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ARTICLE

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-Rodriguez & 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 OTDM 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.

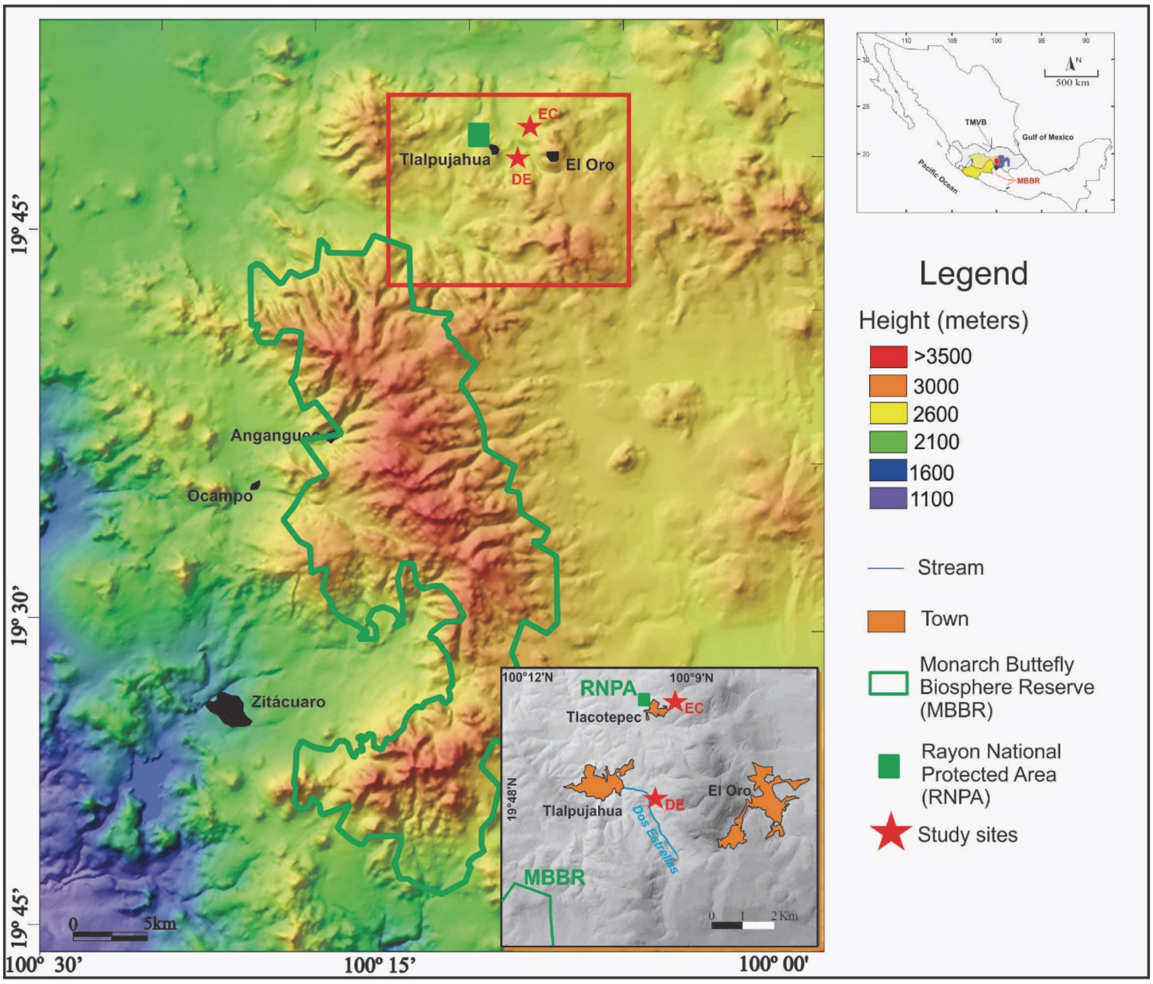

Figure 1. The Oro-Tlalpujahua Mining District study area in central Mexico (EC = El Castillo, S_1; DE = Mina Dos Estrellas, S_2).

