Temperate forest bird communities associated with a historic mining impact area: do tailing remnant effects modify their structure?

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ABSTRACT: Birds contribute to the stability of ecosystems and represent a tool used to evaluate a variety of anthropogenic impacts. The area known as El Oro-Tlalpujahua Mining District in central Mexico was subjected to significant environmental impacts as a result of ore extraction, including profound habitat transformations, landscape changes, and the accumulation of potentially toxic elements in their tailings (favoring its bioavailability and dispersion). After more than 60 years without extractive activities, there is no knowledge on extant remaining impacts on biological communities. Assuming the presence of negative impacts on birds, we compared the composition and abundance of bird communities in two locations, representing a site without exposure to tailings (S_1) and another one with tailings deposition (S_2). From June 2014 to June 2015, we recorded 2828 individuals of 108 avian species in 369 point counts ($S_1 = 91$, $S_2 = 95$). The Chao1 indicator suggested we recorded 96% of the species present. We found a high similarity in the general composition and abundance of bird species between communities (> 85%). However, there were significant differences in the abundances of 18 species (9 of them higher in the control site); these differences might result from differential effects of potentially toxic elements on functional groups (such as feeding guilds), resource availability, as well as other factors not accounted for. Historically, mining activities in the area generated significant changes in the structure and composition of the forest, and disrupted ecological processes. Despite the fact that current conditions appear favorable to the relative stability of the bird community, specific physiological effects on some species of birds sixty years after the cessation of mineral extraction could occur. Further studies on physiological performance and the effects of potentially toxic elements on local birds could unveil unknown effects at the individual level.

KEY-WORDS: avian communities, diversity, El Oro-Tlalpujahua Mining District, mining tailings, remnant effects.

INTRODUCTION

Information on the diversity and abundance of species in communities represent the basis for assessing the quality of their environment. Through monitoring it is possible to evaluate changes associated with different causal factors; comparisons on the occurrence of species in different environments, and the characterization of their relative abundance is often presented as supporting evidence (Balmer 2002).

Disturbance processes generated by human activities involve habitat changes through the modification of land use for productive activities (*e.g.*, agriculture and livestock), urban development, and mining activities, with the resulting effects on soil and water (Manson & Jardel-Peláez 2009). These events at the landscape level modify the structure of vegetation and generate successional processes that promote changes in the structure and

composition of animal communities (Pickett & White 1985). In birds, these types of changes have been described previously by Ugalde-Lezama *et al.* (2012) and Manson & Jardel-Peláez (2009), who found the simplification of forest structure related to the decrease in the composition of bird communities.

To evaluate anthropogenic impacts on wildlife, it is desirable to have an indicator of the intensity and extent of the impacts; if significant, they might be reflected in changes in the composition and/or abundance of species at the community level. At the population level, impacts may be reflected in changes in survival rates or reproductive success of species, or changes in their distribution (Altaf *et al.* 2018, Mahmoud & Gan 2018, Xu *et al.* 2018). Responses at the individual level are the most sensitive and usually have been assessed through changes in physical and physiological conditions (*e.g.*, height, weight, condition index, quantity of fat reserves)

(Pérez-Tris 1999). Few studies have explored the response of birds to anthropogenic impacts resulting from mining at the community level; most have focused on particular species (*e.g.*, Garitano-Zavala *et al.* 2010, Rubio *et al.* 2016), or ecological settings (*e.g.*, Ouboter *et al.* 1999, Eagles-Smith *et al.* 2016).

Several authors recognize the need for environmental monitoring from geological, ecological, and public health perspectives (Boulet & Larocque 1988, Perotti *et al.* 2017). Reclamation mining sites have sometimes been perceived as sites potentially important for biodiversity (Batty 2005). Mines that have operated for centuries are the source of pollutants that remain stored in tailings or the bottom of reservoirs, and their ecological effects in most cases have not been determined (Kossoff *et al.* 2014). Globally, estimations of mercury released to the environment as a byproduct of the amalgamation for recovery of gold and silver indicate that there has been over 260,000 tons released between 1550 and 1930 (Lacerda 1997). Furthermore, for mining sites that historically ceased production and left a legacy of ecological impact, little is known about the span and intensity of their impacts (Balistrieri *et al.* 2002, Eisler 2004, Cristol *et al.* 2008, Ventakeswarlu *et al.* 2016). Some studies have addressed aspects of geodynamics, bioavailability and transfer of elements in mine tailings, which are potentially toxic elements derived from mining runoff and water currents (*e.g.*, Rösner 1988, Perotti *et al.* 2017), as well as on soil and vegetation (O'Sullivan *et al.* 1999, Jacob & Otte 2004, Struckhoff *et al.* 2013), aquatic and terrestrial animals (such as benthic invertebrates, springtail insects, fish, amphibians, reptiles and birds), remediation, and ecological restoration (Lefcort *et al.* 1988, Gonçalves-Rodríguez & Shraft 2001, Lock *et al.* 2003, Cristol *et al.* 2008, Márquez-Ferrando 2008). Data from historically important mining areas in the world is scarce, and there is no documented information on possible remnant effects in reference to wildlife.

