoreo acústico y el análisis sonoro pueden ser herramientas eficaces para evaluar el impacto de las actividades mineras sobre las especies que vocalizan, y podrían llegar a ser herramientas útiles en las evaluaciones rápidas de impacto ambiental y en las estrategias de mitigación y conservación de biodiversidad en las regiones de minería artesanal.

Palabras clave: Paisajes sonoros, monitoreo acústico, minería, Madre de Dios, evaluación rápida de la biodiversidad

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Introduction

Gold mining is a growing cause of the environmental degradation of tropical protected areas and ecosystems [1]. The recent dramatic increase in gold prices has made it much more feasible to conduct gold mining activities in remote and pristine areas. In South America, approximately 1680 km^2 of tropical forests were lost due to gold mining activities between 2001 and 2013 [2]. Much of the new mining activity in these remote areas is artisanal and small-scale (ASM) [3]. Within the tropical forests biome, the majority of gold mining hotspots occur in areas near protected areas with high levels of biodiversity [2], highlighting an urgent need to improve our understanding about how ASM impacts on the environment and on wildlife.

The majority of wildlife studies related to the impact of gold mining has focused on mercury and cyanide contamination [4], especially in fish [5] and aquatic invertebrates [6]. Other studies have evaluated the degradation of vegetation caused by chemical pollutants [4] and the increased sedimentation in aquatic habitats [7], but few studies have assessed impacts of ASM gold mining activities on terrestrial fauna. Habitat fragmentation and degradation by ASM operations has affected the composition of animal communities [8, 9], and accelerated the extirpation of some species [10]. In addition, ASM operations could alter species behavior (e.g. displace animals deeper into the forest) [9] and have been linked to bushmeat hunting and consumption [1]. Noise produced by motors and vehicles can affect animal abundance, activity, movement patterns, predatory-prey interactions, and increase physiological stress [11–13]. However, the impact of noise generated by ASM activities has received little attention.

The impacts of ASM gold-mining on wildlife can be challenging to monitor because mines are located in remote sites and miners quickly move on to new locations. Furthermore, it can be dangerous to work in these areas because many mines are illegal. Passive acoustic monitoring provides a quick and reliable survey method for improving wildlife monitoring in gold mining areas. For example, automated portable recorders can easily be deployed in remote areas to collect acoustic data from many sites simultaneously. Most importantly, these recorders can collect data 24 hours a day and provide a permanent record for future analyses [14–16].

In the context of biodiversity assessments, passive acoustic monitoring has been used to monitor individual species [15], conduct rapid assessment surveys of biodiversity at the community level using acoustic indexes [17], and document the impacts of anthropogenic activities (such as industrial mining, and oil and gas exploration) [18, 19]. Passive acoustic monitoring can detect more vocal species than traditional methods because it can record large volumes of acoustic data over an extended period. For instance, manually analyzing a fraction of recordings (i.e. inspecting audio and spectrograms) can yield over 25% more detections of bird species than generated by traditional methods [20]. Another advantage of using passive acoustic monitoring is that the recordings can be aggregated to form soundscapes, which can be used to compare the acoustic diversity or the ecological integrity between sites [21, 22].

In this study, we used passive acoustic monitoring to document the soundscape and to record vocal avian and anuran species surrounding an ASM area located in the buffer zone of the Tambopata Nature Reserve in Madre de Dios, Peru. Audio recordings were used to conduct a rapid impact assessment by comparing the soundscape and species composition based on the vocalization of known species in three sites: an active mine, an abandoned mine, and an adjacent closed forest. To understand the impacts of mining we compared: 1) the soundscapes and 2) bird and anuran richness and composition among the three different land-use types.

Methods

Study region

The active mine, abandoned mine, and closed-forest sites were located in the buffer zone of the Tambopata Nature Reserve (BZ-TNR) in the Department of Madre de Dios, Peru (Fig. 1). The Tambopata region occurs within the tropical moist forest biome at an elevation of ~250 m a.s.l. and the mean annual temperature is 25°C. Average annual precipitation is ~2200-2400 mm and, for three months (July-September), rainfall averages less than 100 mm [23]. This region is renowned for high levels of biodiversity including > 1200 species of butterflies, > 1300 species of birds, and many threatened Amazonian species (such as the harpy eagle, the giant river otter and wooly and spider monkeys) [24]. The region also includes old-growth riparian forest, which is increasingly threatened [24]. The region's geology is mostly alluvial and fluvial deposits from the Tertiary and Quaternary periods, which contain primary and secondary (placer) gold deposits [25]. Artisanal gold mining has increased in the region since the early 2000s [26], and the new Interoceanic Highway has facilitated massive migrations of gold miners, who have contributed to unprecedented rates of deforestation in the region [27, 28].

Artisanal and small-scale miners in the Tambopata region are typically equipped with mechanical and hydraulic machinery known as “chupaderas”. Mining with this equipment first involves clearing the land of trees and then the use of 18-20 hp pressurized water pumps to transform the cleared land into slurry, which is usually pumped into a sieve and hopper with a 90 hp suction pump. After sieving, the ore is mixed with mercury for amalgamation and final separation of the gold from other sediment particulates. Each operation uses 2-4 laborers and can run from 12 to 20 hours per day in areas that range from 0.5 to 1 hectare. After the gold is extracted, the operation moves on to a neighboring locality, typically after one week of work [25].

