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Effects of proximity to active oil platforms and gas flares on the diversity of insectivorous birds and their primary food sources

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RESUMEN

La extracción petrolera en la Amazonía Occidental amenaza una de las más diversas comunidades de fauna en el mundo. El uso de mecheros por parte de las empresas petroleras tiene un gran potencial de afectar la diversidad en vastos territorios, a través de la producción de ruido, calor, luz y emisiones gaseosas. Por ejemplo, la contaminación lumínica, anualmente, mata millones de aves migratorias e insectos voladores que son atraídos a la fuente de luz y mueren incinerados o por colisiones. En el presente estudio describimos el impacto de la presencia de plataformas petroleras con mecheros activos en las comunidades de aves insectívoras y macroinvertebrados en ecosistemas de la Amazonia norte del Ecuador y sus bosques adyacentes, comparándolas con bosques distantes. Además, medimos propiedades físico químicas del suelo y el agua en las áreas de estudio en búsqueda de potenciales correlaciones entre contaminación y biodiversidad. Nuestros resultados indican que las plataformas petroleras con mecheros reducen la diversidad e incidencia de aves insectívoras y sus fuentes de alimento en las proximidades, sin mostrar asociación con incrementos en contaminación en agua o suelo. Con este estudio se demuestra preliminarmente que los mecheros estarían reduciendo la presencia de aves insectívoras y macroinvertebrados en los alrededores de plataformas petroleras. Sin embargo, se necesitan investigaciones posteriores que busquen detectar las causas potenciales y los mecanismos que explican la perdida de diversidad reportada cerca de los sitios con actividad petrolera.

Palabras clave: Petróleo, contaminación, Amazonía, macroinvertebrados, ornitología, Yasuní

ABSTRACT

Oil extraction in the Western Amazon threatens the greatest diversity of fauna in the world. The use of gas flares by oil companies has the potential to affect vast areas due to noise, heat, light, and emissions that heavily affect populations of migratory birds and macroinvertebrates worldwide via light pollution that attracts and kills millions of organisms yearly. We studied the impact of gas flaring and oil platform presence in the insectivorous bird and macroinvertebrate community of adjacent forests and compared it with forests distant from oil and gas operations to detect differences in community composition. We also measured soil and water physical-chemical properties to detect the correlation between pollution and biodiversity. Our results showed that gas flares and oil platforms reduced the diversity and incidence of insectivorous birds and their food sources in the surroundings but are not associated with an increase in water or soil pollution. These data warrant concerns that gas flares are depleting insectivorous birds and macroinvertebrates in their proximity, and future research is essential to detect potential causes of this diversity loss.

Key words: Petroleum, pollution, Amazon, macroinvertebrates, ornithology, Yasuní

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Effects of proximity to active oil platforms and gas flares on the diversity of insectivorous birds and their primary food sources

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1. PROJECT DESCRIPTION

The western Amazon arguably bears the greatest diversity of birds and other taxa in the world, making it an important hotspot for biodiversity (Nores, 2000) In addition, this region is home to diverse Indigenous peoples and local communities, including some of the last people in voluntary isolation in the world (Wasserstrom & Bustamante, 2015). Despite its biological and cultural diversity, oil extraction activities have steadily encroached on this region for decades. With the oil boom in the 1970's, the diverse Napo River watershed encompassing Orellana, Napo and Sucumbios provinces has been under oil extraction pressures, driving the development of large cities and road systems that lead to extensive habitat loss in that region (Sabin, 1998). At the moment, ~688,000 km^2 of the western Amazon is concessioned for oil or gas exploitation in 180 blocks delineated for exploitation by different companies, with 85 oil blocks in the Ecuadorian Amazon (Fig.1; Finer et al., 2008; Ministerio de Energía y Recursos Naturales, 2024). These extractive activities impact ancestral territories, national parks and natural reserves, fueling ecological and social problems (Facchinelli et al., 2022).

Since 1940, Ecuador has drilled more than 5000 oil wells with 447 gas flares, leading to a total production of ~173 million oil barrels by 2023 (Ministerio de Energía y Recursos Naturales, 2024; UDAPT, 2025). This production is coupled with emissions of 1.2 million m^3 of gas flared yearly. The gas released to the atmosphere has energetic potential and its non-use creates economic losses of 142 million USD yearly in Ecuador (Orozco, 2022).

Within this rich landscape where oil extraction is a significant threat, two important protected areas have been established in the region, Cuyabeno Wildlife Reserve and Yasuní National Park, the latter forming the core area of the Yasuní Biosphere Reserve (Ministerio de Ambiente, Agua y Transición Ecológica del Ecuador, n.d.; Ministerio de Ambiente del Ecuador, 2015; Ministerio de Ambiente, Agua y Transición Ecológica del Ecuador, 2024; UNESCO, 1989). These reserves have partially stopped some human impacts and allowed large forest fragments to persist (Ministerio de Ambiente, Agua y Transición Ecológica del Ecuador, n.d.). However, the extractive frontier persistently encroaches the boundaries of the protected forest and degrades the habitat in these protected lands (Fig. 1).

Due to their scale, terrestrial oil platforms produce significant air, water and soil pollution (Chang et al., 2014; Ismail & Umukoro, 2012). Also, these activities indirectly lead to forest fragmentation by creating roads that increase human presence, hunting frequency and quantity, and expansion of the agricultural frontier (Curran et al., 1999; Peters, 2001). Of all the oil-related activities, gas flares (that burn natural gas from oil wells) have the greatest potential to affect vast territories, including zones far from the sites they are located due to noise, heat, light, and toxic emissions (Finer et al., 2008; Ronconi et al., 2015).

Gas flares may emit gases nonstop for decades, causing severe air pollution by releasing ~120 known toxins into the atmosphere, including release of known carcinogens (e.g., benzopyrene, carbon disulphide, toluene and mercury; Anejionu et al., 2015; Huang and Fu, 2016; Ismail & Umukoro, 2012). These pollutants create acid rain, change soil chemistry, reduce biodiversity, and disrupt overall ecosystem functioning (Chang et al., 2014; Waldner et al., 2001; Jaja & Ogbalu, 2018; Finer et al., 2008; Boxall et al., 2005; Dung et al., 2008). Despite these numerous risks, oil extraction is expanding worldwide, including in the northwestern Ecuadorian Amazon (Bozigar et al., 2016; Boxall et al., 2005; Sawyer, 2004).

Previous studies in northern temperate ecosystems have found that migratory birds deviate from their natural flight paths towards gas flares from oil platforms where they are either incinerated or collide with the platforms, killing approximately six million birds per year in the North Sea alone (CBC, 2013; Hüppop et al., 2006; Russell, 2005; Sage, 1979). The light of gas flares may create local overabundance of avian food sources (e.g., fish, zooplankton and insects), which in turn increases local abundance and rates of mortality in birds, affecting zones up to 20 radial km from the light source (Burke et al., 2005; Montevecchi, 2006; Ronconi et al., 2015; Russell, 2005).

Even when in other regions of the world the impacts of gas flares are well-documented, the direct and indirect impacts of oil operations, including the presence of gas flares, on bird mortality in tropical forest ecosystems remain unclear and represent an important knowledge gap (Burke et al., 2005; Russell, 2005). Also, the effects of gas flares and oil extraction on the surrounding macroinvertebrates community are poorly known globally (Jaja & Ogbalu, 2018). Some studies found that butterflies and insect pollinators are affected by flaring through CO_2 emission and temperature increase in the surroundings of the oil platform, which affect plant food sources and reduce insect performance (Jaja & Ogbalu, 2018; Sarma et al., 2018).

Additionally, several studies assert that insects are attracted to gas flares, yet none have directly focused on this phenomenon. Anecdotal observations at gas flare sites suggest severe insect mortality due to incineration, with researchers witnessing the death of millions of insects daily (Vargas, Rivadeneyra pers. com.). However, in the absence of targeted research and quantitative assessments of population- or community-level impacts, the potentially severe consequences of oil extraction on macroinvertebrates communities and the trophic levels that depend on macroinvertebrates, such as insectivorous birds, remain largely unaddressed (Thomas, 2015).

Since 2001, bird populations have been annually monitored at Tiputini Biodiversity Station, (hereafter, TBS) located within Yasuní Biosphere Reserve in Orellana Province, Ecuador (Blake & Loiselle, 2015). Their long-term monitoring has focused on the bird community within two 100-hectare plots (Harpía Plot and Puma Plot) situated in non-inundated Amazonian Forest. Data collection has involved both direct observations and bird banding (Blake & Loiselle, 2024). In 2009, a sharp and largely unexplained downward trajectory in bird numbers was observed in most birds with an average 40-50% decline by 2015, most pronounced among insectivorous species. Blake and Loiselle suggest these declines may be linked to effects of climate change, particularly increased annual rainfall associated with recurring La Niña events (2015). Recent analysis revealed that the downward trend has continued, now affecting ~90% of the bird species recorded by observations or captures in the study plots at TBS (Blake & Loiselle, 2024). This critical decline in bird communities that has occurred at TBS has also been noted simultaneously by local guides and visiting birdwatchers over the same period at several ecotourism lodges, privates reserves and community forests in the Napo River Basin (Fig. 1; Rivadeneyra pers. com.).

The reported bird decline occurred in a remote and primary forest. Nonetheless, road openings, oil platforms and one gas flare occur in El Edén community land within a 10 km radius of the study site. These disturbances started in the indigenous territory in the year 2000, by the Ecuadorian state oil company -Petroamazonas-, that established the EPF oil platform (Papa pers. com.). EPF oil platform has a gas flare ~15 m tall and a cylinder of ~40 cm that has been combusting ~500 000 cubic feet of natural gas per day since 2005, enough natural gas released in one day to illuminate 172 houses in USA for a month (González, 2021; Papa pers. com.). The presence of the oil platform and gas flare could have played a key role in the documented avian population decline. Indeed, the EPF oil platform is noticeably audible from the station (Fig. 1). However, no previous research has tested the impacts of oil platforms and gas flares on the diversity in the region.

The objectives of this study were to determine how proximity to active oil platforms and gas flares influences: **(i)** insectivorous bird diversity, (**ii)** their macroinvertebrates diet sources, and (**iii)** changes in physical-chemical water and soil properties across primary and fragmented forests. More broadly, this research aims to explore whether the presence of oil infrastructure and gas flaring may partially account for the observed declines in bird numbers at TBS.

2. METHODS

2.1. Study Site

The study was conducted in the Northern Ecuadorian Amazon, at the Napo River Basin, Orellana Province, within the lowland non-inundated (*terra firme*) rainforest ecosystem (Duivenvoorden et al., 2001). We worked in two study areas with different habitat type, in which we identified the variation of the ornithological and entomological communities near and far from the oil platforms with gas flares (Fig. 1).