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

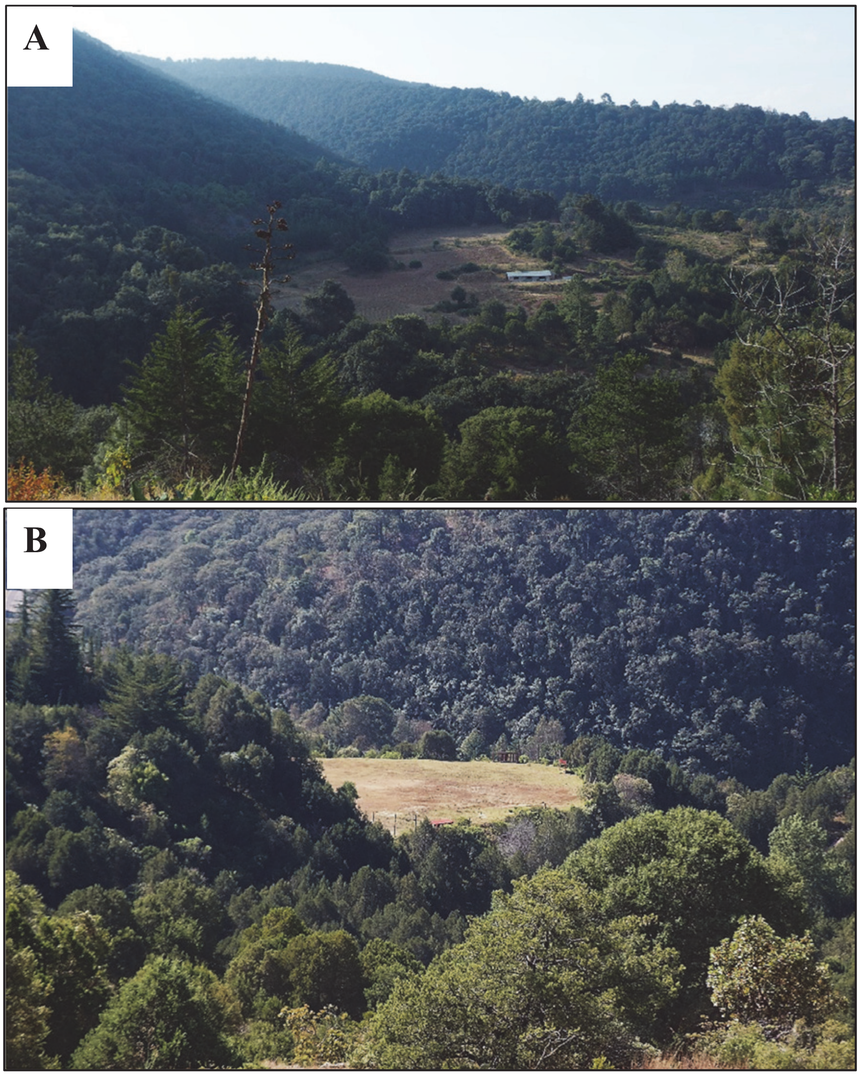

Figure 2. Control site, El Castillo, Tlacotepec, Michoacan (**A**); mining site, Mina Dos Estrellas (**B**), Photo authors: K.I. Lemus-Ramírez (**A**) and J.F. Villaseñor-Gómez (**B**).