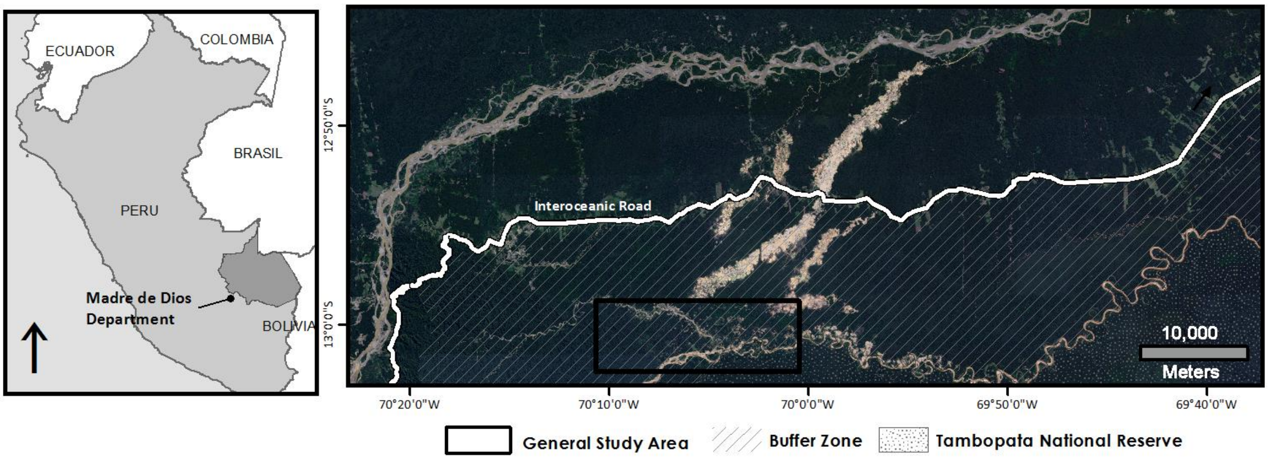

Fig. 1. Map showing the area that encloses the study site within the Buffer Zone of the Tambopata National Reserve in the Department of Madre de Dios, Peru. We have not revealed the exact location of the mining community and the illegal operation. The background is a Landsat image from 2014, band combination 3, 2, 1.

Experimental design

We conducted the study from August 16 to 19, 2014. All land-use types were located in non-flooded *terra firme* humid lowland forest. ARBIMON Touch portable recorders [29] were placed at the fringe of an illegal active mine (recorders, n = 3); in an abandoned (~4 yr) mine (n = 2); and in an adjacent closed forest (n = 2). The recorders were strapped to the trunks of trees or shrubs, placed ~1 meter above the ground. Within each land-use type, recorders were separated by more than 70 m, and the distance between the different land-use types was ~450 m. The general characteristics of the land-use types were as follows. A) the active mining site covered approximately 6350 m^2, predominantly characterized by exposed soil, tailings, and ponds of slurry. A secondary alluvial gold deposit was being mined with a hydraulic machine with suction pumps (*chupaderas*). B) the abandoned mining was approximately 18650 m^2. Soils after mining had occurred in this region are characterized by their high sand content (1.7 times more sand than the soil from the adjacent forest), high pH (1.2 times higher) and poor content of silt and clay (4.9 and 2.3 less, respectively) [30]. With the exception of some bamboo and shrubs, the abandoned mining area was characterized by grasses, bare soils, tailings and water ponds. C) the forest was seasonal tropical moist forest, which was the main land cover in the study area. Recorders were placed in a selectively logged forest near the mining and abandoned mining areas.

Recorders were programmed to collect one-minute recordings simultaneously every 10 minutes, from ~10:00 am on August 16th to ~9:00 am on August 19th, with a total of 2,902 recordings across all sites, for an average of 414 recordings per recorder. The sampling period of one-minute every 10 minutes has been effectively applied to monitor acoustic activity in birds and anurans elsewhere [16, 31]. All recordings were uploaded to the cloud-computing platform ARBIMON II for analysis [29].

Soundscape analyses

Soundscapes are the combination of all sounds (biotic, abiotic, and anthropogenic) from a particular environment, and they can be represented graphically by aggregating all audio recordings over a given time period. We used ARBIMON II [29] to create graphical representations of soundscapes from the recordings collected at each of the seven sampling sites. To create a soundscape graph, we first aggregated the recordings at a time scale of one hour for each of the seven recorders and we used a 86 Hz frequency bin size and an amplitude filtering parameter of 0.2, which is an optimum threshold value to capture biotic activity (i.e. bird and anuran vocalizations) [19]. To control for the different number of recordings collected at each site, all soundscapes were normalized by dividing the number of peaks in each frequency of each hour interval by the total number of recordings collected each hour.

Soundscape composition (Biophony)

We analyzed 252 one-minute recordings from the dawn chorus (05:00-07:00) and 282 recordings from the dusk chorus (18:00-20:00). Recordings were analyzed manually by an ornithologist and a herpetologist with field experience in the region to identify species vocalizing in each one-minute recording sampled. The presence of bird and anuran species was noted based on their sound and frequencies. Sound databases for birds (www.xeno-canto.org) and amphibians ("Frogs of Tambopata") [32] were used as references. Xeno-canto is a comprehensive database that contains recordings from more than 9000 avian species, covering approximately 80% of all vocalizing bird species in the world (August et al. 2015), and Frogs of Tambopata is the most complete inventory for anuran species in the study region. We also noted the presence of insects and anthropogenic noise in each recording during the two periods.

Community-level analysis

We used the first-order Jackknife procedure to estimate bird and anuran species richness in the three land-use types based on the species identified in the audio recordings. To evaluate the variability in species composition across the three land-use types, we used the non-metric, multidimensional scaling (NMDS) ordination of Bray-Curtis' dissimilarity matrices, with a number of reduced dimensions of two, created with the function 'MetaMDS' in the package {vegan} [33] in the R statistical software [34]. In addition, an indicator species analysis (ISA) was carried out in PCOrd (version 5.33) to identify species that were indicative of each land-use type. Indicator species analysis permits a statistically rigorous identification of the species that characterize a given ecosystem [35].