2.1.1. Primary Forest Area

The first study area defined here as "Primary Forest Area" is composed of two sites, EPF and TBS. EPF has three transects near the Amazonian Kichwa community of El Edén and the EPF oil platform with a gas flare (0°31'47.06"S, 76° 7'34.58"W, 196 meters above sea level; Fig. 1). Additionally, the Primary Forest Area includes three transects at TBS, ten kilometers away from the oil platform, located in Orellana, Ecuador (0°37'43.57"S, 76° 8'24.61"W, 220 meters above sea level; Fig. 1). TBS is considered the far site from the gas flare of EPF. Both EPF and TBS sites are connected by continuous primary *terra firme* forest, with a forest edge located in EPF oil platform periphery. The Primary Forest Area is characterized by a canopy height of 15-40 meters and some large emergent trees (>40m) with high plant diversity and a largely open and untangled understory (Kraft et al.,2008).

2.1.2. Forest Patches Area

The second study area defined here as “Forest Patches Area” is composed of two sites Loma del Tigre and San Jacinto (Fig. 1). Loma del Tigre site (hereafter, LOMA; 0°21'1.72"S, 76°50'4.82"W, 310 meters above sea level; Fig. 1) is composed of three active oil platforms with gas flares, and is located near the city of Joya de los Sachas, which has several oil platforms and gas flares. Also, San Jacinto site (hereafter, SJAC; 0°21'51.40"S, 76°43'39.71"W, 290 meters above sea level; Fig. 1) is located ten kilometers from the oil platforms in LOMA. Both sites of the Forest Patches Area consist of degraded forest patches on a matrix of farmland, roads and villages. The forest patches have a canopy height of 15 meters, with tangled understory and a reduced plant diversity (Alvarez-Montalván et al., 2021). Forest patches sampled in the Forest Patches Area were of similar characteristics. We chose forest patches with sizes around twelve hectares. Also, LOMA and SJAC sites had big sized forest patches (~1000 Ha) within 500 meters (Fig. 1).

2.2. Sampling Effort

We conducted sampling in two study areas: Primary Forest Area and Forest Patches Area (Fig. 1a, b). In each area, we established six linear transects, each 800 meters long. Three transects were placed near active gas flares (between 100 and 900 meters from the source), and three were placed far from gas flares (more than 10 kilometers away). Each transect included three sampling points, located at 0, 400, and 800 meters along the transect line. To avoid overlap, transects were spaced at least 500 meters apart and positioned perpendicular to the oil platforms studied (Fig. 2a, b). In total, we set up twelve transects and eighteen sampling points: six transects (nine sampling points) in Primary Forest Area and six transects (nine sampling points) in Forest Patches Area. For both study areas, three transects (with nine sampling points) were located near oil platforms (EPF and LOMA), and the remaining three (with nine sampling points) were located far from them (TBS and SJAC; Fig.

2a, b). Each sampling point included one acoustic recording unit, one flying insect trap, and three subsamples of leaf-litter for collecting macroinvertebrates (Fig. 2c). All these sampling efforts are defined below.

2.2.1 Insectivorous Birds

To measure diversity of insectivorous birds, we set an acoustic remote unit (hereafter, ARU; LABMaker-AudioMoth v1.2.0; 48 kHz, 32 bits) on each sampling point to record audio for two consecutive mornings without rain (Fig. 2c). We followed the Blake protocol (2021) for this method. Each morning, the ARU recorded 10 audio sessions of 10 minutes each with five-minute breaks between each session, starting at 05:45 am and ending at 08:10 am. At the end of the two mornings, each remote acoustic monitor recorded 200 minutes of audio. Consequently, 600 minutes of audio were recorded per transect, a total of 1800 minutes per study site (EPF, LOMA, TBS and SCJ), and 3600 per study area (Primary Forest vs Forest Patches). In total, we recorded a total of 7200 minutes of passive audio (39.49 GB).

The resulting recordings were archived as soundscapes in the Macaulay Library at the Cornell Lab of Ornithology and were analyzed using the Merlin Sound ID machine learning (February, 2025). We obtained a total of species identified in the recordings, and the number of detections per species. Each detection was associated with a confidence score of the certainty of identification by percent (Joachin Godinez, 2024).

To choose the threshold of confidence score to work with the species identified, we ran a histogram of frequencies of the confidence scores higher than 50% and found that most of the detections occurred above 95% and below that value detections drop down precipitously (Supplementary Fig. 1). Therefore, we selected audio recordings in which insectivorous bird species were identified with at least 95% confidence score. Species richness was assessed by counting the number of distinct species detected at sampling point in the sites near and far from the oil platforms. We estimated bird incidence frequency, calculated by counting the number of sampling points where each species was detected with ≥95% confidence. Since each site contained nine sampling points, the maximum possible incidence for any given species was nine.

2.2.2 Macroinvertebrates

2.2.2.1 Pan Traps

At each sampling point, we set up three colors of plastic pan traps (blue, yellow and white, 11.2 cm diameter) for two consecutive days to catch macroinvertebrates attracted to the different colorations (Leong & Thorp, 2019, Fig. 2). Pan traps consist of a shallow colored plate filled partially with soapy water that attracts macroinvertebrates. Three traps were set up at 11:00 am in each sampling point. We used three drops of commercially available dish detergent and approximately 200 mL of water per pan. At 11:00 am on the second day after the pan traps were set, we removed the trap, strained the insects and fluid through a fine cloth, and stored the macroinvertebrates from the three different pan trap colors captured in one jar with 90% ethanol. Via manual counting and separation, we quantified the richness and abundance of macroinvertebrates captured in the traps. Due to the high number of specimens per pan trap, we identified macroinvertebrates at the order level, except for the families Formicidae, Curculionidae and Staphylinidae. We sorted insects with the aid of a dissecting microscope (Nikon SMZ645 C-PSC) and used taxonomic keys for identification when necessary (MacGavin-George, 2005; Vargas, et al., 2014). Voucher specimens were stored in the entomological collection at Museum of Zoology of USFQ, Quito, Ecuador.

2.2.2.2 Leaf-litter Macroinvertebrates

For each sampling point we obtained three replicate samples of leaf-litter macroinvertebrates using leaf-litter extraction and mini-Winkler funnels (Fig. 2). We sampled between 8:00 am– 01:00 pm in fair weather. Each quadrat (1 m^2) was marked by a sampling frame, then all materials and debris within the quadrat were collected down to mineral soil. We separated fine from coarse materials using a 1 cm mesh litter sifter and shaking the contents to disperse for 1 min. Fine sifted material was stored in linen bags for < 4 h, then placed in passive mini-Winkler bags, with Whirlpak™ bags with 90% ethanol at the bottom, for 48 h. At the end of the sampling time, samples and ethanol were collected from the Whirlpak™ bag. Macroinvertebrates were preserved in 90% ethanol for transport to the laboratory where they were identified with the aid of a dissecting microscope (Nikon SMZ645 C-PSC) and sorted using established taxonomic keys (MacGavin-George, 2005; Vargas, et al., 2014). Samples were stored in plastic vials for long-term preservation. The macroinvertebrates were identified to the order level, with exception of the Formicidae, Curculionidae and Staphylinidae families. Voucher specimens were deposited in the entomological collection at Museum of Zoology of USFQ, Quito, Ecuador.

2.2.3 Physical-chemical Water and Soil Samples

Physical-chemical analysis of water and soil samples were conducted to evaluate the abiotic properties of the sites studied. In Primary Forest Area, near the oil platform of EPF, we collected three samples of soil and one water sample (Fig. 2). The same protocol was applied far from the oil platform in TBS. In the Forest Patches Area, we took three samples of soil and one water sample near and far from the LOMA oil platforms, following the standard protocol of American Public Health Association, American Water Works Association & Water Environment Federation (2017). We obtained concentration and quality analyses in the samples of water and soil by applying different methodologies. In the water samples we measured physical-chemical parameters following the standard protocols of

American Public Health Association, American Water Works Association & Water Environment Federation (2017). Electric conductivity (SM 2510 B), pH (SM 4500 H), temperature (SM 4500 H), total dissolved solids (SM 2510 A), were analyzed in-situ using a YSI Professional Plus hand multi-parameter according to the manufacturer's instructions (Ohio, United States). Alkalinity (SM 2320 B), ammonium (Salicilate Method HACH 8155), nitrite (HACH 8507), nitrate (HACH 8507), phosphate (SM 4500-P-E), chloride (HACH 8113), fluoride (USEPA 10225), sulfate (USEPA 375.4; SM4500-SO42-E), chemical oxygen demand (SM 5220 D), hardness (HACH 8030), total solids (SM 2540 B), and turbidity (ISO 7027) were analyzed in the AQUA-BIO Laboratory at Universidad San Francisco de Quito (Supplementary Table 3).

Additionally, the presence of major elements (high quantities) and minor elements (small quantities) in the soil and water samples obtained, including heavy metals, was analyzed at Universidad de las Américas (UDLA-Ecuador) using a ThermoScientific iCAP 7400 ICP-OES Duo spectrophotometer in filtered and acidified water samples and digested soil samples digested with nitric and hydrochloric acid trace metal grade, following the standard protocol of Thermo Fisher Scientific. (2018). Standard solutions were prepared in dilute nitric acid from commercial standards (ICP multi-element standard solution IV 23 elements diluted in nitric acid LOT: HC31118355). The detection and quantification limits were calculated by analyzing blank samples with at least eight replicates, adding the average of the blank values with 3 and 10-fold the standard deviation to obtain the limit of detection (LOD) and the limit of quantification (LOQ), respectively, following the standard protocol of International Conference on Harmonisation (2005). Quality control in metallic analysis was conducted using National Institute of Standards and Technology, Gaithersburg, USA NIST CRM 1646a–Estuarine Sediment, which was measured every ten samples. The recovery percentages of the 33 metallic elements analyzed varied from 75-105%.

2.3. **Data Analysis**

2.3.1. **Insectivorous Birds**

We counted the incidence of insectivorous bird species by presence per sampling point. The maximum possible incidence for any species was nine, corresponding to the total number of sampling points per distance category (near or far from the oil platform). To assess how study area identity (Primary Forest vs. Forest Patches) influenced species incidence and overall diversity, we performed a Non-Metric Multidimensional Scaling (NMDS) analysis. The NMDS allowed us to visualize patterns of community composition, using metaMDS from vegan R package (Oksanen et al., 2020). To test the statistical significance of these patterns, we conducted a PERMANOVA, evaluating whether differences in species composition were driven by habitat type rather than proximity to oil platforms (Supplementary Fig. 2a).

We test the significance of our insectivorous bird incidence with a Poisson model, with logarithmic link, using the glmmTMB R package (Brooks et al., 2017). We used insectivorous bird incidence as response variable and site as explanatory variable with no random effect. Finally, we used DHARMa R package to evaluate residuals normal distribution (Hartig, 2023). We found no violations of model assumptions. Later, we built violin-bar plots to understand bird incidence response to gas flares using ggplot2 R package (Wickham, 2016).