The Oro-Tlalpujahua Mining District (OTMD) in central Mexico has been the site of ecological changes associated with the settlement of a very important center of gold and silver ore extraction, from the middle 19th to early 20th century (Corona-Chávez & Uribe-Salas 2009). Mina Dos Estrellas was an exceptional settlement in its time, whose establishment and operation with major infrastructure caused the almost complete deforestation of the original forests, and led to the creation of roads, landscape alteration, and the accumulation of waste materials from ore extraction, among others. As a result of continued activities, the area gradually accumulated tailings of momentous volume. These elements have defined the environmental history of the region, and have stimulated interest in understanding the long term consequences of disturbance in the area (Corona-Chávez *et al.* 2010).

During the 65 years after cessation of activities in Mina Dos Estrellas, the region has experienced ecological succession that led to the reestablishment of secondary temperate forest made up of tolerant and pioneer tree species that survived the disturbance period on impoverished soil conditions (Muñiz-Castro 2008).

Because of the demands of wood and other materials for the construction and maintenance of mine galleries, the surrounding areas, and even those far away were also overexploited (Corona-Chávez & Uribe-Salas 2009). While the area was subjected to a strong mining impact, at the end of the mine's active life some nearby areas remained free from the effects of ore wastes, deforestation, agriculture and cattle grazing. These areas offer the possibility of investigating if some remnant effects derived from mining in the past are maintained and affect bird communities. Considering the possibilities of extant impacts, we analyzed and compared the richness and abundance of forest bird communities inhabiting tailings sites (abandoned approximately 65 years ago) and sites free from mine wastes, in order to determine differences that might be indicative of remnant impacts on the avifauna. Facing a possible scenario of intense and prolonged impact induced by the bioavailability of potentially toxic elements in tailings, we expected bird communities away from tailings to be more diverse and have higher abundance at least for the most common species, in comparison to the polluted area.

METHODS

Study area

The OTMD is situated in the limits of the states of Michoacan and Mexico (19°18'N; 100°09'W; Fig. 1) (Nieto-Monroy 2007), as part of the Trans-Mexican Volcanic Belt. At an elevation ranging from 2600 to 2850 m a.s.l., 45% of its surface is covered by secondary forest of Cedars (*Cupressus lusitanica*), Junipers (*Juniperus deppeana*), oaks (*Quercus* spp.), and pines (*Pinus* spp.). Its climate is temperate sub-humid with rainfall in summer (800–1100 mm per year), and the soils are mainly represented by andosols and luvisols (INEGI 2009). The OTMD area is adjacent to the polygons of the Monarch Butterfly Biosphere Reserve (MBBR) (Coronado-Martínez 2016). Although OTMD is not part of the reserve, it has had influences within the protected area because of historical extraction of materials in the past and tourism activities in the present (Ramírez-Ramírez 2001, SEMARNAT 2001, Coronado-Martínez 2016). Due to the limited and specific features of the area, the study sites are included only in one site, without replicates.

Figure 1. The Oro-Tlalpujahua Mining District study area in central Mexico (EC = El Castillo, S_1 ; DE = Mina Dos Estrellas, S_2).

Bird sampling

Bird sampling was carried out in two study sites: a) a control site far from tailings (El Castillo, Tlacotepec, S_1 ; 19.822°N; -100.145°W, 2750 m a.s.l.; Fig. 2A) and b) a tailings site (Mina Dos Estrellas, Tlalpujahua, S_2 ; 19.793°N; 100.156°W, 2648 m a.s.l.; Fig. 2B), both within the municipality of Tlalpujahua, Michoacan. Vegetation in both sites resulted from a natural secondary succession process and have similar structure and composition (Osuna-Vallejo *et al.* 2016). To determine the composition and abundance of bird communities, every month from June 2014 to June 2015, we conducted a total of 369 point counts (10 min) (169 in the control site S_1 and 200 in the tailings site S_2), located randomly every 200 m along independent paths, in which we registered individuals detected visually and acoustically (by songs or calls) within a fixed 50 m radius (to avoid bias due to detectability) (Hutto *et al.* 1986, Buskirk & McDonald 1995). The taxonomic arrangement adopted here was that proposed by the American Ornithological Society (AOS 2017), while the assignment of species to seasonality categories was based on our own experience

and Howell & Webb (2005). Species considered in any concern category were defined according to *Norma Oficial Mexicana* NOM-059-SEMARNAT-2010, where native species of wild flora and fauna in Mexico considered in any conservation risk are listed (SEMARNAT 2010).

Data analysis

We estimated the relative abundance and frequency of occurrence of bird species by site. The former was expressed by the number of individuals in 100 point counts, and the latter was evaluated through the percentage of counts where the species was recorded, which can reflect the detection probability of the species (Hutto *et al.* 1986).

We used the Completeness Index (Chao 1 estimator) to make a prediction of the expected species in the community based on our sampling (Chao *et al.* 2005). For each site we generated species accumulation curves to ensure sampling effort was adequate and to compare richness among sites (Colwell & Coddington 1994). These analyses were performed in EstimateS 9.1.0 (Colwell 2013).