Finally, to investigate the effect of the different land-use types on birds sharing similar species traits, we grouped them according to two life history and ecological traits: 1) sensitivity to disturbance and 2) habitat specialization [36]. Sensitivity is based on a qualitative assessment of sensitivity to human disturbances (high, medium or low), based on field experience and knowledge of the natural history of birds [36]. We also used the first-order Jackknife procedure to estimate sensitive species richness in the three land-use types.

Habitat specialization refers to the number of habitats where a species can be found (range 1-7) [36], and was used in this study to describe differences in species traits among the birds found across the three land-use types. According to Stotz et al. [36], the range of habitats that birds in our study site can occupy include: tropical lowland evergreen forest, flooded tropical evergreen forest, river-edge forest, montane evergreen forest, tropical deciduous forest, gallery forest, white sand forest, mangrove forest, secondary forest, riparian thickets, river island scrubs, pastures/agricultural lands, second-growth scrub, fresh water lakes and ponds, and rivers.

Results

Soundscapes

Analyses of soundscapes showed that most of the acoustic activity was below 9 kHz (Fig. 2, Appendix 1). The majority of the biological sounds occurring between 2 to 9 kHz was from insects, birds, and anurans. Most bioacoustic activity or biophony occurred in the night and early morning and there was a noticeable gap of activity during the day between 08:00 to 17:00 from 2 to 6 kHz due to a decrease in bird and anuran vocalizations. Insect sounds were detected in all sampled recordings, and they dominated both the diurnal and nocturnal biophony, with most activity in the 4 to 9 kHz range. Geophony sounds from precipitation or strong wind events were not registered.

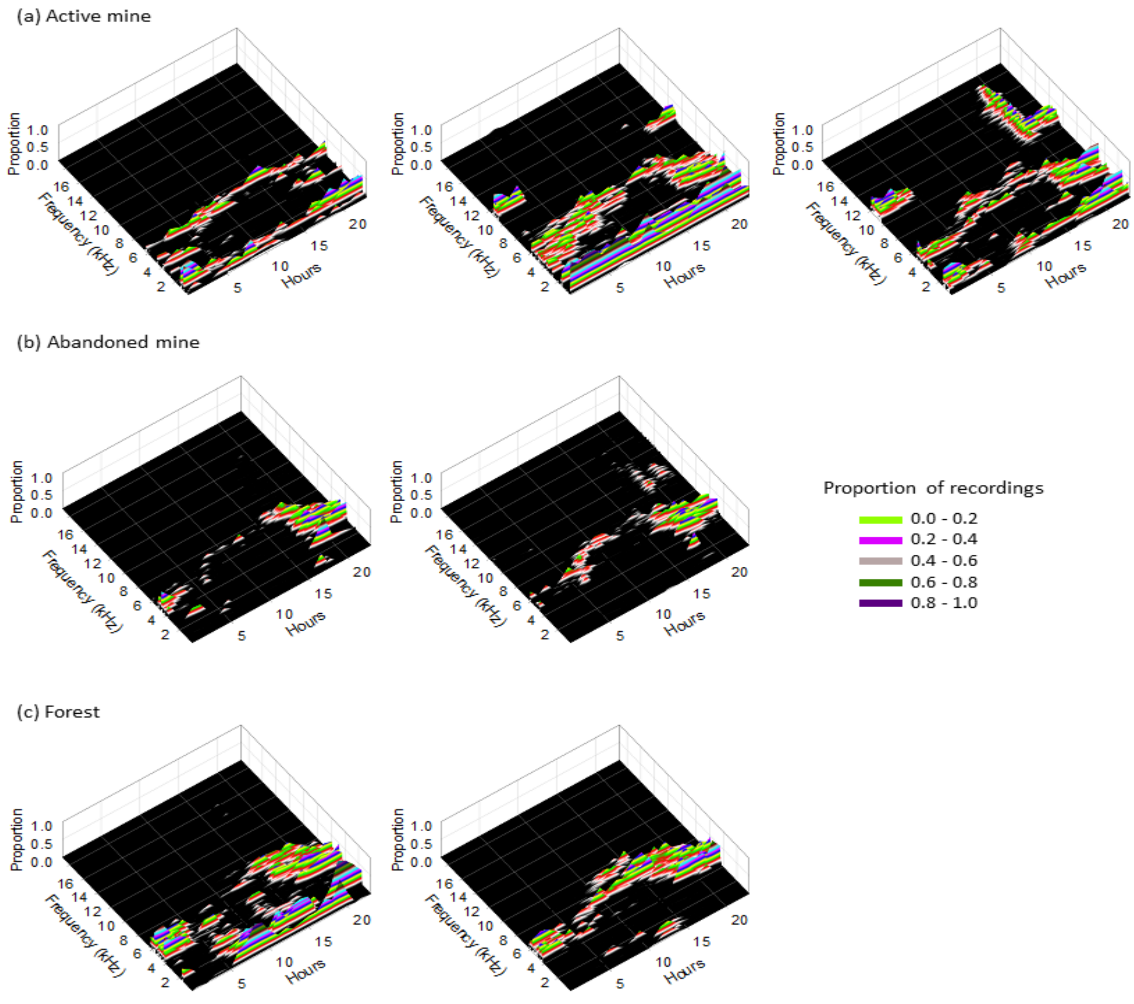

Fig. 2. Soundscapes for each of the recorders in the active mine (a), abandoned mine (b), and closed-forest area (c). The z-axis represents the proportion of recordings with peak activity in a given frequency/time period.