Additionally, to compare how insectivorous bird communities change in proximity to gas flares, we calculated *Alpha* and *Beta* diversity metrics from frequency incidence values. For this, the iNEXT R package was employed to calculate effective diversity indices (Hill numbers) and sample coverage estimation with extrapolation and interpolation (Chao & Hsieh, 2016). Also, we used SpadeR package to estimate *Beta* diversity by applying Sorensen, Horn and Morisita indexes (Lilleskov, et al. 2004). By applying these different effective diversity metrics, we interpreted the rough richness (q = 0), richness and incidence (q = 1), and dominance (q = 2; Chao & Jost, 2012).

To measure how noise of oil extraction activities arising from the oil platforms changes detectability of birds by the ARUs (Quinn, et al., 2023), we used Ocenaudio (2025) program for Windows to analyze the frequencies at FFT (Fast Fourier Transform) graph (settings: triangular window, 8129 bins, linear scale). We reviewed frequency variation in the background noise. We detected the frequencies of constant noises originating in the oil platform and discussed their potential to interfere with bird detectability.

2.3.2. **Macroinvertebrates**

We measured incidence frequency by presence per sampling point for macroinvertebrate orders, apart from three families (Formicidae, Curculionidae and Staphylinidae). In this case, the highest value was nine sampling points for pan traps, but 27 for leaf-litter macroinvertebrates due to the three replicas taken per sampling point.

We used NMDS to detect variation resulting from habitat type (Primary Forest vs. Forest Patches) and by trapping method (pan traps vs. Winkler traps). Later, we detected spatial partitioning in NMDS graph and ran a PERMANOVA test to determine significance of the variation produced by these confounding factors, using metaMDS from vegan R package (Supplementary Fig. 2b, c; Oksanen et al., 2020).

We tested significance of our macroinvertebrates diversity incidence results with a negative binomial model, with logarithmic link, using the glmmTMB R package (Brooks, et al., 2017). We used macroinvertebrates incidence as response variable, and site as explanatory variable, with no random effect. Also, we used DHARMa R package to evaluate residuals normal distribution, with no violations of model assumptions (Hartig, 2023). Finally, we build up jitter plots to interpret macroinvertebrates response, in which we subclassified by trapping method (pan trap vs. Winkler trap), using ggplot2 R package (Wickham, 2016).

Additionally, to detect changes in macroinvertebrates numbers driven by gas flares proximity, we considered the total amount of specimens collected per trap, ignoring their taxa. We treated the two traps (pan trap vs. Winkler trap) together and independently. We ran three statistical analyses using glmmTMB R package and found that the best fit model for the data was a negative binomial for pan traps, Winkler traps and rough abundance in general (Brooks, et al., 2017). We used macroinvertebrates rough abundance as the response variable, and site as explanatory variable, with no random effect. Finally, we constructed a bar plot with the arithmetic mean and standard error of the macroinvertebrates number by study area, distance and trapping method to visualize comparisons.

As part of macroinvertebrates abundance response to gas flares, we analyzed how macroinvertebrates body size affects their response. With a commercial ruler, we visually classified macroinvertebrates between two size categories (<5 mm and >5 mm) and ran two statistical analyses for the two size categories using glmmTMB R package. In this case, we used a negative binomial model for both sizes (Brooks, et al., 2017). We used macroinvertebrates rough abundance as response variable, and site as explanatory variable, with trapping method as random effect. We constructed a bar plot with the arithmetic mean and standard error of the macroinvertebrates number by size and distance to the oil platform to visualize comparisons.

2.3.3. Physical-chemical Water and Soil Samples

Our methodology to detect potential pollution in the study areas was comparing element concentrations in the different distances to the oil platform with the referential normative of MAATE (2015) and TULSMA (2009). We performed a data analysis to identify any irregular values that exceeded the maximum permissible limits established by the referenced regulatory standards. Using these standards and supporting literature, we reviewed the potential causes for any detected irregularities. In cases where applicable, we discussed the possibility of anthropogenic pollution as a contributing factor (Supplementary Tables 2, 4)

3. RESULTS

3.1. Insectivorous Birds

We detected a total of 362 bird species, with at least 10% in their confidence score using Merlin Sound ID (221 insectivorous bird species). This group of birds make 804444 identified sounds over 7200 minutes of passive audio recording. From the total, 95 bird species had ≥95% of confidence, with 440 events of incidence, of which 65 were insectivorous bird species, with 331 events of incidence. All analysis was performed on this subset of insectivorous birds with ≥95% of confidence in their identification.

Habitat type produces significant spatial partitioning of the incidence of insectivorous birds under NMDS (PERMANOVA test; df = 1, R^2 = 0.27, F = 13.09, p = 0.001; Supplementary Fig. 2), independently from the proximity to the oil platform. Therefore, all analysis to understand oil platform impacts were performed independently for Primary Forest and Forest Patches Areas.

3.1.1. Primary Forest Area (TBS – EPF)

Proximity to EPF oil platform significantly reduced the incidence frequency for the 42 insectivorous bird species detected in this study area (Poisson; Est. = 1.44, S.E. = 0.26, z = 5.49, p = 0.00000004). The incidence was higher in TBS for 83% of the species (Fig. 3). Moreover, diversity analysis by incidence frequency follows the same sharp reduction. Whereas, EPF has an insectivorous bird richness of 17 species and 42 detection events, TBS recorded 38 species with 92 detection events. Consequently, effective diversity numbers when rarefied are approximately half of the diversity near the oil platform, even when incidence and dominance are considered (q=1 and q=2, Table 1).

High *Beta* diversity for insectivorous birds was found between the two distances (EPF vs. TBS, 10 km apart) to the oil platform with 46% of shared species. When considering species incidence (q=1) and dominance (q=2) the *Beta* diversity was 58% and 52% of shared species (Table 1).

3.1.2. Forest Patches Area (LOMA – SJAC)

Proximity to the three oil platforms of LOMA produced no significant increase in the frequency of the 35 insectivorous bird species detected in the area (Poisson; Est. = -0.20, S.E. = 0.25, z = -0.82, p = 0.409). In total, SJAC site, far from the oil platforms, has an insectivorous bird richness of 30 species and 92 detection events, while LOMA recorded 28 species with 105 detection events (Table 1). Insectivorous bird incidence was higher in LOMA for 45% of the species, in contrast to 37% species with a higher incidence in SJAC (with no oil flares; Fig. 3). In contrast, diversity analysis by incidence shows that SJAC has higher diversity values. The richness (q=0) is 50% greater far from the gas flare, while richness and incidence (q=1) are 25% higher and dominance (q=2) was 11% higher.

Beta diversity of insectivorous birds between sites in the Forest Patches Area (LOMA vs SJAC sites) was only high by Sorensen dissimilarity index, with half of the species shared between the two sites. Species incidence (q=1) has 88% of species shared and for the dominant species (q=2) 100% of the species were shared.

3.2. Macroinvertebrates

We collected a total of 19811 macroinvertebrates from 26 orders and three families (Formicidae, Curculionidae and Staphylinidae) within the orders Hymenoptera and

Coleoptera. The broad community of macroinvertebrates at the order level did not show any significant pattern in response to oil platform proximity (near site vs. far site). On the NMDS analysis we detected spatial partitioning of the macroinvertebrate community driven by habitat type (PERMANOVA test; df = 1, R^2 = 0.08, F = 13.67, p = 0.001; Supplementary Fig. 2), and by trapping method (pan traps vs. Winkler traps) (PERMANOVA test; df = 1, R^2 = 0.19, F = 35.18, p = 0.001; Supplementary Fig. 2c). To avoid the interference of these confounding factors we ran the analysis independently for each area (Primary Forest and Forest Patches) and trapping method (pan and Winkler traps).

3.2.1. Primary Forest Area (EPF-TBS)

The 25 orders and three families of macroinvertebrates collected in the Primary Forest Area showed a negligible increase of incidence near the oil platform (EPF; Negative Binomial; Est. = 0.01, S.E. = 0.27, z = 0.05, p = 0.95). Similarly, the 19 orders and three families captured in pan traps showed a non-significant increase near the oil platform (Negative Binomial; Est. = -0.10, S.E. = 0.39, z = -0.27, p = 0.78; Fig. 4a). Macroinvertebrates captured with pan traps were 43% more frequent at the EPF area, while 24% were more frequent at TBS. In contrast, Winkler traps captured 25 orders and three families. In this case, 25% were recorded more in the oil platform proximities and 46% were more frequent in the far TBS site (Negative Binomial; Est. = -0.05, S.E. = 0.33, z = 0.17, p = 0.86; Fig. 4b). However, the changes in frequency are negligible (e.g., Diplopoda abundance: EPF = 13; TBS = 15) in most cases.

3.2.1.1. **Rough Abundance**

When the trapping method is not considered, we detected an increase in abundance for macroinvertebrates near the oil platform (Negative Binomial; Est. = 0.30, S.E. = 0.15, z = -1.89, p = 0.058; Fig. 5). In EPF site we captured 4337 individuals and 3210 at TBS using both trapping methods. By pan trapping we collected a total of 3163 macroinvertebrates (EPF = 1792 vs. TBS = 1371). We detected a non-significant increase in abundance near the gas flare (Negative Binomial; Est. = -0.26, S.E. = 0.26, z = -0.99, p = 0.32; Fig. 5). Additionally, the leaf-litter macroinvertebrate abundance was significantly higher near the oil platform of EPF (EPF = 2545 vs. TBS = 1839; Negative Binomial; Est. = -0.32, S.E. = 0.16, z = -2.02, p = 0.043; Fig. 5). The rough abundance of macroinvertebrates clearly increases near the EPF oil platform, which is significant for the leaf-litter community.

3.2.1.2. **Body Size**

The two classifications (<5 mm vs. >5 mm) of body size showed opposite and both significant responses to the EPF oil platform. On one hand, small insects (<5 mm) were significantly more abundant near the oil platform (Negative Binomial; Est. = -0.45, S.E. = 0.15, z = -3.01, p = 0.002; Fig. 6), while, large sized insects (>5 mm) were significantly more abundant 10 kilometers from the oil platform at TBS (Negative Binomial; Est. = 0.62, S.E. = 0.22, z = 2.81, p = 0.004; Fig. 6).

3.2.2. Forest Patches Area (LOMA – SJAC)

In the Forest Patches Area near the oil platforms and gas flares at LOMA we collected a total of 23 macroinvertebrates orders and three families. On the other hand, 10 kilometers apart from oil operations at SJAC site, we collected 24 orders and the three families. In total, we obtained specimens from 25 orders and the three families. In the LOMA-SJAC sites the incidence of macroinvertebrates showed no significant reduction to the oil platforms (Negative Binomial; Est. = -0.01, S.E. = 0.27, z = 0.05, p = 0.95). However, the community captured with pan traps presented higher incidence in SJAC (Negative Binomial; Est. = 0.08, S.E. = 0.35, z = 0.22, p = 0.82; Fig. 4c). In opposition, the leaf-litter community of macroinvertebrate taxa is negligible attracted to the oil platform (Negative Binomial; Est. = -0.04, S.E. = 0.30, z = -0.14, p = 0.88; Fig. 4d).