In order to compare the similarity of communities

Figure 2. Control site, El Castillo, Tlacotepec, Michoacan (A); mining site, Mina Dos Estrellas (B), Photo authors: K.I. Lemus-Ramírez (A) and J.F. Villaseñor-Gómez (B).

between sites, we computed the qualitative Sorensen index and the quantitative Morisita-Horn index using Excel 2013. The former index is based on species presence/absence data, and indicates the composition resemblance of the communities; while the latter considers the number of individuals registered for each one of the species (Badii *et al.* 2007). To evaluate differences in species' abundance between sampling sites we applied a nonparametric Mann-Whitney U test using IBM SPSS Statistics 20.0). We also used an Analysis of Similarity (ANOSIM) to compare the degree of correspondence in the composition of communities (*sensu* Blake 2007, Edwards *et al.* 2011); as this method evaluates a dissimilarity matrix, values of R closer to zero reflect very similar communities, and values close to unity reflect significant differences between the communities being compared (PAST version 2.17 c). In order to gain further information about the species' contribution to the differences between communities, we applied a Similarity Percentage Analysis SIMPER (PAST version 2.17 c), that breaks up the contribution of each

one of the species to the similarity observed between communities, and defines the most important species responsible for the observed pattern (Clarke 1993).

RESULTS

From June 2014 to June 2015 we conducted a total of 369 point counts (169 in the control site S_1 and 200 in the tailings site S_2), and detected a total of 4364 individuals ($S_1 = 2043$, $S_2 = 2321$) from 108 species and 30 families ($S_1 = 97$, $S_2 = 91$); 85 are resident, 20 are winter visitors, two are considered transitory, and one is an introduced resident species (Table 1). We identified ten functional or guild groups (groups of species in a community that exploit the same set of resources in a similar manner, but are not necessarily closely related taxonomically). In the two study sites the insectivorous guild was the most abundant ($S_1 = 48\%$ species, 35% individuals; $S_2 = 51\%$ species, 35% individuals), followed by the omnivorous guild (S_1

= 19% species, 30% individuals; S_2 = 20% species, 23% individuals). In general, the communities showed very similar functional structure (species: $\chi^2 = 1.928$, $P = 0.993$; individuals: $\chi^2 = 2.856$, $P = 0.970$; Fig. 3).

Species accumulation curves exhibited an asymptotic behavior suggesting an adequate sampling effort for the detection of most species in the area. The Completeness Index (CI = Sobs/Sest) that is computed along with log-linear 95% confidence intervals (CI), indicated the recording of 96% of species for the OTMD region. The number of estimated species for the control site S_1 was 83% of the species recorded (117 estimated species, IC = 104–157 species), meanwhile for the tailings site S_2 , the estimated species corresponded to 93% of the detected ones (98 estimated species, IC = 93–116 species). Eighteen species were exclusive to the control site S_1 , ten were exclusive to the tailings site S_2 , and 88 species were present in both communities (Table 1). All exclusive species for each site were rare and infrequently recorded.

With respect to their relative abundances, our results showed that at the control site S_1 , *Ptiliogonys cinereus* (Gray Silky-flycatcher), *Hylocharis leucotis* (White-eared Hummingbird), *Spizella passerina* (Chipping Sparrow), *Regulus calendula* (Ruby-crowned Kinglet), and *Turdus migratorius* (American Robin) were the most abundant species. Correspondingly, at the tailings site S_2 , the species with the greatest relative abundance were *Setophaga coronata* (Yellow-rumped Warbler), *P. cinereus*, *H. leucotis*,

Figure 3. Bar chart of (A) number of species and (B) individuals belonging to different guilds at two sites within the El Oro-Tlalpujahua Mining District area. Legend: C: Carnivorous, F: Frugivorous, G: Granivorous, I: Insectivorous, N: Nectarivorous, O: Omnivorous.

Table 1. Seasonal status and relative abundances of bird species recorded in a control site and a mining site at El Oro-Tlalpujahua Mining District, central Mexico.

Family	Common name ^a	Seasonal status ^b	El Castillo (S ₁ Control site)		Mina Dos Estrellas (S ₂ Mining site)	
			FRE S ₁ ^c	ABU S ₁ ^d	FRE S ₂ ^c	ABU S ₂ ^d
Species						
Odontophoridae						
<i>Colinus virginianus</i>	Northern Bobwhite	PR	0.59	1.18	NR	NR
Columbidae						
<i>Patagioenas fasciata</i>	Band-tailed Pigeon	PR	0.59	0.59	NR	NR
<i>Columbina inca</i>	Inca Dove	PR	5.92	14.20	2.00	5.25
Cuculidae						
<i>Geococcyx californianus</i>	Greater Roadrunner	PR	0.59	0.59	NR	NR
Caprimulgidae						
<i>Antrostomus arizonae</i>	Mexican Whip-poor-will	PR	NR	NR	0.50	0.75
Trochilidae						
<i>Colibri thalassinus</i>	Mexican Violetear	PR	4.14	4.73	4.50	6.75
<i>Eugenes fulgens</i>	Rivoli's Hummingbird	PR	4.73	5.92	4.00	6.75
<i>Lampornis clemenciae</i>	Blue-throated Humming.	PR	1.78	2.96	2.50	3.75
<i>Archilochus colubris</i>	Ruby-throated Humming.	TR	1.18	1.18	NR	NR
<i>Selasphorus platycercus</i>	Broad-tailed Hummingbird	PR	1.78	1.78	0.50	0.75
<i>Selasphorus rufus</i>	Rufous Hummingbird	VI	0.59	0.59	0.50	0.75
<i>Amazilia beryllina</i>	Berylline Hummingbird	PR	0.59	1.18	3.00	6.00