Anthropogenic noise was concentrated at lower frequencies (ranging from 0-2 kHz) and was associated with mining machinery and motorcycles (Fig. 2, Appendix 1). Soundscapes from recordings collected near the active mine indicated that mining machinery was running at intermittent intervals during the day and night. Mining machinery activity was highest and most consistent at night (between 17:00 and 05:00). In recordings from the active mine, the presence of mining machinery noise was detected in 13 of the 108 recordings between 05:00-7:00 and 82 of the 120 recordings between 18:00-20:00.

In the forest area, peaks in the 0-2 kHz frequency range were also detected in one of the recorders. These peaks were all associated with motorcycles in transit during the day on a nearby trail (Fig. 2, Appendix 1). In the forest recordings, the presence of motorcycle noise was detected in 5 of the 252 recordings between 05:00-7:00 and in none of the 282 recordings between 18:00-20:00. Peak activities within this low-frequency range could also be attributed to vocalizations of the Screaming Piha bird *(Lipaugus vociferans)* (~0.8 to 6 kHz).

Within our three land-use types, insects (such as cicada, Hemiptera and Orthoptera) were a major component of the soundscape. Although insects were detected in all recordings, we did not analyze them separately given limitations in identifying insect species. We limited our analysis of insects to test the significance of the number of insect detections across the three land-use types using a Kruskall-Wallis Nonparametric Analysis of Variance. All species richness and composition analyses were limited to avian and anuran species.

Bird assemblage at land-use types

A total of 56 bird species were identified in the three land-use types during the dawn chorus (05:00-07:00). The number of bird species was similar between land-use types with 24 bird species identified near the active mine, 25 species in the abandoned mine, and 28 species in the forest area (Appendix 2). The frequency of detections (the number of recordings with a species) also showed a similar pattern with a similar number of detections between land-use types, revealing 111 detections near the active mine, 115 detections in the abandoned mine, and 133 detections in the closed forest.

Between 05:00 and 07:00, the russet-backed oropendola *(Psarocolius angustifrons)* was the most acoustically active species (detected 44 times) followed by the buff-throated Woodcreeper (*Xiphorhynchus guttatus)* (29 times) and the undulated tinamou (*Crypturellus undulatus)* (25 times). The most widespread bird species was the buff-throated woodcreeper *(Xiphorhynchus guttatus)* (all 7 sites), followed by the black-faced antthrush (*Formicarius analis)* (6 sites), and the chestnut-fronted macaw *(Ara severus)*, the red-throated caracara *(Ibycter americanus)* and the russet-backed oropendola *(Psarocolius angustifrons)* (5 sites) (Appendix 2).

The results show no differences in the estimated species richness between land-use types (Fig. 3a), with a mean of 34.7 (SD ±3.38) in the mining area, 32.77 ±2.45 in the abandoned area, and 37.72 ±2.99 in the forest. However, there were considerable differences in species composition: 22 of the 28 species in the forest area were not observed near the active mine, and 21 of the 25 species in the abandoned mine were not observed near the active mine. The highest number of overlapping species occurred in the abandoned mine and the active mine (11 species). Furthermore, a total of 27 species (47%) were detected on fewer than two occasions across all land-use types. The results of the NMDS ordination for bird species presence and absence showed a strong clustering according to land-use type (Fig. 4a).

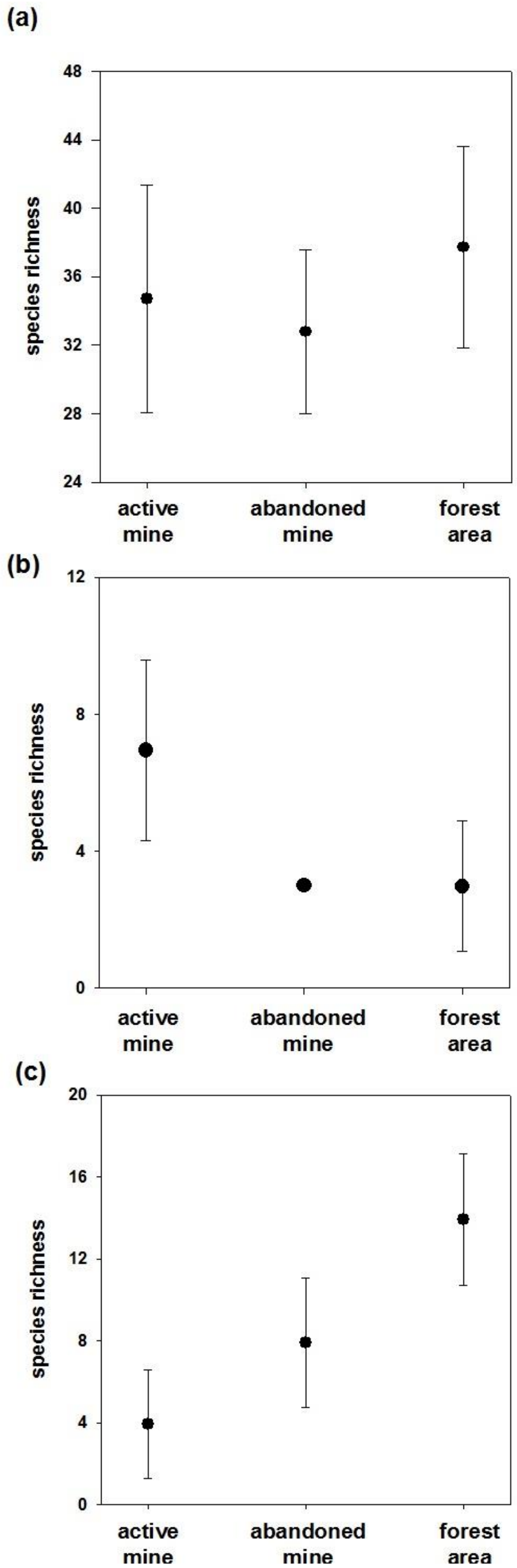

Fig. 3. Estimated (Jackknife) species richness for bird (a), anuran (b), and high sensitive bird species (c) per land-use type. Dots indicate estimated richness and error bars represent 95% confidence intervals.