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*,

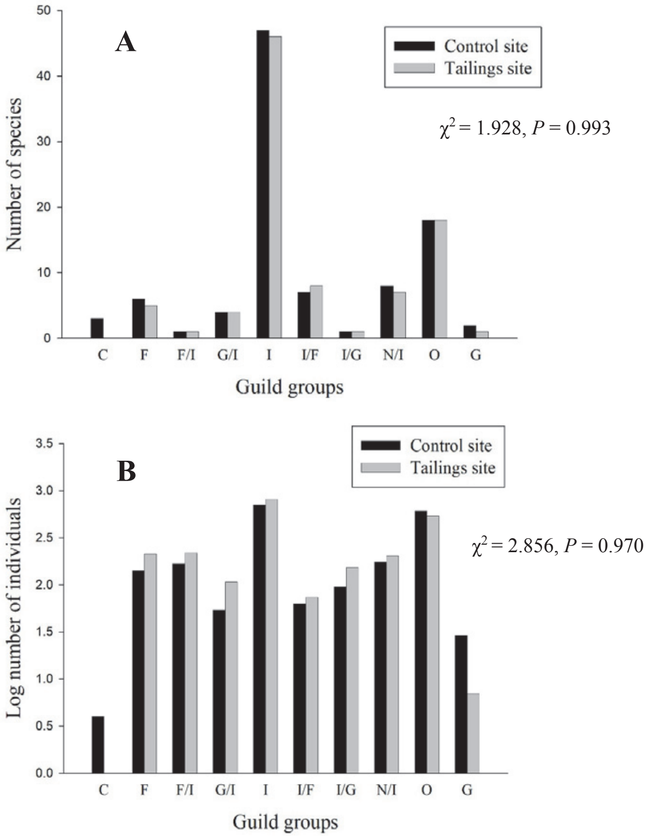

Figure 3. Bar chart of (**A**) number of species and (**B**) individuals belonging to different guilds at two sites within the El Oro-Tlalpujahua Mining District area. Legend: C: Carnivorous, F: Frugivorous, G: Granivorous, I: Insectivorous, N: Nectarivorous, O: Omnivorous.

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)**	
Species			**FRE S_1**[c]	**ABU S_1**[d]	**FRE S_2**[c]	**ABU S_2**[d]
Odontophoridae						
Colinus virginianus	Northern Bobwhite	PR	0.59	1.18	NR	NR
Columbidae						
Patagioenas fasciata	Band-tailed Pigeon	PR	0.59	0.59	NR	NR
Columbina inca	Inca Dove	PR	5.92	14.20	2.00	5.25
Cuculidae						
Geococcyx californianus	Greater Roadrunner	PR	0.59	0.59	NR	NR
Caprimulgidae						
Antrostomus arizonae	Mexican Whip-poor-will	PR	NR	NR	0.50	0.75
Trochilidae						
Colibri thalassinus	Mexican Violetear	PR	4.14	4.73	4.50	6.75
Eugenes fulgens	Rivoli's Hummingbird	PR	4.73	5.92	4.00	6.75
Lampornis clemenciae	Blue-throated Humming.	PR	1.78	2.96	2.50	3.75
Archilochus colubris	Ruby-throated Humming.	TR	1.18	1.18	NR	NR
Selasphorus platycercus	Broad-tailed Hummingbird	PR	1.78	1.78	0.50	0.75
Selasphorus rufus	Rufous Hummingbird	VI	0.59	0.59	0.50	0.75
Amazilia beryllina	Berylline Hummingbird	PR	0.59	1.18	3.00	6.00