Family	Common name ^a	Seasonal status ^b	El Castillo		Mina Dos Estrellas	
			(S ₁ Control site)		(S ₂ Mining site)	
Species			FRE S ₁ ^c	ABU S ₁ ^d	FRE S ₂ ^c	ABU S ₂ ^d
<i>Hylocharis leucotis</i>	White-eared Hummingbird	PR	63.31	85.21	59.50	128.25
Accipitridae						
<i>Accipiter cooperii</i> **	Cooper's Hawk	VI	1.18	1.18	NR	NR
<i>Buteo jamaicensis</i>	Red-tailed Hawk	PR	0.59	0.59	NR	NR
Trogonidae						
<i>Trogon mexicanus</i>	Mountain Trogon	PR	4.14	5.92	NR	NR
Picidae						
<i>Melanerpes formicivorus</i>	Acorn Woodpecker	PR	9.47	15.98	18.50	64.50
<i>Picoides scalaris</i>	Ladder-backed Woodpeck.	PR	6.51	6.51	4.50	6.75
<i>Picoides villosus</i>	Hairy Woodpecker	PR	3.55	4.14	3.50	5.25
<i>Colaptes auratus</i>	Northern Flicker	PR	5.33	5.33	0.50	0.75
Tyrannidae						
<i>Mitrephanes phaeocercus</i>	Tufted Flycatcher	PR	8.28	8.88	5.50	10.50
<i>Contopus pertinax</i>	Greater Pewee	PR	14.79	15.98	12.00	18.00
<i>Empidonax affinis</i>	Pine Flycatcher	PR	0.59	0.59	NR	NR
<i>Empidonax difficilis</i>	Pacific-slope Flycatcher	VI	1.18	1.18	NR	NR
<i>Empidonax occidentalis</i>	Cordilleran Flycatcher	PR	12.43	13.02	10.00	17.25
<i>Empidonax fulvifrons</i>	Buff-breasted Flycatcher	PR	1.18	1.18	2.50	4.50
<i>Sayornis nigricans</i>	Black Phoebe	PR	NR	NR	0.50	1.50
<i>Sayornis saya</i>	Say's Phoebe	VI	0.59	1.18	NR	NR
<i>Pyrocephalus rubinus</i>	Vermilion Flycatcher	PR	2.96	5.33	0.50	0.75
<i>Myiarchus tuberculifer</i>	Dusky-capped Flycatcher	PR	1.78	2.37	1.50	3.00
<i>Tyrannus vociferans</i>	Cassin's Kingbird	PR	5.92	7.69	2.00	3.75
Tityridae						
<i>Pachyramphus aglaiae</i>	Rose-throated Becard	PR	0.59	0.59	0.50	1.50
Vireonidae						
<i>Vireo huttoni</i>	Hutton's Vireo	PR	5.92	7.10	5.50	9.00
<i>Vireo cassinii</i>	Cassin's Vireo	VI	4.73	5.92	2.50	4.50
<i>Vireo plumbeus</i>	Plumbeous Vireo	PR	0.59	0.59	0.50	0.75
<i>Vireo gilvus</i>	Warbling Vireo	PR	0.59	0.59	0.50	0.75
Corvidae						
<i>Cyanocitta stelleri</i>	Steller's Jay	PR	5.33	20.71	1.00	5.25
<i>Corvus corax</i>	Common Raven	PR	NR	NR	0.50	0.75
Hirundinidae						
<i>Tachycineta thalassina</i>	Violet-green Swallow	PR	0.59	0.59	1.50	2.75
Paridae						
<i>Poecile sclateri</i>	Mexican Chickadee	PR	3.55	8.28	1.00	4.50
<i>Baeolophus wollweberi</i>	Bridled Titmouse	PR	NR	NR	0.50	1.50
Aegithalidae						
<i>Psaltiriparus minimus</i>	Bushtit	PR	8.88	56.21	9.00	116.25
Sittidae						
<i>Sitta carolinensis</i>	White-breasted Nuthatch	PR	23.08	29.59	12.00	18.75