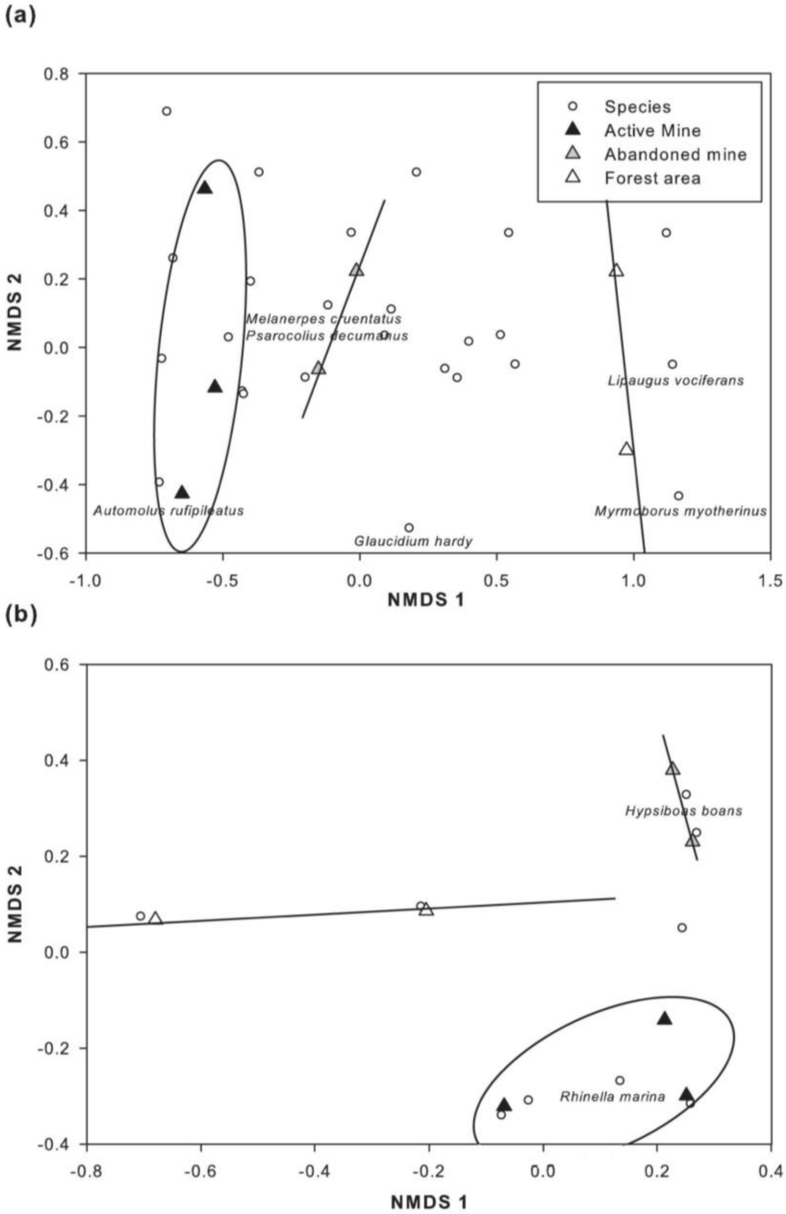

Fig. 4. Nonmetric multidimensional scaling of species composition for birds (a), and anurans (b) in the different land-use types using presence/absence data. Ellipses and lines indicate standard error confidence intervals (95%). For both birds and amphibians, the stress was nearly zero; non-metric fit, R^2=1; linear fit, R^2=1. The species listed are the indicator species in each group.

Results of the indicator species analysis did not find species that had significant indicator values for the different land-use types at the significance threshold chosen for this study (p<0.05). At a significance of p<0.1, the only species with significant indicator values in the active mining site was the chestnut-crowned foliage-gleaner *(Automolus rufipileatus)*. Two species: the yellow-tufted woodpecker *(Melanerpes cruentatus)* and the crested oropendola (*Psarocolius decumanus)* were indicative of abandoned mining, and three species: the amazonian pygmy-owl *(Glaucidium hardyi),* the screaming piha *(Lipaugus vociferans)*, and the black-faced antbird *(Myrmoborus myotherinus)* were indicative of the forest.

The species richness of the highly sensitive bird species in the forest area (13.91; SD ±1.63) was ~3 times greater than species richness near the active mine (3.94 ±1.35). Additionally, sensitive species richness in the abandoned mine (7.9 ±1.61) was ~2 times greater than sensitive species richness near the active mine (Fig. 3c).

Sensitivity, as measured by the number of habitat categories used by a species, was also correlated with land-use type (habitat specialization). Seventy-two percent of species found in the forest only used 1-2 habitats, whereas the majority of bird species (61%) found near the active mine used between 4-6 habitats and could be categorized as generalists (Appendix 3).