Family	**Common name**[a]	**Seasonal status**[b]	**El Castillo (S_1 Control site)**		**Mina Dos Estrellas (S_2 Mining site)**	
Species			**FRE S_1**[c]	**ABU S_1**[d]	**FRE S_2**[c]	**ABU S_2**[d]
Hylocharis leucotis	White-eared Hummingbird	PR	63.31	85.21	59.50	128.25
Accipitridae						
*Accipiter cooperii***	Cooper's Hawk	VI	1.18	1.18	NR	NR
Buteo jamaicensis	Red-tailed Hawk	PR	0.59	0.59	NR	NR
Trogonidae						
Trogon mexicanus	Mountain Trogon	PR	4.14	5.92	NR	NR
Picidae						
Melanerpes formicivorus	Acorn Woodpecker	PR	9.47	15.98	18.50	64.50
Picoides scalaris	Ladder-backed Woodpeck.	PR	6.51	6.51	4.50	6.75
Picoides villosus	Hairy Woodpecker	PR	3.55	4.14	3.50	5.25
Colaptes auratus	Northern Flicker	PR	5.33	5.33	0.50	0.75
Tyrannidae						
Mitrephanes phaeocercus	Tufted Flycatcher	PR	8.28	8.88	5.50	10.50
Contopus pertinax	Greater Pewee	PR	14.79	15.98	12.00	18.00
Empidonax affinis	Pine Flycatcher	PR	0.59	0.59	NR	NR
Empidonax difficilis	Pacific-slope Flycatcher	VI	1.18	1.18	NR	NR
Empidonax occidentalis	Cordilleran Flycatcher	PR	12.43	13.02	10.00	17.25
Empidonax fulvifrons	Buff-breasted Flycatcher	PR	1.18	1.18	2.50	4.50
Sayornis nigricans	Black Phoebe	PR	NR	NR	0.50	1.50
Sayornis saya	Say's Phoebe	VI	0.59	1.18	NR	NR
Pyrocephalus rubinus	Vermilion Flycatcher	PR	2.96	5.33	0.50	0.75
Myiarchus tuberculifer	Dusky-capped Flycatcher	PR	1.78	2.37	1.50	3.00
Tyrannus vociferans	Cassin's Kingbird	PR	5.92	7.69	2.00	3.75
Tityridae						
Pachyramphus aglaiae	Rose-throated Becard	PR	0.59	0.59	0.50	1.50
Vireonidae						
Vireo huttoni	Hutton's Vireo	PR	5.92	7.10	5.50	9.00
Vireo cassinii	Cassin's Vireo	VI	4.73	5.92	2.50	4.50
Vireo plumbeus	Plumbeous Vireo	PR	0.59	0.59	0.50	0.75
Vireo gilvus	Warbling Vireo	PR	0.59	0.59	0.50	0.75
Corvidae						
Cyanocitta stelleri	Steller's Jay	PR	5.33	20.71	1.00	5.25
Corvus corax	Common Raven	PR	NR	NR	0.50	0.75
Hirundinidae						
Tachycineta thalassina	Violet-green Swallow	PR	0.59	0.59	1.50	2.75
Paridae						
Poecile sclateri	Mexican Chickadee	PR	3.55	8.28	1.00	4.50
Baeolophus wollweberi	Bridled Titmouse	PR	NR	NR	0.50	1.50
Aegithalidae						
Psaltriparus minimus	Bushtit	PR	8.88	56.21	9.00	116.25
Sittidae						
Sitta carolinensis	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						
Certhia americana	Brown Creeper	PR	0.59	0.59	NR	NR
Troglodytidae						
Catherpes mexicanus	Canyon Wren	PR	1.78	1.78	2.00	3.00
Troglodytes aedon parkmani	House Wren (in part)	VI	7.10	8.28	3.00	5.25
T. aedon brunneicollis	House Wren (in part)	PR	2.96	2.96	8.50	14.25
Thryomanes bewickii	Bewick's Wren	PR	10.06	11.83	18.00	34.50
Campylorhynchus gularis	Spotted Wren	PR	0.59	1.18	NR	NR
Regulidae						
Regulus satrapa	Golden-crowned Kinglet	VI	0.59	0.59	NR	NR
Regulus calendula	Ruby-crowned Kinglet	PR	35.50	57.99	29.50	69.00
Turdidae						
*Myadestes occidentalis***	Brown-backed Solitaire	PR	12.43	15.38	22.50	38.25
Catharus aurantiirostris	Orange-billed Nightingale-Thrush	PR	0.59	0.59	4.00	7.00
Catharus occidentalis	Russet Nightingale-Thrush	PR	5.92	6.51	12.00	23.25
Catharus guttatus	Hermit Thrush	VI	0.59	1.18	NR	NR
Turdus assimilis	White-throated Thrush	PR	0.59	0.59	3.00	4.75
Turdus migratorius	American Robin	PR	33.14	56.80	33.00	86.25
Mimidae						
Melanotis caerulescens	Blue Mockingbird	PR	2.96	2.96	11.00	17.75
Toxostoma curvirostre	Curve-billed Thrasher	PR	7.10	8.88	7.50	12.75