Family Species	Common name ^a	Seasonal status ^b	El Castillo (S ₁ Control site)		Mina Dos Estrellas (S ₂ Mining site)	
			FRE S ₁ ^c	ABU S ₁ ^d	FRE S ₂ ^c	ABU S ₂ ^d
Certhiidae						
<i>Certhia americana</i>	Brown Creeper	PR	0.59	0.59	NR	NR
Troglodytidae						
<i>Catherpes mexicanus</i>	Canyon Wren	PR	1.78	1.78	2.00	3.00
<i>Troglodytes aedon parkmani</i>	House Wren (in part)	VI	7.10	8.28	3.00	5.25
<i>T. aedon brunneicollis</i>	House Wren (in part)	PR	2.96	2.96	8.50	14.25
<i>Thryomanes bewickii</i>	Bewick's Wren	PR	10.06	11.83	18.00	34.50
<i>Campylorhynchus gularis</i>	Spotted Wren	PR	0.59	1.18	NR	NR
Regulidae						
<i>Regulus satrapa</i>	Golden-crowned Kinglet	VI	0.59	0.59	NR	NR
<i>Regulus calendula</i>	Ruby-crowned Kinglet	PR	35.50	57.99	29.50	69.00
Turdidae						
<i>Myadestes occidentalis</i> **	Brown-backed Solitaire	PR	12.43	15.38	22.50	38.25
<i>Catharus aurantirostris</i>	Orange-billed Nightingale-Thrush	PR	0.59	0.59	4.00	7.00
<i>Catharus occidentalis</i>	Russet Nightingale-Thrush	PR	5.92	6.51	12.00	23.25
<i>Catharus guttatus</i>	Hermit Thrush	VI	0.59	1.18	NR	NR
<i>Turdus assimilis</i>	White-throated Thrush	PR	0.59	0.59	3.00	4.75
<i>Turdus migratorius</i>	American Robin	PR	33.14	56.80	33.00	86.25
Mimidae						
<i>Melanotis caerulescens</i>	Blue Mockingbird	PR	2.96	2.96	11.00	17.75
<i>Toxostoma curvirostre</i>	Curve-billed Thrasher	PR	7.10	8.88	7.50	12.75
<i>Mimus polyglottos</i>	Northern Mockingbird	PR	NR	NR	0.50	0.75
Ptiliognatidae						
<i>Ptiliognys cinereus</i>	Gray Silky-flycatcher	PR	25.44	99.41	37.50	163.50
Peucedramidae						
<i>Peucedramus taeniatus</i>	Olive Warbler	PR	18.93	21.30	13.00	19.50
Passeridae						
<i>Passer domesticus</i>	House Sparrow	PR/ INTRO	1.18	4.73	0.50	1.50
Fringillidae						
<i>Euphonia elegantissima</i>	Elegant Euphonia	PR	NR	NR	0.50	1.50
<i>Haemorhous mexicanus</i>	House Finch	PR	16.57	52.07	19.50	78.75
<i>Spinus pinus</i>	Pine Siskin	PR	4.14	8.88	3.00	9.75
<i>Spinus psaltria</i>	Lesser Goldfinch	PR	15.98	52.07	15.50	90.25
Passerellidae						
<i>Arremon virenticeps</i>	Green-striped Brushfinch	PR	NR	NR	0.50	1.50
<i>Atlapetes pileatus</i>	Rufous-capped Brushfinch	PR	2.96	3.55	3.50	9.00
<i>Pipilo maculatus</i>	Spotted Towhee	PR	15.38	18.93	20.50	38.25
<i>Aimophila rufescens</i>	Rusty Sparrow	PR	0.59	0.59	0.50	1.50
<i>Melospiza fusca</i>	Canyon Towhee	PR	15.38	33.73	20.50	44.75
<i>Oriturus superciliosus</i>	Striped Sparrow	PR	5.33	14.79	NR	NR

Family	Common name ^a	Seasonal status ^b	El Castillo (S ₁ Control site)		Mina Dos Estrellas (S ₂ Mining site)	
			FRE S ₁ ^c	ABU S ₁ ^d	FRE S ₂ ^c	ABU S ₂ ^d
Species						
<i>Spizella passerina</i>	Chipping Sparrow	PR	4.73	60.36	1.50	6.00
<i>Spizella atrogularis</i>	Black-chinned Sparrow	PR	1.18	2.96	NR	NR
<i>Melospiza melodia</i>	Song Sparrow	PR	1.18	1.78	2.50	5.25
<i>Junco phaeonotus</i>	Yellow-eyed Junco	PR	15.38	34.32	22.00	64.50
Icteridae						
<i>Sturnella magna</i>	Eastern Meadowlark	PR	0.59	0.59	NR	NR
<i>Icterus bullockii</i>	Bullock's Oriole	PR	2.96	4.14	1.50	3.75
<i>Icterus abeillei</i>	Black-backed Oriole	PR	NR	NR	3.00	9.75
<i>Icterus parisorum</i>	Scott's Oriole	PR	0.59	1.78	1.00	5.25
<i>Molothrus aeneus</i>	Bronzed Cowbird	PR	0.59	0.59	0.50	1.50
<i>Molothrus ater</i>	Brown-headed Cowbird	PR	0.59	2.37	0.50	0.75
Parulidae						
<i>Mniotilta varia</i>	Black-and-white Warbler	VI	1.78	1.78	1.00	1.50
<i>Oreothlypis superciliosa</i>	Crescent-chested Warbler	PR	21.30	32.54	13.00	23.25
<i>Oreothlypis celata</i>	Orange-crowned Warbler	VI	4.73	7.69	10.50	24.00
<i>Oreothlypis crissalis</i>	Colima Warbler	VI	NR	NR	1.00	1.50
<i>Oreothlypis ruficapilla</i>	Nashville Warbler	VI	0.59	0.59	0.50	0.75
<i>Geothlypis tolmiei</i>	MacGillivray's Warbler	VI	NR	NR	0.50	0.75
<i>Setophaga ruticilla</i>	American Redstart	TR	0.59	0.59	NR	NR
<i>Setophaga coronata</i>	Yellow-rumped Warbler	VI	17.16	56.21	35.50	168.00
<i>Setophaga graciae</i>	Grace's Warbler	PR	NR	NR	0.50	0.75
<i>Setophaga nigrescens</i>	Black-throated Gray Warbl.	VI	1.78	1.78	2.50	3.75
<i>Setophaga townsendi</i>	Townsend's Warbler	VI	14.20	33.73	15.50	49.50
<i>Setophaga occidentalis</i>	Hermit Warbler	VI	9.47	17.75	5.00	11.25
<i>Basileuterus rufifrons</i>	Rufous-capped Warbler	PR	2.37	2.96	4.50	9.50
<i>Basileuterus belli</i>	Golden-browed Warbler	PR	4.73	7.10	1.50	3.00
<i>Cardellina pusilla</i>	Wilson's Warbler	VI	5.92	5.92	7.50	12.00
<i>Cardellina rubrifrons</i>	Red-faced Warbler	VI	NR	NR	1.00	2.25
<i>Cardellina rubra</i>	Red Warbler	PR	2.37	3.55	2.50	5.25
<i>Myioborus pictus</i>	Painted Redstart	PR	22.49	26.04	12.50	20.25
<i>Myioborus miniatus</i>	Slate-throated Redstart	PR	2.37	3.55	1.00	1.50
Cardinalidae						
<i>Piranga flava</i>	Hepatic Tanager	PR	6.51	6.51	7.50	13.50
<i>Piranga ludoviciana</i>	Western Tanager	VI	2.96	2.96	1.00	1.50
<i>Piranga bidentata</i>	Flame-colored Tanager	PR	1.18	1.18	1.00	2.25
<i>Pheucticus melanocephalus</i>	Black-headed Grosbeak	PR	27.81	38.46	18.50	37.50
<i>Passerina caerulea</i>	Blue Grosbeak	PR	2.96	5.92	1.50	3.00
Thraupidae						
<i>Diglossa baritula</i>	Cinnamon-bellied flowerpiercer	PR	1.78	4.73	0.50	0.75