Anuran assemblage and insects detections in each land-use type
Nine anuran species were identified in the three land-use types during the 18:00-20:00 period. Anuran species richness was higher near the active mining operation (5 species) than the abandoned mine area (3 species) and the forest area (2 species) (Table 1). The Jackknife estimated species richness in the active mine was significantly higher than in the abandoned mine and forest areas (Fig. 3b), with a mean of 6.94 (SD ±1.35) species in the mining area, a mean of 3 (SD = 0) in the abandoned area, and 2.97 ±0.97 in the forest. The number of anuran detections was also higher in the active mine (n = 48) than in the abandoned mine (n = 15), or the forest (n = 35).

Table 1. Anuran species identified in each sampling site.

		Active mine			Abandoned		Forest	
Scientific name	**Common name**	**1**	**2**	**3**	**1**	**2**	**1**	**2**
Rhinella marina	Cane toad	*	*	*				
Dendropsophus acreanus	Acre tree frog	*						
Adenomera andreae	Lowland tropical bullfrog	*						
Pristimantis reichlei			*			*		
Anuran 1				*				
Hypsiboas boans	Rusty tree frog				*	*		
Anuran 2						*		
Hypsiboas cinerascens	Demerara Falls tree frog						*	
Pristimantis sp								*

Between 18:00-20:00, the demerara falls tree frog *(Hypsiboas cinerascens)* was the most acoustically active species (detected 49 times, but in only one of the 2 recorders in the forest area); followed by the cane toad *(Rhinella marina;* 30 times) and the acre treefrog *(Dendropsophus acreanus;* 14 times). As with the avian composition, there were considerable differences in species composition: only 1 species overlapped between land-use types (the active and the abandoned mine) and only 3 species were detected in more than one recorder. The NMDS of presence and absence data grouped species according to the three land-use types (Fig. 4b). During the morning period (06:00-08:00) insect activity was similar in all of the land-use types (*H=4.0385, 2 d.f., p =0.1069*). In total, we counted 239 insect detections. The number of detections per recorder ranged from 29 to 36. In the 18:00-20:00 period, insect activity was also similar in all of the sites (*H=1.4615, 2 d.f., p =0.482*). In total there were 308 detections, and the number of detections per recorder ranged from 29 to 43.

Discussion
The two major components of the soundscapes in this region were: 1) the biophony, which was dominated by sounds of insects, birds and anurans; and 2) anthropogenic noise from mining machinery and motorcycles. Whereas noise from mining machinery and motorcycles was present during the day, noise from the mining machinery was dominant at night. The

recurrent motorcycles in transit to and from the mining site generated intermittent noise in the closed-forest site. As ASM continues to advance in the tropical forests, these human-generated sounds will continue to spread to remote natural areas, with a variety of negative consequences for the natural soundscape. For example, motorized noise disturbances can mask the acoustic signals of species [37], affecting prey and predator interactions and intraspecific and interspecies communication [38]. Furthermore, some species may completely abandon an area and others might change the amplitude or frequency of their acoustic signals [37, 39].

Using sound recordings to monitor biodiversity and individual species, especially in the tropics, is a useful tool to improve the understanding of wildlife and to evaluate impacts of extractive activities on vocalizing fauna [18, 19]. In a recent study, Duarte et al. [18] found that mining noise from an open-cast mine (for example, trucks transiting, sirens, horns, and explosions) exhibited 1-22 dB(Z) higher levels of noise near the mining operations than in a forest site far from the mine. They also found significantly higher levels of noise at night during the wet season. Mining noise was related to a switch in the biophony patterns, with a higher biophony during the day at the site close to the mine and a higher biophony during the night at the site far from the mine, indicating an alteration of the temporal dynamics and patterns of animal sounds [18]. In another related study, Deichmann et al. [19] used soundscape analysis to evaluate the impact of gas exploratory operations on biodiversity in a pre-montane forest in Peru, and found that noise from the operation negatively impacted the richness of sound frequencies of fauna up to ~500 m from the exploratory platform. In general, soundscape quality is increasingly considered an important component for biodiversity monitoring and conservation [17, 22].

Our community acoustic monitoring analyses revealed that despite overall bird species richness being similar across the land-use types, species composition was significantly affected by the three different land uses. Ordination analysis indicated the grouping of bird communities according to land-use types. Furthermore, we found that relative to the forest land-use type, at the abandoned and active mining sites there were fewer species that are highly sensitive to environmental disturbance [36]. Site abandonment by certain bird species is a known response to noise [38]. Birds may abandon areas when prolonged noise interferes with cue detection or erratic noise is perceived as a threat [13]. Interference of cues can raise stress levels, inhibit social interactions and intensify the perception of predation risk [13,38]. For example, an experiment with noise coming from an intermittent road found that erratic noise impacted more on the greater sage grouse (*Centrocercus* sp.) than continuous noise [40]. In addition, noise from motors has been shown to increase physiological stress and decrease the fitness of some bird species [40, 41]. The avoidance behavior of highly sensitive species is an indicator of environmental health and shows how noise disturbance in mining sites are affecting bird species [36]. Additionally, while bird species richness was high in the ASM area, most of the species were habitat generalists that can also inhabit disturbed habitats. These data are important for conservation purposes because as mining continues to advance in the tropical forest of Peru, it is likely that only forests far from mining areas and far from the noise associated with mining activities will be able to sustain the full range of bird species in this region. With extractive activities encroaching into remote regions, the loss of certain sensitive birds or forest specialists could result in critical ecological consequences, such as changes in pollination and seed dispersal patterns, which can impact heavily on forest regeneration [19].