Mimus polyglottos	Northern Mockingbird	PR	NR	NR	0.50	0.75
Ptiliogonatidae						
Ptiliogonys cinereus	Gray Silky-flycatcher	PR	25.44	99.41	37.50	163.50
Peucedramidae						
Peucedramus taeniatus	Olive Warbler	PR	18.93	21.30	13.00	19.50
Passeridae						
Passer domesticus	House Sparrow	PR/ INTRO	1.18	4.73	0.50	1.50
Fringillidae						
Euphonia elegantissima	Elegant Euphonia	PR	NR	NR	0.50	1.50
Haemorhous mexicanus	House Finch	PR	16.57	52.07	19.50	78.75
Spinus pinus	Pine Siskin	PR	4.14	8.88	3.00	9.75
Spinus psaltria	Lesser Goldfinch	PR	15.98	52.07	15.50	90.25
Passerellidae						
Arremon virenticeps	Green-striped Brushfinch	PR	NR	NR	0.50	1.50
Atlapetes pileatus	Rufous-capped Brushfinch	PR	2.96	3.55	3.50	9.00
Pipilo maculatus	Spotted Towhee	PR	15.38	18.93	20.50	38.25
Aimophila rufescens	Rusty Sparrow	PR	0.59	0.59	0.50	1.50
Melozone fusca	Canyon Towhee	PR	15.38	33.73	20.50	44.75
Oriturus superciliosus	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)**	
Species			**FRE S_1**[c]	**ABU S_1**[d]	**FRE S_2**[c]	**ABU S_2**[d]
Spizella passerina	Chipping Sparrow	PR	4.73	60.36	1.50	6.00
Spizella atrogularis	Black-chinned Sparrow	PR	1.18	2.96	NR	NR
Melospiza melodia	Song Sparrow	PR	1.18	1.78	2.50	5.25
Junco phaeonotus	Yellow-eyed Junco	PR	15.38	34.32	22.00	64.50
Icteridae						
Sturnella magna	Eastern Meadowlark	PR	0.59	0.59	NR	NR
Icterus bullockii	Bullock's Oriole	PR	2.96	4.14	1.50	3.75
Icterus abeillei	Black-backed Oriole	PR	NR	NR	3.00	9.75
Icterus parisorum	Scott's Oriole	PR	0.59	1.78	1.00	5.25
Molothrus aeneus	Bronzed Cowbird	PR	0.59	0.59	0.50	1.50
Molothrus ater	Brown-headed Cowbird	PR	0.59	2.37	0.50	0.75
Parulidae						
Mniotilta varia	Black-and-white Warbler	VI	1.78	1.78	1.00	1.50
Oreothlypis superciliosa	Crescent-chested Warbler	PR	21.30	32.54	13.00	23.25
Oreothlypis celata	Orange-crowned Warbler	VI	4.73	7.69	10.50	24.00
Oreothlypis crissalis	Colima Warbler	VI	NR	NR	1.00	1.50
Oreothlypis ruficapilla	Nashville Warbler	VI	0.59	0.59	0.50	0.75
Geothlypis tolmiei	MacGillivray's Warbler	VI	NR	NR	0.50	0.75
Setophaga ruticilla	American Redstart	TR	0.59	0.59	NR	NR
Setophaga coronata	Yellow-rumped Warbler	VI	17.16	56.21	35.50	168.00
Setophaga graciae	Grace's Warbler	PR	NR	NR	0.50	0.75
Setophaga nigrescens	Black-throated Gray Warbl.	VI	1.78	1.78	2.50	3.75
Setophaga townsendi	Townsend's Warbler	VI	14.20	33.73	15.50	49.50
Setophaga occidentalis	Hermit Warbler	VI	9.47	17.75	5.00	11.25
Basileuterus rufifrons	Rufous-capped Warbler	PR	2.37	2.96	4.50	9.50
Basileuterus belli	Golden-browed Warbler	PR	4.73	7.10	1.50	3.00
Cardellina pusilla	Wilson's Warbler	VI	5.92	5.92	7.50	12.00
Cardellina rubrifrons	Red-faced Warbler	VI	NR	NR	1.00	2.25
Cardellina rubra	Red Warbler	PR	2.37	3.55	2.50	5.25
Myioborus pictus	Painted Redstart	PR	22.49	26.04	12.50	20.25
Myioborus miniatus	Slate-throated Redstart	PR	2.37	3.55	1.00	1.50
Cardinalidae						
Piranga flava	Hepatic Tanager	PR	6.51	6.51	7.50	13.50
Piranga ludoviciana	Western Tanager	VI	2.96	2.96	1.00	1.50
Piranga bidentata	Flame-colored Tanager	PR	1.18	1.18	1.00	2.25
Pheucticus melanocephalus	Black-headed Grosbeak	PR	27.81	38.46	18.50	37.50
Passerina caerulea	Blue Grosbeak	PR	2.96	5.92	1.50	3.00
Thraupidae						
Diglossa baritula	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.