3.2.2.1. **Rough Abundance**

A total number of 12264 macroinvertebrates were captured in Forest Patches Area revealing a reduction in proximity to the oil platforms of LOMA (Negative Binomial; Est. = 0.22, S.E. = 0.12, z = 1.88, p = 0.059; Fig. 5). This is associated with the change of abundance from 7366 individuals ten kilometers apart the oil platforms, with 4898 near the oil platforms - a 33% decrease. Pan trap samples showed an even more pronounced pattern, with a highly significant increase in macroinvertebrates abundance at distant sites (LOMA = 581 vs. SJAC = 1772) (Negative Binomial; Est. = -0.70, S.E. = 0.17, z = 3.94, p = 0.00008; Fig. 5). Similarly, leaf-litter macroinvertebrate abundance was higher far from the oil platform, but in this case non-significant (LOMA = 4317 vs. SJAC = 4821) (Negative Binomial; Est. = 0.14, S.E. = 0.12, z = 1.18, p = 0.24; Fig. 5). In the leaf-litter macroinvertebrates negative binomial test, we excluded one upper outlier from SJAC to ensure proper model fit. In general, the abundance of macroinvertebrates is sharply reduced near the oil platforms of LOMA in the Forest Patches Area.

3.2.2.2. **Body Size**

The body size of macroinvertebrates showed the same response to the rough abundance, but with non-significant effects. Small insects (<5 mm) were reduced near the gas flare (Negative Binomial; Est. = 0.20, S.E. = 0.11, z = 1.78, p = 0.074; Fig. 6). Similarly, large sized insects (>5 mm) were more abundant in SJAC, far from the oil platform (Negative Binomial; Est. = 0.22, S.E. = 0.15, z = 1.42, p = 0.153; Fig. 6). The size did not play an important role in the Forest Patches Area. In this case, macroinvertebrates were reduced near the oil platform, independently of size.

3.3. Physical-chemical Water and Soil Properties

The soil and water physical-chemical analysis did not have any clear pattern in proximity to the oil platform. Near the gas flares, we detected a total of eight parameters above referential values for both areas. In contrast, far from the gas flare both sites counted 14 parameters above reference. We found no clear signs of pollution near the oil platform in soil and water in comparison to the referential normative used.

3.3.1. Soil Matrix

For the 30 chemical elements studied, we counted 14 potential environmental pollutants. In the two areas, Primary Forest and Forest Patches, we detected a total of 12 minor elements above referential values. The site with most signs of anthropogenic pollution was SJAC, in which five minor elements were above referential values (Ag: >100, Ba: 275.53, Cu 35.55, Ni: 23.65, Zn: 60.49; mg/kg). On the other hand, TBS showed only in one sampling point irregular values for three minor elements (Ba: 250.75, Ni: 31.71, Zn: 67.18; mg/kg).

3.3.2. Water Matrix

In the case of chemical elements pollution, we detected no irregularities in the water analyzed, but a high value of manganese in Tiputini River at TBS site (Mn: 259 mg/kg). On the other hand, physical-chemical properties of the water were not changed by oil platform proximity. One irregular value was the acidic water of the Tiputini River (pH= 6) and the high concentration of solids (130 mg/L) and high electric conductivity (115.35 uS/cm) in the water of SJAC sample.

4. DISCUSSION

Habitat type and oil platform presence drives important changes in faunal diversity relative to the presence of oil platforms with gas flares. In the Primary Forest Area, the proximity to an oil platform with gas flare is associated with reductions of the diversity and incidence of insectivorous birds. The same pattern occurs with large-sized macroinvertebrates. In contrast, the rough abundance of macroinvertebrates increases near the oil platform in the Primary Forest Area. In the case of Forest Patches Area, oil platform proximity is associated with a reduction insectivorous bird diversity and a non-signifcantly increase of incidence, while macroinvertebrates were more numerous far from the three oil platform sampled.

4.1. Primary Forest Area (EPF – TBS)

4.1.1. Insectivorous Birds

Although, gas flares are expected to attract birds due to light pollution and the congregation of insects (Russell, 2005; Hüppop et al., 2006), our findings show a substantial reduction in the insectivorous bird community in Primary Forest Area near the forest edge created by oil infrastructure. This original assemblage was largely replaced by a different bird community, as indicated by high *Beta* diversity. A similar pattern was observed by Canaday (1996) in the Ecuadorian Amazon, where insectivorous bird populations declined near agricultural forest edges. This decline particularly affected the infraorder Furnariides, which includes several neotropical bird families such as Furnariidae (ovenbirds, woodcreepers), Thamnophilidae (antbirds), and Rhinocryptidae (tapaculos) (Moyle et al., 2009). In our study, the results from audio analyses, allowed to observe such patterns, with most members of these families absent from EPF—except for the Sooty Antbird (*Hafferia fortis*), a specialized ant follower that appeared resilient to the proximity of the oil platform (Martínez et al., 2021).

Other anthropogenic disturbances in tropical forests, such as agriculture and logging, have also been shown to reduce insectivorous bird diversity (Barbaro et al., 2012; Moradi et al., 2009). Therefore, to better understand the unique influence of oil infrastructure, the effects of oil platform and gas flare forest edges should be compared to other types of anthropogenic edges. Nonetheless, our results proved that the EPF oil platform represents a significant threat to insectivorous bird communities, leading to notable declines in their incidence and diversity.

4.1.2. Macroinvertebrates

Order level analysis are important and can disentangle ecological process, but are incomplete and sometimes insufficient to interpret results properly (Novotny, & Miller, 2014; Pos, et al.,2014; Timms, et al., 2013). In our case, we detected no clear pattern in the order incidence frequency analyses performed here. Then, we can conclude that order level was not enough to detect significant patterns in response to oil platforms. We got a better understanding of the oil platform impacts by the rough abundance of macroinvertebrates. This attribute was higher near the EPF oil platform as expected (Jokimäki, et al., 1998; De Smedt, et al., 2019).

Macroinvertebrates body size showed a clear response to oil platform proximity. Individuals larger than 5 mm were significantly less abundant near the EPF oil platform, while smaller macroinvertebrates (<5 mm) were more abundant. This size-based shift indicates a negative impact on larger macroinvertebrates, contrasting with patterns observed at other forest edges where larger individuals are typically not excluded (Fowler et al., 1993; Ferguson, 2000). Although we cannot define causality of this pattern, we cannot underestimate the potential impact on large-size macroinvertebrates of gas flares, which are known to attract and kill flying insects daily by incineration and disorientation (Jaja &

Ogbalu, 2018; Thomas, 2015; Vargas, Rivadeneyra pers. com). Flying insect mortality by gas flares could be responsible for depleting vast forest areas of large-sized flying insects. This potential impact possibly affects other trophic levels, like insectivorous birds that depend on large-sized macroinvertebrates. This study was not able to perform a correlational analysis to test this last assertion, and future investigations should perform such comparisons in order to explore what are the mechanisms explaining bird populations declines in the region.

4.1.3. Physical-chemical Water and Soil Properties

We detected no important soil and water pollution caused by oil platform proximity in our analysis. In the sampling points there were no important signs of anthropogenic pollution caused by the oil platform. We suggest this pattern was detected due to sampling collection in non-disturbed locations near the oil platform. In our protocol we did not choose water drains from the oil platform, old oil spills or other potentially more polluted sites (Truskewycz, et al., 2019; Carls, et al., 1995). Hence, in the forest floor and adjacent natural water sources we did not detect pollution using our methodologies. However, the Primary Forest Area (EPF and TBS) showed a high concentration of thallium, which can be a property of the soil for that location. Additionally, one sampling point of soil from TBS has high values of minor elements that can be associated with oil pollution (Ba, Co and Ni; Essoka, et al., 2006; Amaral-Sobrinho, et al., 2020). However, it is highly unlikely that this pristine forest has been exposed to greater levels of soil pollution than the surroundings of EPF. This suggests that the detected pollution may originate from natural sources or from another unidentified anthropogenic activity.

4.1.4. Noise Confounding Factor

We detected a constant low-frequency noise in ARUs (65 – 95 Hz) caused by oil platform engines and power sources. Most of the birds vocalize between 1 – 5 kHz, with some

Columbiformes and other birds singing down to 250 Hz (All About Birds, 2022; Holzman, 2024). The noise produced by the oil platform does not interfere directly with any bird vocalization, and it is not likely masking bird sound detections.

4.1.5. Oil Platform Impacts

In the Primary Forest Area, the insectivorous birds were sharply reduced by the oil platform presence, this is associated with a reduction of large-sized macroinvertebrates. Contrary to expectations, the presence of the oil platform was associated with a reduction in large macroinvertebrates. This is particularly important because insectivorous birds are known to rely heavily on large macroinvertebrates as a food source (Mansor et al., 2018; Manhães, Dias, & Lima, 2015). Therefore, it is possible that gas flaring near the EPF oil platform is reducing the availability of large macroinvertebrates, which in turn may be contributing to the observed decline in insectivorous bird detections in the same site.

4.2. Forest Patches Area (LOMA – SJAC)

4.2.1. Insectivorous Birds

At LOMA oil platforms, we observed a non-significant increase in the incidence of insectivorous birds near the gas flare, while a noticeable reduction in species diversity was detected in the same site. Both LOMA and SJAC sites are located within a degraded farmland matrix characterized by small forest patches. Although the slight increase in bird incidence near the gas flare is a weak pattern, it may be linked to light pollution from gas flaring, which is known to attract birds in other ecosystems (Russell, 2005; Burke et al., 2005).

Despite this, we found a clearer and more consistent pattern of reduced diversity near the oil platforms. Similar to observations in Primary Forest Area (EPF and TBS sites), insectivorous birds appear to be reduced near oil infrastructure. This suggests that the presence of oil platforms introduces an additional negative impact on bird communities, beyond general forest degradation. Notably, many of the bird species detected in these Forest Patches Area are known to tolerate or even prefer anthropogenic landscapes such as agricultural or livestock-modified environments (Rutt et al., 2019).

In conclusion, even insectivorous bird species that are typically resilient to habitat degradation are negatively affected by the presence of oil platforms, indicating that the impact is driven more by oil industrial activity than by other anthropogenic disturbances alone.

4.2.2. Macroinvertebrates

The abundance of macroinvertebrates was significantly lower near the oil platforms of LOMA, when compared to SJAC. In the Forest Patches Area, we observed a response from the macroinvertebrate community that contrasted with what we found in the Primary Forest Area. Interestingly, this response mirrored the pattern seen in insectivorous birds: both groups showed reduced presence near the oil platforms of LOMA. This finding is unexpected, as studies in other ecosystems have shown that flying insects are often attracted to gas flares (Jaja & Ogbalu, 2018; Thomas, 2015; Vargas & Rivadeneyra, pers. comm.). Additionally, macroinvertebrate body size did not vary in response to proximity to oil platforms, indicating that size was not a factor in their response to oil platforms. Overall, our results suggest that the macroinvertebrate community in Forest Patches Area is reduced near oil platforms and gas flares.