We also found significant differences in the composition of anuran populations across the land-use types. Unlike with birds, there was a greater richness in the periphery of the active mine than in the forest or the abandoned mine. While birds are highly mobile, anuran species generally have restricted ranges and poor dispersal capacity, limiting their ability to escape areas of high noise disturbance that may be competing with their calls [42]. Moreover, many anuran species adapt to high levels of noise [12], and others tolerate a high degree of habitat modification. For example, two of the species found in our study area (the acre tree frog and the cane toad) are reported to increase in number when their habitats are disturbed [43, 44]. This observation of higher anuran species closer to extractive operations is similar to the pattern found in an oil exploration facility elsewhere in Madre de Dios, Peru [19]. The number of anuran species was higher closer to the exploration platform than further into the forest, which was possibly because new water ponds had been created surrounding the exploration platform that provided water for anuran reproduction and proliferation [19]. In ASM, the extraction process results in many ponds, which can be a limiting microhabitat for amphibian reproduction. The presence of ponds from past mining activities could also explain the higher species richness and number of frogs in the abandoned mine in comparison to the closed forest.

While the limited duration and geographical extent of our study limits the extrapolation possibilities of our findings, our rapid impact assessment demonstrates that gold mining has a significant impact on biodiversity composition and highlights a need for more comprehensive studies on the ecological impact of gold mining. We report on a single case study and further research should consider different sizes of mining operations and encompass a broader area of study. Our data collection was only during the dry season, and it is important for future studies to increase the sampling effort to include the rainy season, which is an reproductive season for some birds and anuran in the region. It is important to highlight, however, that the use of acoustic monitoring provided an effective mechanism to detect the presence and absence of vocal species in a remote mining site, a task that would have been nearly impossible to accomplish using traditional methods such as transects, point-counts and mist-nets, particularly given the safety concerns that often characterize ASM mining sites in the tropics.

However, although acoustic monitoring has many advantages it also has certain limitations, the most obvious being that detections are limited to vocal individuals. Another limitation is that it is difficult to estimate population densities. Yet, despite these limitations the use of passive acoustic devices has been shown, in comparison to traditional methods, to be more effective for detecting avian and anuran species [14]. In addition to acoustic monitoring for species identification, the analysis of the soundscape provides an overall view or big-picture perspective of the sound environment at each site, which helps to better understand how the natural environment changes in response to anthropogenic activities. Acoustic monitoring and soundscape analyses are effective tools for conducting rapid assessments on the impact of human activities on biodiversity and could be useful in gathering data for environmental impact assessment of extractive activities in regions of high biodiversity.

Implications for conservation

This study highlights the vulnerability of birds and anurans to ASM activities in the Tambopata region in Peru. In particular, birds that are sensitive to disturbance are missing from areas of active mining due to habitat degradation and noise pollution. Even areas of abandoned mining activities could not sustain the range of bird species of forest sites. Although noise from mining machinery may be transient and may only last for a week in a specific locality, the effect of noise pollution caused by the large amount of machinery operating in this region (e.g. between 800 and 1000 *chupaderas* or hydraulic jets in the Department of Madre de Dios in 2011 [45]) could pose a threat to the ecological integrity and wildlife wellbeing of this tropical forest [45]. In addition to the effects of noise pollution, habitat disturbance caused by mining activities in this region can have long-term effects given the absence of natural regeneration [30]. Given that gold mining is likely to continue to increase there is an urgent need to investigate further the impacts of gold mining on terrestrial wildlife, including the effects caused by soil denudation, chemical pollution, and the different types of noise pollution generated by mining operations. To help design future conservation strategies and inform decision-making for natural resource management and biodiversity conservation, it is important to develop new sampling techniques for rapid evaluations of the impact of mining on fauna. Passive acoustic monitoring can provide a rapid and efficient way to assess biodiversity, as well as the general quality of the soundscape, in areas where there are mining activities.

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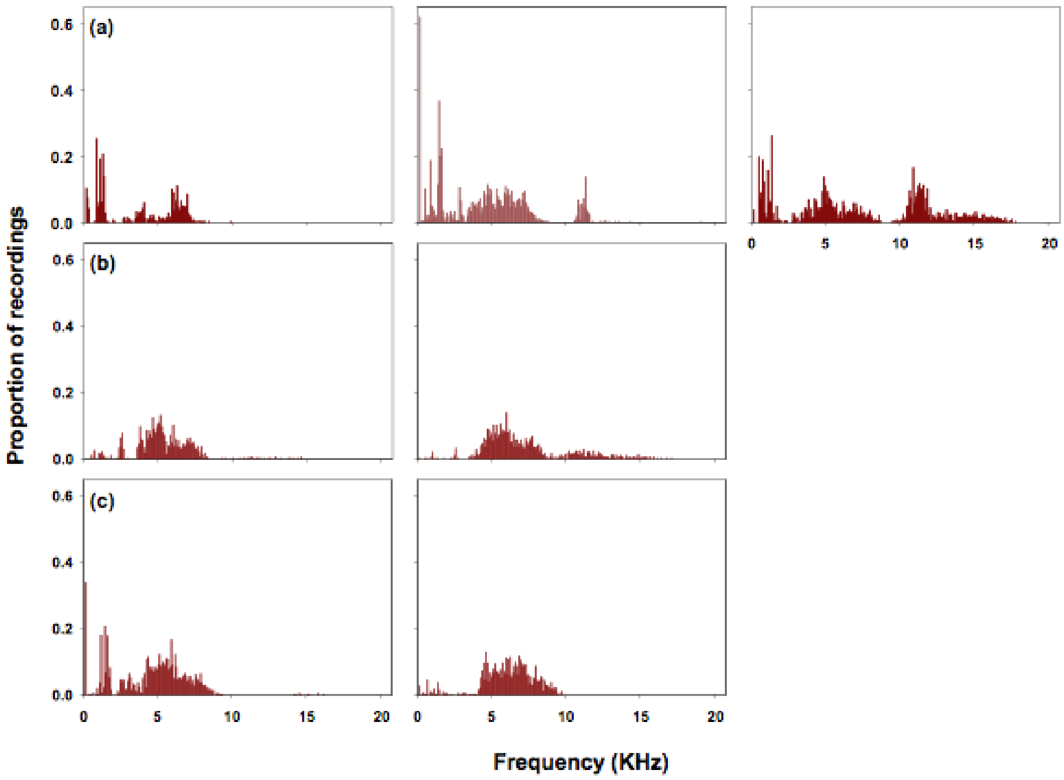
Appendices