Psaltriparus 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-Tlalpujahua, 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*
Setophaga coronata	145	Omn	**0.237 (0.044)**	0 (0)	0.001**
Myadestes occidentalis	75	Fru	0.147 (0.032)	**0.25 (0.034)**	0.014*
Sitta carolinensis	69	Gra	**0.266 (0.042)**	0.120 (0.023)	0.008**
Myioborus pictus	68	Ins	**0.248 (0.037)**	0.130 (0.024)	0.010*
Oreothlypis superciliosa	67	Ins	**0.230 (0.036)**	0.140 (0.026)	0.045*
Melanerpes formicivorus	61	Omn	0.094 (0.022)	**0.225 (0.035)**	0.010*
Thryomanes bewickii	56	Ins	0.100 (0.023)	**0.195 (0.03)**	0.028*
Catharus occidentalis	40	Fru	0.065 (0.020)	**0.145 (0.03)**	0.043*
Oreothlypis celata	33	Ins	0.059 (0.021)	**0.115 (0.024)**	0.043*
Melanotis caerulescens	28	Ins/Fru	0.029 (0.013)	**0.115 (0.023)**	0.003**
Troglodytes a. brunneicollis.	22	Ins	0.029 (0.013)	**0.085 (0.020)**	0.025*
Cyanocitta stelleri	16	Omn	**0.076 (0.027)**	0.015 (0.011)	0.015*
Tyrannus vociferans	15	Ins	**0.065 (0.020)**	0.020 (0.010)	0.049*
Oriturus superciliosus	12	Omn	**0.071 (0.025)**	0 (0)	0.001**
Catharus aurantiirostris	10	Fru	0.005 (0.005)	**0.045 (0.016)**	0.035*
Colaptes auratus	10	Gra/Ins	**0.053 (0.017)**	0.005 (0.005)	0.005**
Trogon mexicanus	10	Ins/Fru	**0.059 (0.024)**	0 (0)	0.004**
Icterus abeillei	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**
Hylocharis leucotis	6.79	6.79	0.75	0.811
Setophaga coronata	5.18	11.97	**0.525**	**0.237**
Turdus migratorius	5.16	17.12	0.405	0.438
Ptiliogonys cinereus	4.96	22.08	0.465	0.325
Regulus calendula	4.53	26.61	0.32	0.432
Pheucticus melanocephalus	3.50	30.11	0.21	0.325
Haemorhous mexicanus	3.18	33.29	0.22	0.237
Junco phaeonotus	3.12	36.41	0.23	0.195
Melozone fusca	3.02	39.42	0.215	0.219
Myadestes occidentalis	2.83	42.26	0.25	0.148
Spinus psaltria	2.77	45.03	0.18	0.195
Pipilo maculatus	2.63	47.66	0.23	0.172
Sitta carolinensis	2.59	50.25	0.12	0.266
Myioborus pictus	2.50	52.75	0.13	0.249
Oreothlypis superciliosa	2.47	55.22	0.14	0.231
Setophaga townsendi	2.42	57.64	0.195	0.148
Melanerpes formicivorus	2.30	59.94	**0.225**	**0.0947**
Peucedramus taeniatus	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 south-western 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 pseudostrobus*) 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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