4.2.3. Physical-chemical Water and Soil Properties

At both distances of the Forest Patches Area (LOMA vs. SJAC sites), we detected a high concentration of silver, as well in EPF oil platform surroundings in the Primary Forest Area. It is not expected to detect silver associated with oil extraction, but these high values of silver can be an indicator of anthropogenic activities in the locality (Padhye, et al., 2023). The use of silver by industry, mining and domestic uses can be a source of silver pollution (Purcell & Peters, 1998). However, the high values of silver can be from a natural source (Zhang et al. 2023).

The most polluted site was SJAC with signs of anthropogenic pollution in soil and water samples. As we mentioned before, the degraded landscape in the Northern Ecuadorian Amazon is interspersed with oil extraction activities including pipelines, oil drills, gas flares, etc. (Ministerio de Energía y Recursos Naturales, 2024; UDAPT, 2025). We chose the site SJAC by the absence of gas flares, but oil production is active in the surroundings. Although it is not possible to exclude agricultural activities as a potential source of pollution, we suspect that oil extraction activities brought soil pollutants by previous activities, as the high concentration of nickel, copper and barium are associated with oil extraction activities.

4.2.4. Oil Platform Impacts

In the western Amazon rainforest, the typically resilient insectivorous bird community found in Forest Patches Area does not appear to tolerate the presence of oil platforms with active gas flares. These platforms not only negatively affect bird populations but also reduce the availability of their primary food sources. Our results show a significant decline in macroinvertebrate abundance near oil platforms, suggesting a potential food shortage that may contribute to reduce the diversity of insectivorous birds. Interestingly, this pattern cannot be explained by soil or water pollution, as the distant control site—far from oil infrastructure—showed higher levels of contamination. Although we cannot establish a direct causal relationship, we hypothesize that light pollution from gas flaring may be a key factor driving the decline in bird diversity near oil platforms.

5. CONCLUSION

Oil platforms with active gas flares have a measurable negative impact on insectivorous bird diversity and the availability of their macroinvertebrate prey in the Western Amazon. In primary forests, these platforms function similarly to other types of forest edges, where insectivorous bird diversity tends to decline. However, they also exhibit the unique effect of reducing the abundance of large-sized macroinvertebrates, which are essential food sources for many bird species.

In Forest Patches Area, which is already subject to anthropogenic pressures such as agriculture and livestock, the presence of oil infrastructure further exacerbates biodiversity loss. Our findings show that oil platforms and gas flares reduce both insectivorous bird and macroinvertebrate diversity more significantly than agricultural activities alone, suggesting an added layer of ecological disruption.

While we observed clear patterns of decline, the underlying drivers of biodiversity loss associated with oil platform activities remain unclear. Neither soil nor water pollution alone explain the observed trends, and although light pollution from gas flares is a plausible factor, causality has not been established. Therefore, future research should focus on identifying the specific mechanisms—such as light pollution, noise, chemical exposure, or habitat fragmentation—that contribute to these ecological changes.

In addition, understanding how oil platforms affect bird demography, behavior, and bioaccumulation of contaminants will be crucial for developing more effective conservation and mitigation strategies. As oil extraction continues to expand in sensitive regions like the Amazon, it is imperative to evaluate its full ecological footprint and implement policies that safeguard biodiversity beyond the obvious impacts of habitat degradation.

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8. TABLES

Table 1. Summary of observations, sample completeness and estimated *Alpha* and *Beta* diversity metrics for insectivorous birds.

	EPF	TBS	LOMA	SJAC
No. detection events	42	92	105	92
No. species	17	38	28	30
Hill Numbers				
q0	22.54	43.07	26.68	40.36
q1	15.64	33.37	20.87	25.89
q2	11.26	25.79	17.46	19.40
Similarity Indexes				
q0 - Beta Sørensen	46.64%		56.85%	
q1 – Horn	57.69%		88.80%	
q2 – Morisita-Horn	52.08%		100%	
Completeness	91.26%		91.17%	

9. FIGURES

Figure 1. Referential map of study broad region, highlighting landmarks, distances and study areas (Forest Patches Area and Primary Forest Area). On each area oil platforms with gas flares and transect locations are referenced **a.** Forest Patches Area: LOMA – SJAC sites **b.** Primary Forest Area: EPF – TBS sites.

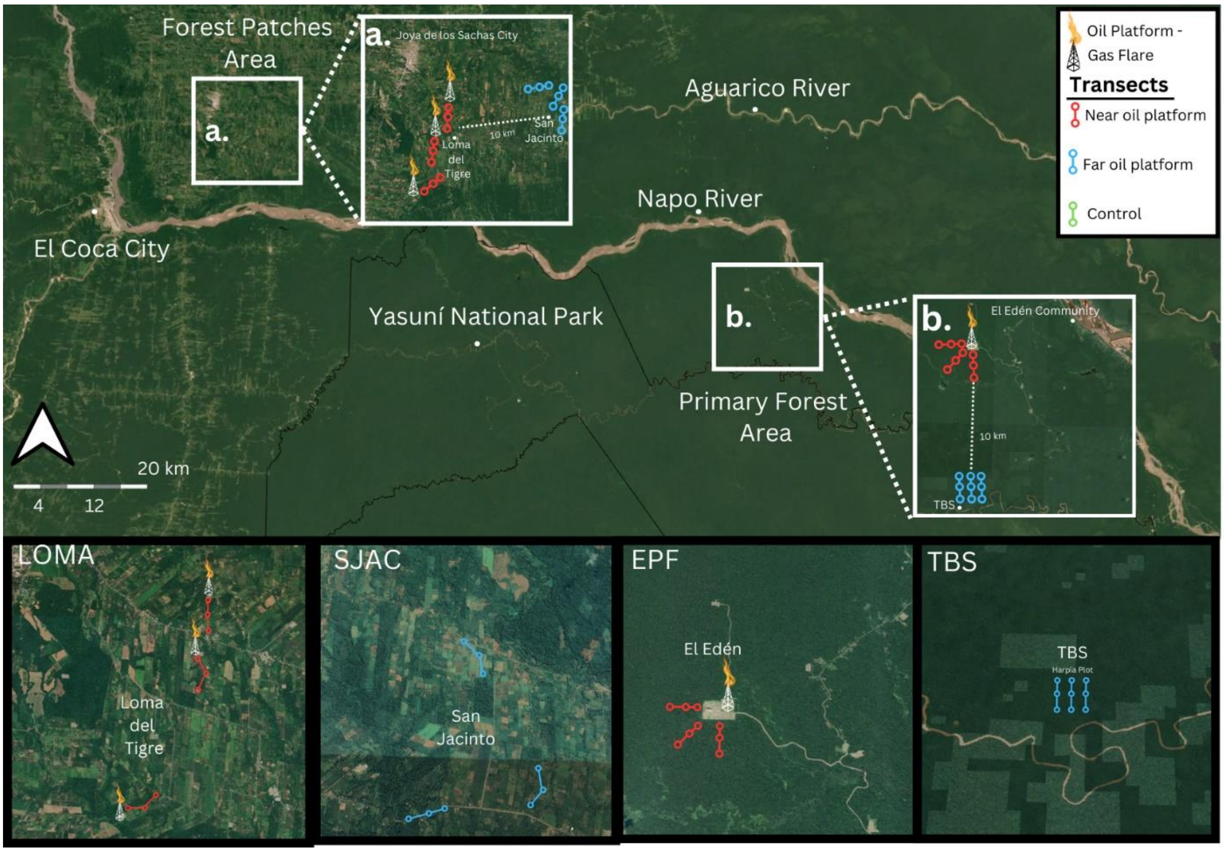


Figure 2. Methodology diagram showing locations of the transects, distances between locations and protocols followed **a.** LOMA – SJAC sites diagram **b.** EPF – TBS sites diagram **c.** Diagram of sampling protocol description for the three biological groups studied and abiotic metrics per sampling point.