(a) Common name according to AOS (2017). ** Species under special protection (SEMARNAT 2010). (b) Seasonal status, PR: Permanent resident, VI: Winter visitant, TR: Transitory, INTRO: Introduced. (c) FRE = frequency (probability of presence in point counts); (d) ABU = relative abundance expressed in number of individuals in 100 point counts; (e) NR = Non recorded species.

Psaltiriparus minimus (Bushtit) and *Spinus psaltria* (Lesser Goldfinch) (Table 1). On the other hand, the species with the highest frequency of occurrence in S_1 were *H. leucotis*, *R. calendula*, *T. migratorius*, *P. cinereus* and *Myioborus pictus* (Painted Redstart); while in S_2 , the most frequent species were *H. leucotis*, *P. cinereus*, *S. coronata*, *R. calendula*, and *Myadestes occidentalis* (Brown-backed Solitaire) (Table 1).

The Mann-Whitney U test showed no significant differences in the average number of species and individuals per count between sites ($P > 0.1$). However, there were significant differences in the abundance of 18 species (Table 2). In reference to the similarity between sites, the Sorensen index revealed 85% qualitative similarity, while the Morisita-Horn index showed 93% quantitative similarity.

The Analysis of Similarity (ANOSIM) indicated a high level of correspondence between both communities ($R = 0.0445$, $P = 0.0001$). On the other hand, the SIMPER analysis suggested that the few extant differences between them are attributable to 18 species (Table 3), which add up to 62% of the differences between sites. The SIMPER test gives greater weight to abundance, such that species contributing to the differences between communities are those with the highest number of records. Overall the bird

communities at the study sites were very similar to one another (as it was also evident with ANOSIM), although some species had clear differences in their abundance in both sites (Table 2), such as *S. coronata*, *M. caerulescens*, *O. superciliosus*, *C. auratus*, and *T. mexicanus*.

DISCUSSION

Despite the fact that the OTMD has historically been very important for its economic prosperity, biological inventories in the area are virtually non-existent. This work provides the first bird species inventory for Mina Dos Estrellas and Tlacotepec, with 108 species (19.7% of those registered in the state of Michoacan) (Villaseñor-Gómez 2005), and 83% of the species recorded from Sierra Chincua at MBBR (SEMARNAT 2001), the nearest area with available ornithological information. According to the NOM-059 (SEMARNAT 2010), two species are under special protection: *Accipiter cooperi* (Cooper's Hawk) and *M. occidentalis*.

After 65 years of the cessation of extractive mining activities, bird communities at the OTMD have a high degree of similarity (85% qualitative and 93% quantitative), a pattern that coincides with the results

Table 2. Mean relative abundance of the species with significant differences in abundance between study sites in El Oro-Tlalpujahuá, Mining District, during 2014–2015.