Appendix 1. Histograms of frequencies detected at the recorders in the active mine (a), abandoned mine (b), and forest area (c).



Appendix 2. Bird species identified in each sampling site with level of sensitivity to disturbance and number of habitats used by each species.

		Active mine			Aband.		Forest			
Scientific name	**Common name**	**1**	**2**	**3**	**1**	**2**	**1**	**2**	**Sens.**	**#**
Psarocolius angustifrons	Russet-backed Oropendola	*	*	*	*	*			low	5
Crypturellus undulatus	Undulated Tinamou	*		*	*	*			low	4
Automolus rufipileatus	Chestnut-crowned Foliage-gleaner	*	*	*					med	2
Pionus menstruus	Blue-headed Parrot	*							low	4
Ara severus	Chestnut-fronted Macaw	*	*	*	*	*			med	4
Formicarius analis	Black-faced Antthrush	*	*		*	*	*	*	med	2
Xiphorhynchus guttatus	Buff-throated Woodcreeper	*		*	*	*	*	*	low	3
Momotus momota	Amazonian Motmot	*		*					med	6
Megarynchus pitangua	Boat-billed Flycatcher	*				*			low	5
Trogon melanurus	Black-tailed Trogon	*					*		med	3
Cacicus cela	Yellow-rumped Cacique	*							low	4
Myrmoborus leucophrys	White-browed Antbird	*							med	3
Synallaxis gujanensis	Plain-crowned Spinetail	*							low	3
Glaucidium brasilianum	Ferruginous Pygmy-Owl		*	*					low	6
Saltator coerulescens	Grayish Saltator		*	*					low	6
Pitangus sulphuratus	Great Kiskadee		*	*					low	5
Amazona ochrocephala	Yellow-crowned Parrot		*	*					med	4
Cyanocorax violaceus	Violaceous Jay		*	*	*	*			low	4
Pachyramphus polychopterus	White-winged Becard		*	*	*	*			low	4
Ortalis guttata	Speckled Chachalaca		*	*					low	4
Thamnophilus schistaceus	Plain-winged Antshrike		*					*	high	2
Ibycter americanus	Red-throated Caracara			*	*		*	*	high	2
Campylorhynchus turdinus	Thrush-like Wren			*	*				low	4
Myrmeciza hemimelaena	Chestnut-tailed Antbird			*		*	*	*	med	2
Ramphastos tucanus	White-throated Toucan				*	*	*	*	high	1
Myiopagis gaimardii	Forest Elaenia				*	*		*	med	3
Melanerpes cruentatus	Yellow-tufted Woodpecker				*	*			low	3
Psarocolius decumanus	Crested Oropendola				*	*			med	3
Furnarius leucopus	Pale-legged Hornero				*				low	5
Ramphastos vitellinus	Channel-billed Toucan				*				high	1
Zimmerius gracilipes	Slender-footed Tyrannulet				*				med	2
Ammodramus aurifrons	Yellow-browed Sparrow					*			low	3
Ramphocelus carbo	Silver-beaked Tanager					*			low	5
Saltator maximus	Buff-throated Saltator					*	*		low	3

Phaethornis ruber	Reddish Hermit	*		*	med	3
Pionites leucogaster	White-bellied Parrot	*			high	2
Myiophobus fasciatus	Bran-colored Flycatcher	*			low	3
Pteroglossus castanotis	Chestnut-eared Aracari	*			high	4
Lipaugus vociferans	Screaming Piha		*	*	high	1
Arremon taciturnus	Pectoral Sparrow		*		med	1
Trogon collaris	Collared Trogon		*	*	med	4
Myrmoborus myotherinus	Black-faced Antbird		*	*	high	1
Glaucidium hardyi	Amazonian Pygmy-Owl		*	*	high	1
Crypturellus cinereus	Cinereous Tinamou		*		low	3
Xenops tenuirostris	Slender-billed Xenops			*	med	2
Xiphorhynchus elegans	Elegant Woodcreeper			*	high	1
Xenops minutus	Plain Xenops			*	med	2
Cyanocompsa cyanoides	Blue-black Grosbeak			*	med	2
Pygiptila stellaris	Spot-winged Antshrike			*	high	1
Aratinga weddellii	Dusky-headed Parakeet			*	low	3
Attila spadiceus	Bright-rumped Attila			*	med	3
Harpagus bidentatus	Double-toothed Kite			*	med	2
Hylophilus hypoxanthus	Dusky-capped Greenlet			*	high	1
Myrmotherula longipennis	Long-winged Antwren			*	high	1
Pharomachrus pavoninus	Pavonine quetzal			*	high	1
Trogon violaceus	Guianan Trogon			*	med	2

Appendix 3. Number of species versus the number of habitat categories that the species can inhabit in the three land-use types.