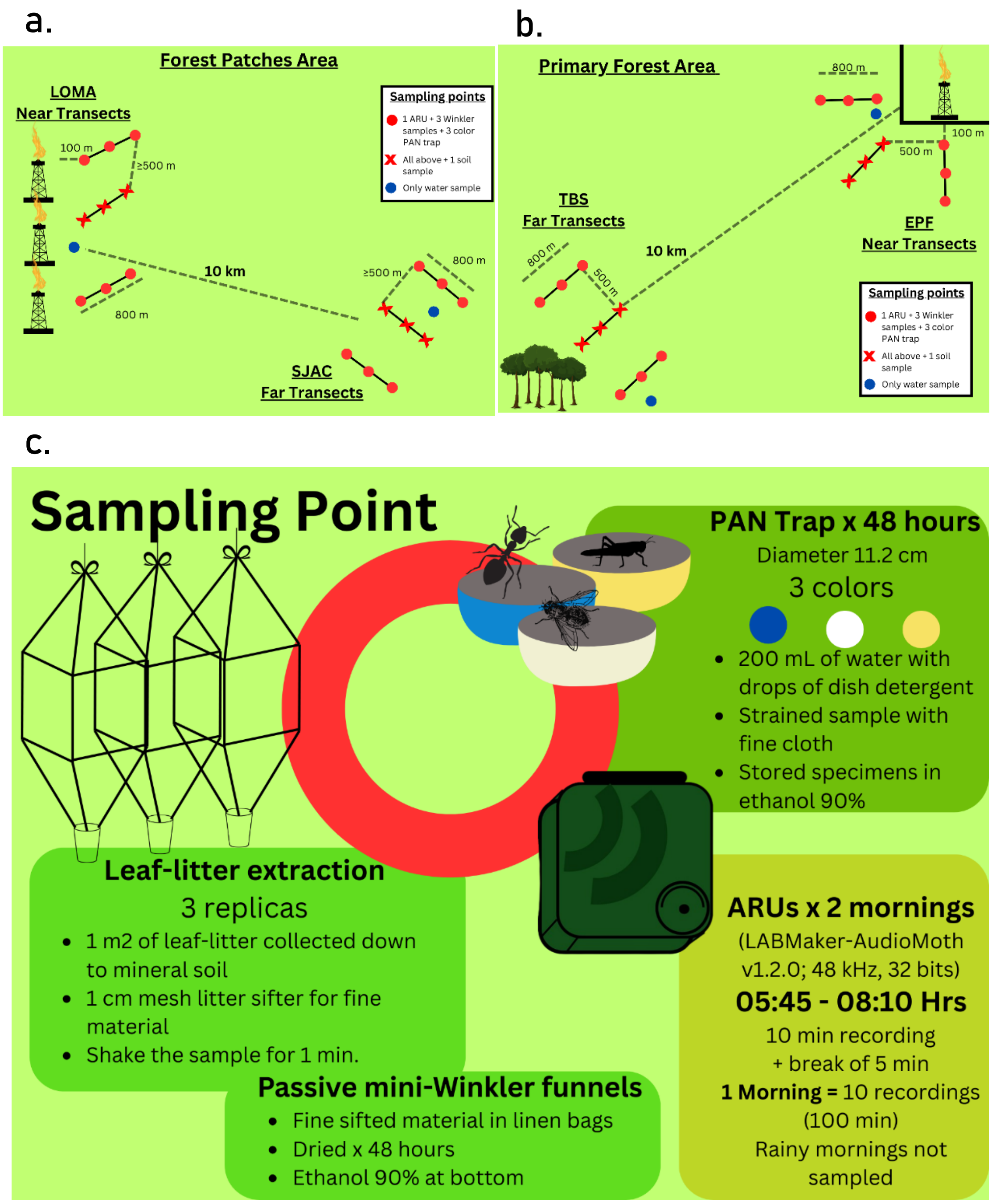
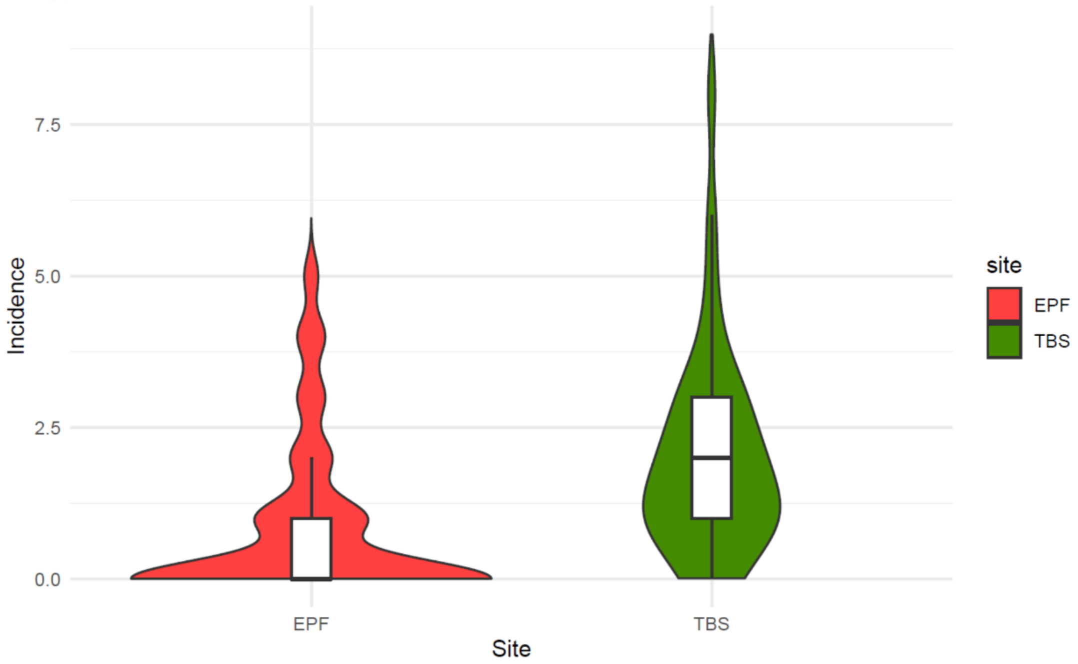
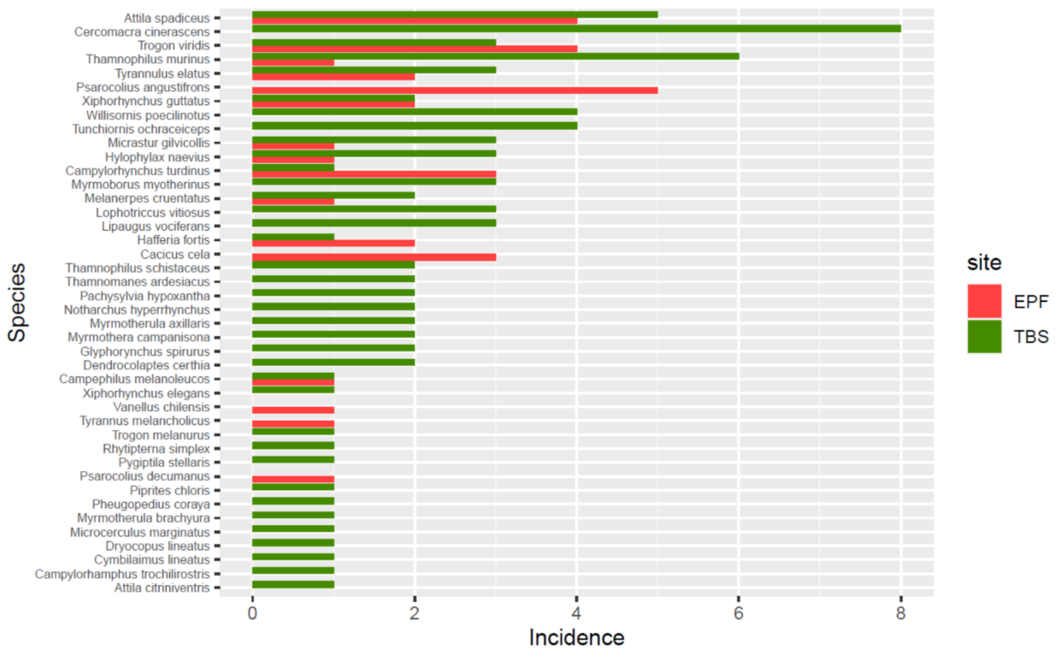


Figure 3. Incidence frequency of insectivorous birds on nine sampling points per distance to an oil platform. Violin graph with box plots of insectivorous bird incidence in **a.** Primary Forest Area (EPF – TBS sites), and **c.** Forest Patches Area (LOMA – SJAC sites). Insectivorous bird species incidence in **b.** Primary Forest Area, and **d.** Forest Patches Area.

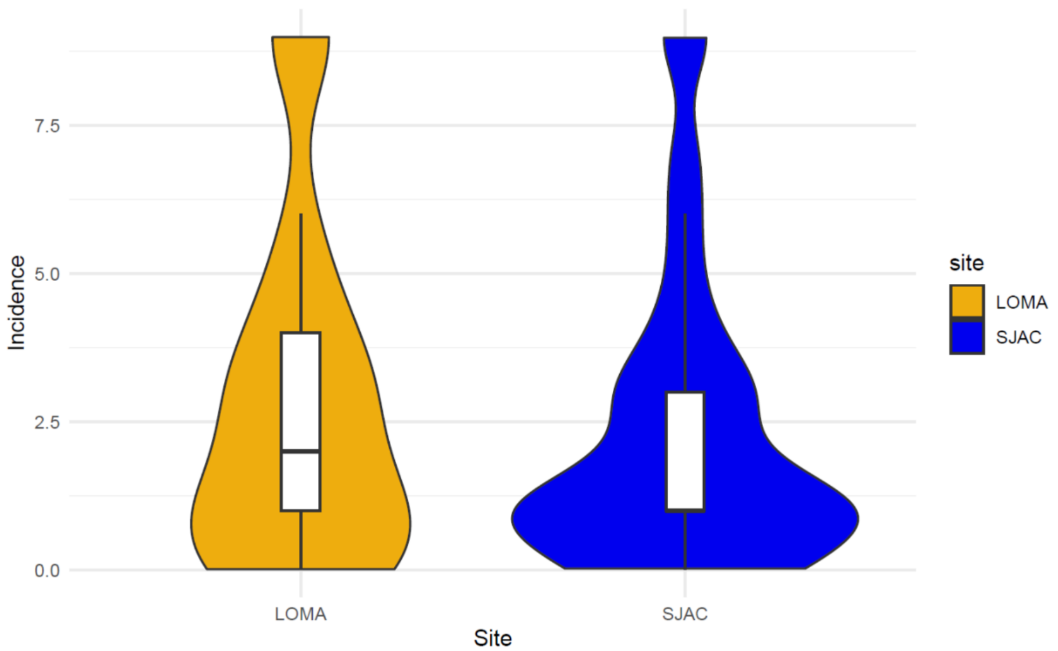
a.



b.

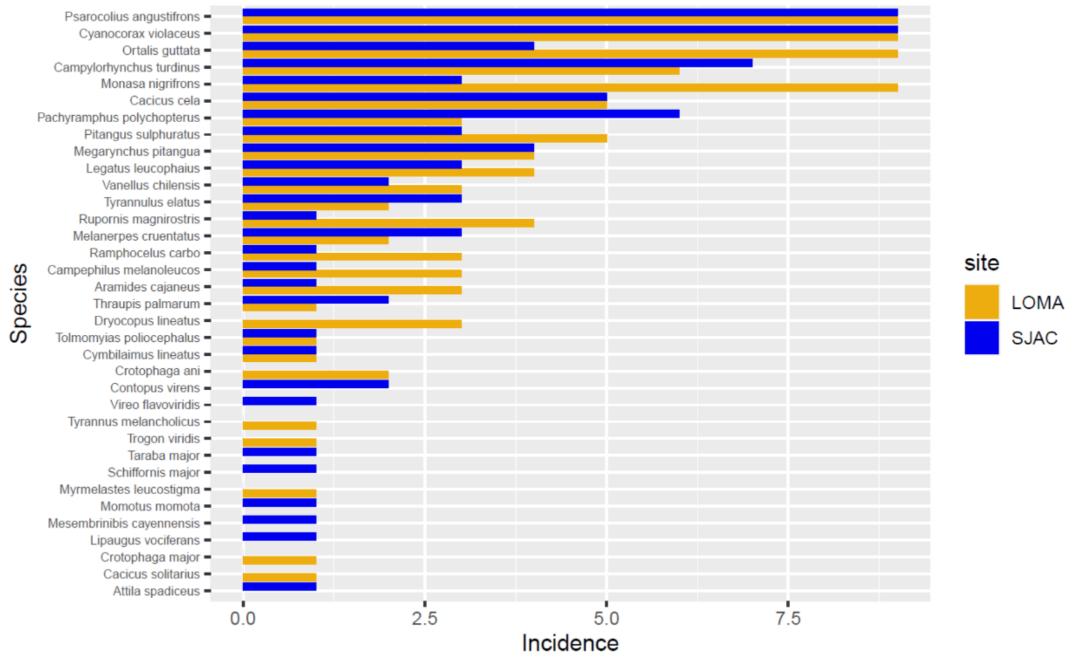


c.



Incidence
7.5
5.0
2.5
0.0
LOMA
SJAC
Site
site
LOMA
SJAC

d.



Psarocolius angustifrons
Cyanocorax violaceus
Ortalis guttata
Campylorhynchus turdinus
Monasa nigrifrons
Cacicus cela
Pachyramphus polychopterus
Pitangus sulphuratus
Megarynchus pitangua
Legatus leucophaius
Vanellus chilensis
Tyrannulus elatus
Rupornis magnirostris
Melanerpes cruentatus
Ramphocelus carbo
Campephilus melanoleucos
Aramides cajaneus
Thraupis palmarum
Dryocopus lineatus
Tolmomyias poliocephalus
Cymbilaimus lineatus
Crotophaga ani
Contopus virens
Vireo flavoviridis
Tyrannus melancholicus
Trogon viridis
Taraba major
Schiffornis major
Myrmelastes leucostigma
Momotus momota
Mesembrinibis cayennensis
Lipaugus vociferans
Crotophaga major
Cacicus solitarius
Attila spadiceus
Species
0.0
2.5
5.0
7.5
Incidence
site
LOMA
SJAC

Figure 4. Jitter plot of macroinvertebrates incidence by trapping method and proximity to an oil platform **a.** Pan-trapped macroinvertebrate incidence in Primary Forest Area (EPF – TBS sites). **b.** Leaf-litter macroinvertebrate incidence in Primary Forest Area. **c.** Pan-trapped macroinvertebrate incidence in Forest Patches Area (LOMA – SJAC sites). **d.** Leaf-litter macroinvertebrate incidence in Forest Patches Area. Gas flare icon indicates oil platform proximity.