Species	Individuals recorded	Feeding guild ^a	Mean Control Site, El Castillo S_1 (EE)	Mean Tilings site, Mina Dos Estrellas S_2 (EE)	P
<i>Setophaga coronata</i>	145	Omn	0.237 (0.044)	0 (0)	0.001**
<i>Myadestes occidentalis</i>	75	Fru	0.147 (0.032)	0.25 (0.034)	0.014*
<i>Sitta carolinensis</i>	69	Gra	0.266 (0.042)	0.120 (0.023)	0.008**
<i>Myioborus pictus</i>	68	Ins	0.248 (0.037)	0.130 (0.024)	0.010*
<i>Oreothlypis superciliosa</i>	67	Ins	0.230 (0.036)	0.140 (0.026)	0.045*
<i>Melanerpes formicivorus</i>	61	Omn	0.094 (0.022)	0.225 (0.035)	0.010*
<i>Thryomanes bewickii</i>	56	Ins	0.100 (0.023)	0.195 (0.03)	0.028*
<i>Catharus occidentalis</i>	40	Fru	0.065 (0.020)	0.145 (0.03)	0.043*
<i>Oreothlypis celata</i>	33	Ins	0.059 (0.021)	0.115 (0.024)	0.043*
<i>Melanotis caerulescens</i>	28	Ins/Fru	0.029 (0.013)	0.115 (0.023)	0.003**
<i>Troglodytes a. brunneicollis</i>	22	Ins	0.029 (0.013)	0.085 (0.020)	0.025*
<i>Cyanocitta stelleri</i>	16	Omn	0.076 (0.027)	0.015 (0.011)	0.015*
<i>Tyrannus vociferans</i>	15	Ins	0.065 (0.020)	0.020 (0.010)	0.049*
<i>Oriturus superciliosus</i>	12	Omn	0.071 (0.025)	0 (0)	0.001**
<i>Catharus aurantirostris</i>	10	Fru	0.005 (0.005)	0.045 (0.016)	0.035*
<i>Colaptes auratus</i>	10	Gra/Ins	0.053 (0.017)	0.005 (0.005)	0.005**
<i>Trogon mexicanus</i>	10	Ins/Fru	0.059 (0.024)	0 (0)	0.004**
<i>Icterus abeillei</i>	6	Ins	0 (0)	0.030 (0.012)	0.023*

(a) Fru: Frugivorous; Gra: Granivorous; Ins: Insectivorous; Omn: Omnivorous.

Non-parametric Mann-Whitney U tests: * $P < 0.5$ and > 0.1 , ** $P < 0.01$; SE = Standard error.

Table 3. Contribution of the bird species to the differences between the communities at the control site and a mining site at El Oro-Tlalpujahua Mining District, central Mexico.

Species	Contribution (%) to the difference	Cumulative percentage of the difference	Species abundance per count at the control site	Species abundance per count at the mining site
<i>Hylocharis leucotis</i>	6.79	6.79	0.75	0.811
<i>Setophaga coronata</i>	5.18	11.97	0.525	0.237
<i>Turdus migratorius</i>	5.16	17.12	0.405	0.438
<i>Ptiliogonys cinereus</i>	4.96	22.08	0.465	0.325
<i>Regulus calendula</i>	4.53	26.61	0.32	0.432
<i>Pheucticus melanocephalus</i>	3.50	30.11	0.21	0.325
<i>Haemorhous mexicanus</i>	3.18	33.29	0.22	0.237
<i>Junco phaeonotus</i>	3.12	36.41	0.23	0.195
<i>Melospiza fusca</i>	3.02	39.42	0.215	0.219
<i>Myadestes occidentalis</i>	2.83	42.26	0.25	0.148
<i>Spinus psaltria</i>	2.77	45.03	0.18	0.195
<i>Pipilo maculatus</i>	2.63	47.66	0.23	0.172
<i>Sitta carolinensis</i>	2.59	50.25	0.12	0.266
<i>Myioborus pictus</i>	2.50	52.75	0.13	0.249
<i>Oreothlypis superciliosa</i>	2.47	55.22	0.14	0.231
<i>Setophaga townsendi</i>	2.42	57.64	0.195	0.148
<i>Melanerpes formicivorus</i>	2.30	59.94	0.225	0.0947
<i>Peucedramus taeniatus</i>	2.22	62.16	0.13	0.195

of other studies. In southern Spain, at the Guadiamar corridor, a severely contaminated environment at the Aznalcollar mine, in restoration since 2000, Márquez-Ferrando (2008) found that the composition of bird communities exposed to mining waste remnants after eight years of abandonment was 80% similar to those at natural sites without exposure to mining wastes. Similarly, Osipov & Biserov (2017) studied the succession of bird communities in a Boreal Mountain-Valley landscape disturbed by gold mining in the Niman River (at the Bureya mountains, Russia); their findings indicate that sites with tailings 35–40 years after abandonment were similar in species composition to areas of valleys without disturbance, even though density of species was lower in the mining sites. On the other hand, abandoned tailing sites had a more complex successional vegetation and their communities of birds were more diverse and abundant, as were the mountain forest communities without disturbance. Nichols & Watkins (1984) and Armstrong & Nichols (2000) studied the avifaunal recolonization of rehabilitated bauxite mines in the Jarrah Forest of southwestern Australia. They compared bird communities in a forest where extraction started in 1963 in rehabilitated

Eucalyptus (*Eucalyptus marginata*) forest, and found that avian communities were very similar after a period of 24 and 30 years, and that the bird communities could reach up to 65% similarity within the first 4–5 years of abandonment, and 73.5% similarity after 16–17 years. According to this, similarity of communities increases with time in disturbed environments, where natural regeneration or restoration processes have taken place.