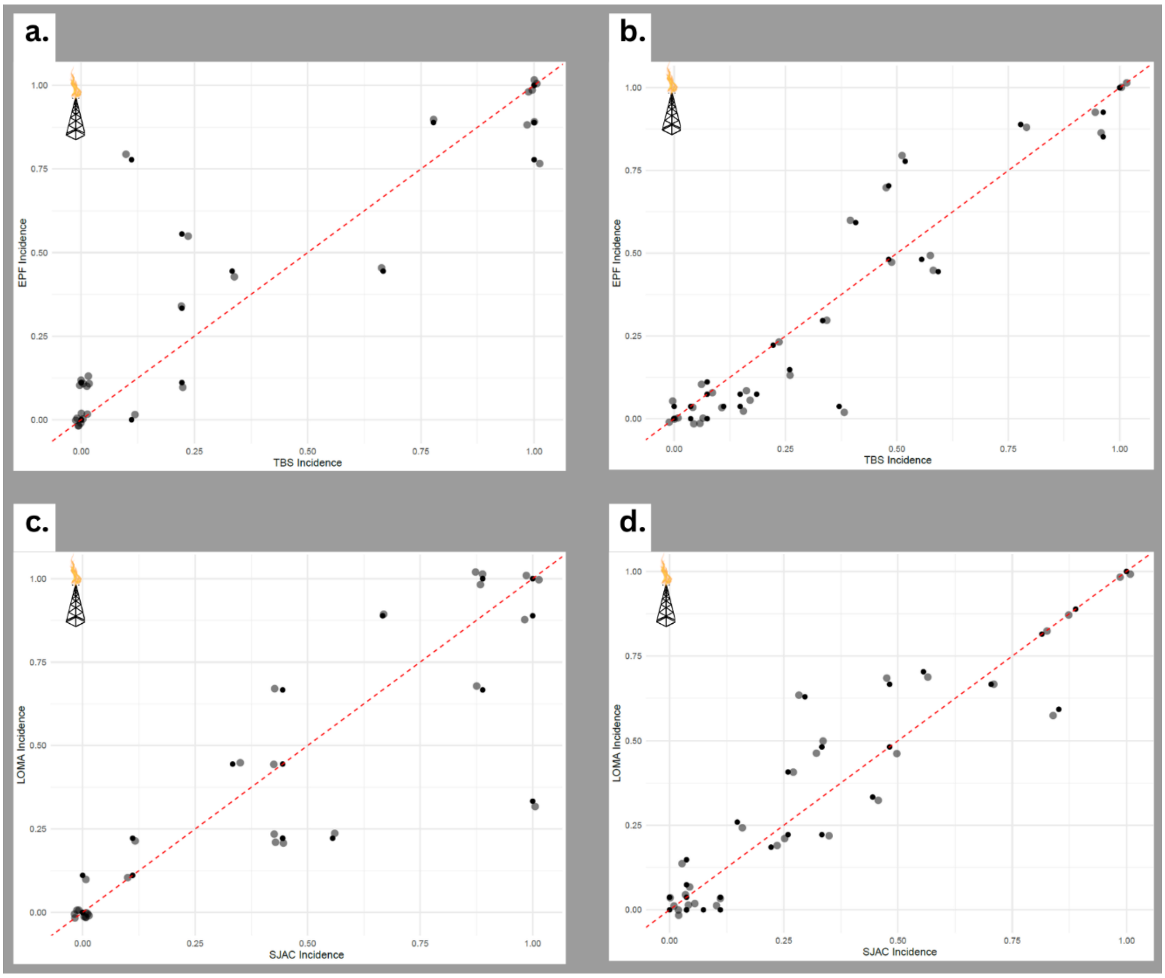


Figure 5. Bar plot of mean and standard error of macroinvertebrates captured by site (Primary Forest Area: EPF-TBS sites; Forest Patches Area: LOMA-SJAC sites) **a.** collected by pan traps **b.** collected by mini-Winkler traps.

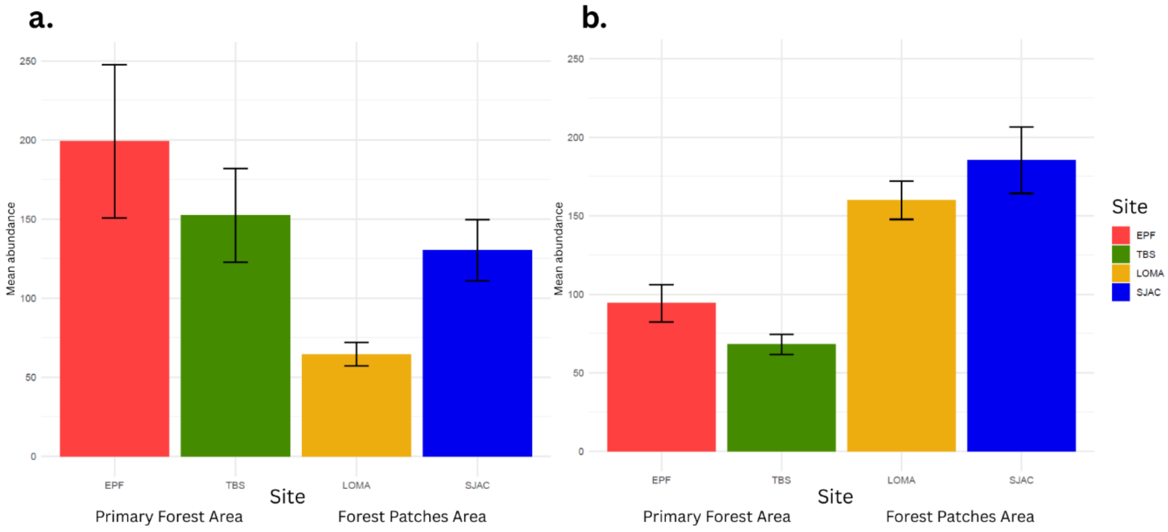
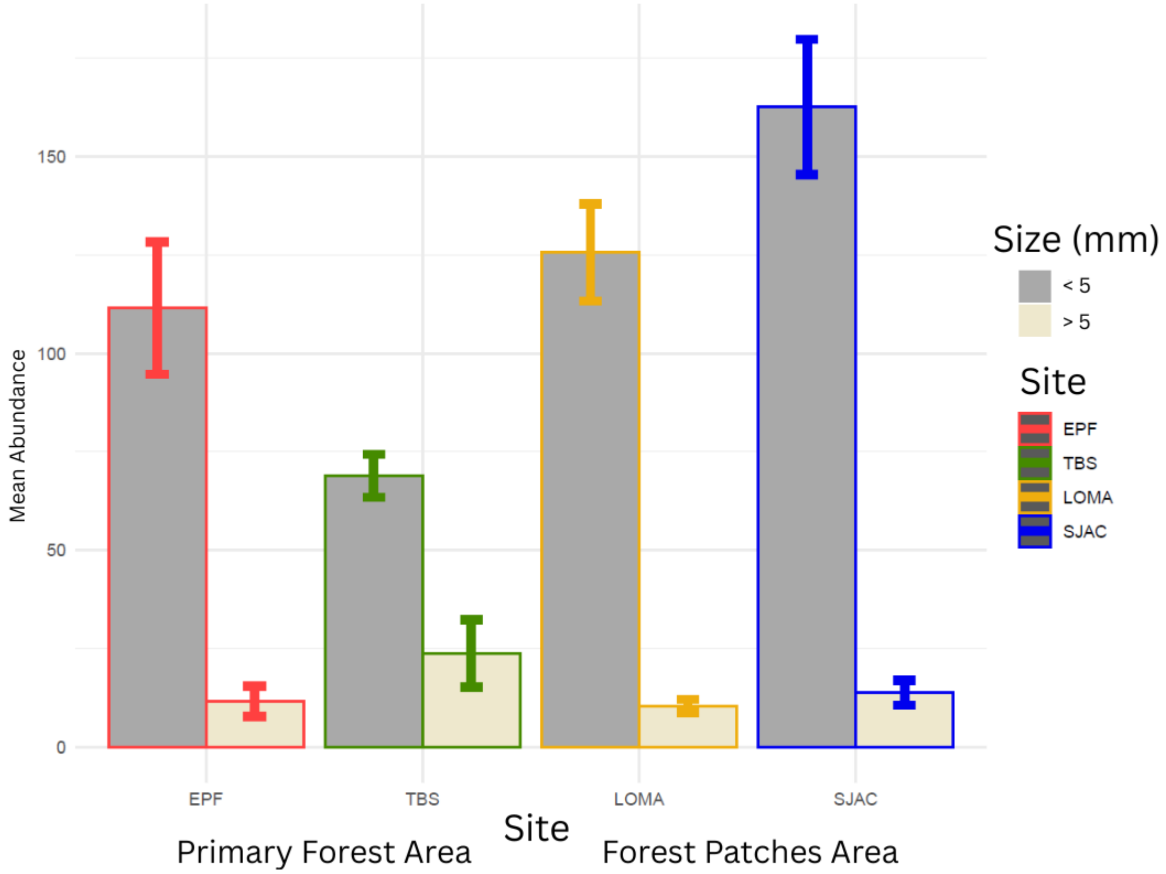
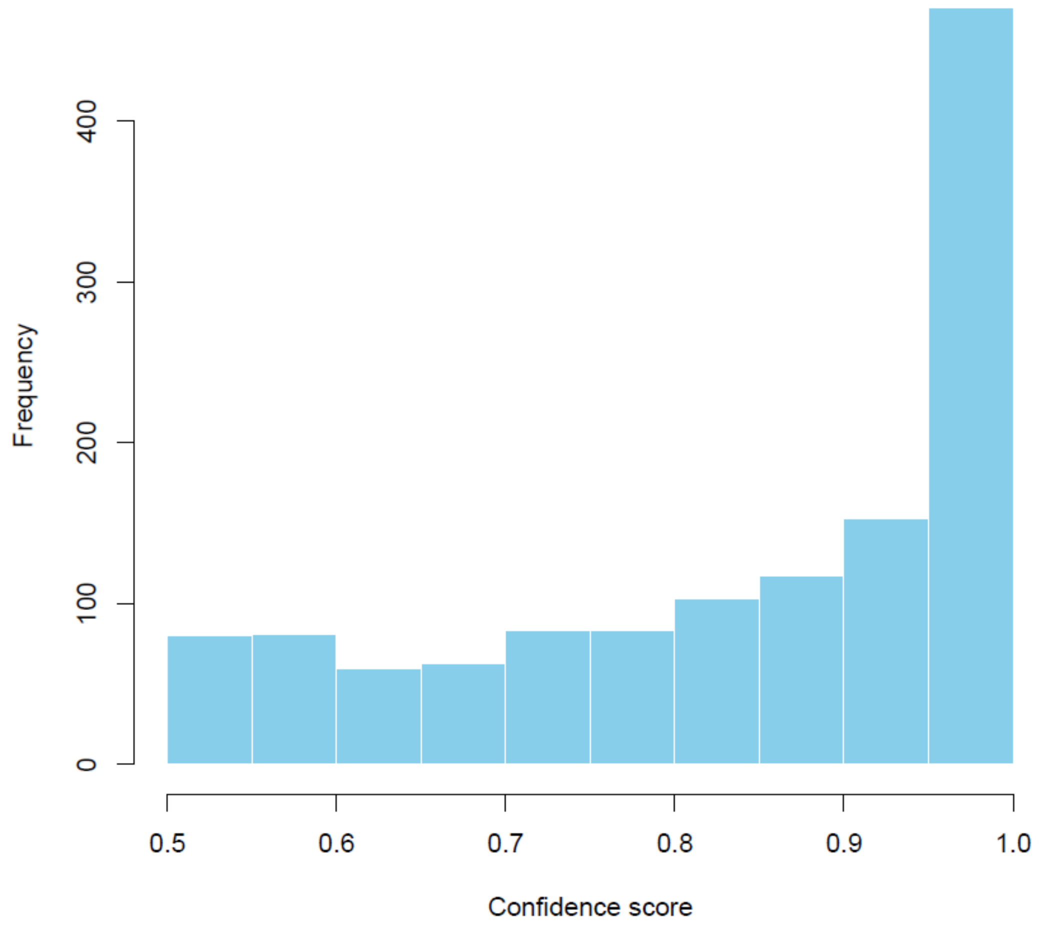