The area of OTMD has gone through a process of natural regeneration, in which those plant species most tolerant to disturbance, and/or those that were exploited to a lesser extent, reestablished the vegetation on the area, and its composition and structure support very similar bird communities. The reestablishment of forests with similar physiognomy in the study site may indicate the presence of suitable resources that maintain similar bird communities at both sites (McArthur & McArthur 1961). However, differences in the abundance of 18 species also suggests the existence of specific effects. They might be related to the sensitivity to pollutants, differences in the availability of specific resources (*e.g.*, food, breeding sites, feeding territories, perching structures), or other factors not taken into account (Loyn 1985, Gould & Mackey

2015). For example, differences found in *M. formicivorus* might reflect the presence of tall eucalyptus trees and snags at the tailings site (Mina Dos Estrellas), where most individuals were recorded. As suggested, food resources, perching structures, and breeding sites can be some of the primary limiting factors in the species distributions and preferences within a given habitat (Cody 1985, Hutto 1985, Jones 2001).

Studies on the effects of secondary succession in forests have shown that in general, early successional bird communities include more generalist granivorous, omnivorous and insectivorous species, considered as pioneer species indicative of disturbance (Rangel-Salazar *et al.* 2009, Becker *et al.* 2013). As succession progresses, structural diversity of vegetation increases and, depending on the community composition, specialized frugivorous, nectarivorous, and specialized insectivorous species (soil, bark, understory and foliage gleaning) colonize the habitat and increase in numbers (May 1982, Winkler 2005, Rangel-Salazar *et al.* 2009). Becker *et al.* (2013) found that bird communities in restored mining areas in southern Brazil had similar species richness between sites after 10–20 years of abandonment, although differences in the abundance of species according to feeding guild were evident: granivorous species decreased, whereas carnivorous, frugivorous, and nectarivorous increased (especially those forests dependent species); omnivorous species remained stable. Their findings suggest that effects could be reflected through changes in functional groups, or can be species specific. In the case of OTMD, some generalists, omnivorous and ground insectivorous species (*M. formicivorus*, *S. coronata*, *J. phaeonotus* and *O. celata*) were significantly more abundant in the tailings site, meanwhile at the control site more specialized species such as nectarivorous and bark insectivores prevailed (*H. leucotis*, *R. calendula*, *S. carolinensis*, *M. pictus* and *O. superciliosa*). Further study is needed to determine whether these differences are attributable to the existence of remnant mining effects after 65 years of abandonment.

Dendrochronological analysis of trees at MBBR suggested that individuals of Sacred Fir (*Abies religiosa*) are 106 years old, and those of Smooth-bark Mexican Pine (*Pinus pseudostrabus*) are 120 years old. Evidence indicates that the MBBR region has also been subjected to historical disturbance regimes caused by logging (Sáenz-Ceja 2015). The presence of old railway tracks in the core zone of MBBR at Sierra Chincua supports the idea of active logging in the past. Probably, regeneration processes took place almost at the same time, and, as such, the similarities in avian communities between MBBR and OTMD may reflect the effects of succession in a wider geographic area. We suggest that OTMD represents an important habitat for resident and migratory bird species in the surroundings of MBBR.

Information on remnant effects of abandoned mines is very scarce. It might prove useful to explore their effects on animal communities under scenarios of revegetation (natural succession) or restoration. Current information on mining impacts refers mostly to the response of biotic communities in active mining districts, where negative effects have been found on birds, rodents, and vegetation. In vertebrates, high concentrations of toxic elements are present in kidney and liver tissues, and they relate to their concentrations in the plants on which they feed (Espinosa-Reyes *et al.* 2014). Bioaccumulation of these elements is known to cause negative effects at the neurological (lethargy), physiological (chronic stress and changes in DNA structure), behavioral (decrease of appetite), and reproductive level (low production of eggs in birds) (Festa *et al.* 2003, Seewagen 2009, Chapa-Vargas *et al.* 2010), contributing to the decline of biodiversity at contaminated sites. The rivers of Santa Cruz, San Pedro and Colorado in Sonora, Mexico, which receive flows from copper mines, are very important sites for breeding and wintering birds, despite the negative impacts of their low water quality (Sprouse 2005, Villaseñor-Gómez 2006); they have not been studied in detail. Little is known on the effects of potentially toxic elements in tailing residual soils and their bioavailability. It would be necessary to study tailing chemistry, the exposure paths for those elements, and bio-magnification effects on functional groups or specific bird species that may be affected at the physiological level (Hudson & Bouwman 2008).

While the establishment of the DMOT historically generated a significant disturbance in the ecosystem, 65 years after the end of its activities current conditions seem favorable for the maintenance of avian communities as a major component of the regional biodiversity, since differences at the community level were not remarkable. Although it is not possible to assess the intensity of the environmental effects caused by mining at DMOT in the past, modification of the natural environment has left permanent traces, such as soil derived from tailings and the absence of some tree species (such as Sacred Fir, *A. religiosa*, present in neighboring forests) that were not able to cope with changes. The relative geochemical stability and the revegetation of tailings may indicate the existence of low intensity impacts at the present. Although there is no evidence at this time, the bioavailability of some potentially toxic elements could trigger processes of bio-magnification in some species, inducing negative health effects on bird individuals in the region. Therefore, it is important to continue working on this subject and to analyze some physiological indicators of performance (such as robustness, condition index, fat reserves, and the Heterophile/Lymphocyte Index) in local birds, in order to evaluate their health and fitness. We also suggest to gain further insights on the role of vegetation structure,

functional responses of communities (through feeding guilds), and the current anthropogenic impacts that may be influencing bird communities.

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