Figure 6. Bar plot of mean and standard error of two categorical sizes (< 5 mm and > 5 mm) of macroinvertebrates by site (Primary Forest Area: EPF-TBS sites; Forest Patches Area: LOMA-SJAC sites).

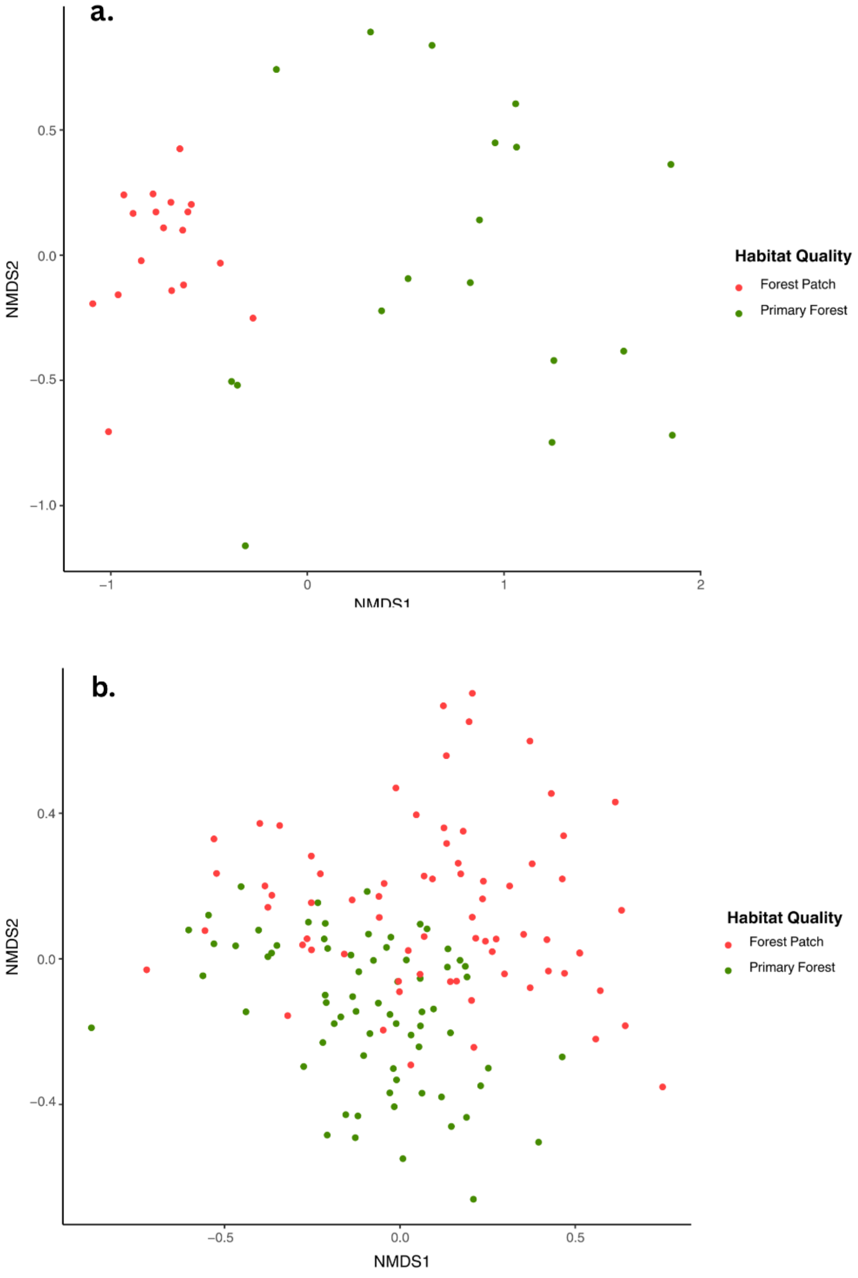


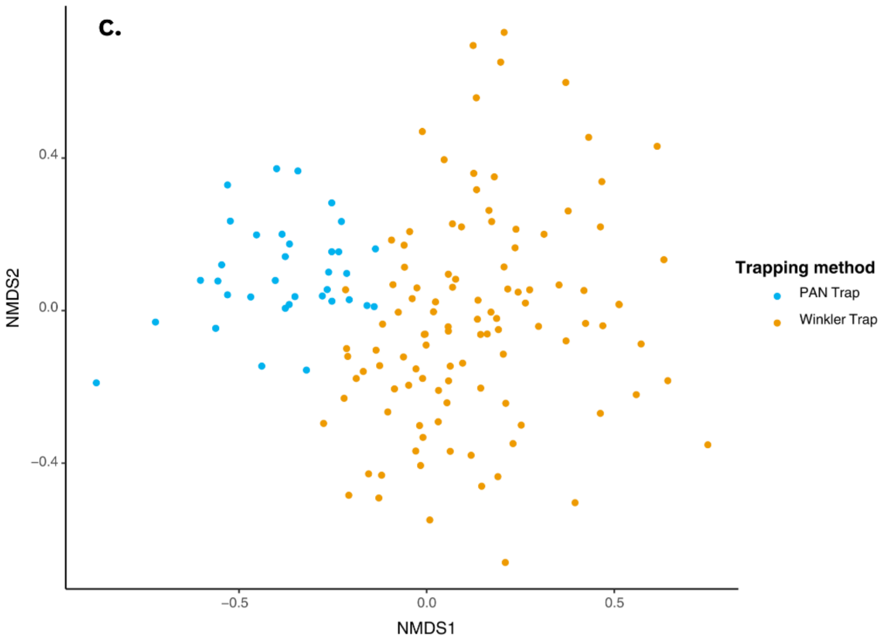
10. SUPPLEMENTARY FIGURES

Supplementary Figure 1. Histogram of frequency of confidence scores (50% - 100%) in bird species identification performed by Merlin Sound ID with the bird sounds detected by ARUs.



Supplementary Figure 2. Non-Metric Multidimensional Scaling for incidence frequency of **a.** Insectivorous birds in relation to habitat type **b.** Macroinvertebrates in relation to habitat type and **c.** Macroinvertebrates in relation to trapping method




c.
0.4
0.0
−0.4
NMDS2
−0.5
0.0
0.5
NMDS1
Trapping method
PAN Trap
Winkler Trap

Supplementary Table 1. Sampling dates

Site	Distance	Dates
EPF - TBS	Near the oil platform	07/02/2024 - 07/08/2024
EPF - TBS	Far from the oil platform	06/24/2024 - 06/27/2024
LOMA – SJAC	Near the oil platform	10/29/2024 – 11/3/2024
LOMA – SJAC	Far from the oil platform	11/4/2024 – 11/9/2024

Supplementary Table 2. Concentration values of chemical elements of water matrix by site (Primary Forest Area: EPF-TBS sites; Forest Patches Area: LOMA-SJAC sites), including referential values to detect irregularities. Red numbers refer to values above reference (MAATE, 2015).

	NEAR THE OIL PLATFORM				FAR FROM THE OIL PLATFORM				REF
	EPF		**LOMA**		**TBS**		**SJAC**		
WATER MATRIX									
Major Elements (mg/kg)									
Ca	10.47	-	18.64	18.56	<0.01	<0.01	14.8	20.35	N/A
K	0.75	-	8.01	6.97	<0.01	<0.01	6.1	5.12	N/A
Mg	2.09	-	4.72	4.67	<0.01	<0.01	3.8	5.15	N/A
Na	3.08	-	9.84	12.05	<0.01	<0.01	7.86	12.41	N/A
P	0.11	-	0.11	0.1	0.01	<0.01	0.16	0.13	N/A
S	10.47	-	0.77	0.96	<0.01	<0.01	0.71	1.02	N/A
Minor elements (mg/kg)									
Ag	<0,01	-	0.05	0.04	<0.01	<0.01	0.04	0.05	N/A
Al	0.68	-	0.34	0.62	N/A	N/A	0.3	0.42	100
As	< 0,01	-	< 0,01	< 0,01	N/A	N/A	< 0,01	< 0,01	50
B	0.23	-	< 0,01	< 0,01	N/A	N/A	< 0,01	< 0,01	750
Ba	0.03	-	0.13	0.15	5.00	0.00	0.1	0.15	1000
Be	< 0,01	-	< 0,01	< 0,01	<0.01	<0.01	< 0,01	< 0,01	100
Bi	< 0,01	-	< 0,01	< 0,01	<0.01	<0.01	< 0,01	< 0,01	N/A
Cd	< 0,01	-	< 0,01	< 0,01	<0.01	<0.01	< 0,01	< 0,01	1
Co	< 0,01	-	< 0,01	< 0,01	<0.01	<0.01	< 0,01	< 0,01	200
Cr	< 0,01	-	< 0,01	< 0,01	<0.01	1.00	< 0,01	< 0,01	32
Cu	0.03	-	0.03	0.04	0.00	0.00	0.02	0.02	5
Fe	0.67	-	0.67	0.56	N/A	N/A	0.49	0.2	300
Ga	< 0,01	-	< 0,01	< 0,01	8.00	14.00	< 0,01	< 0,01	N/A
Hg	-	-	< 0,01	< 0,01	-	-	< 0,01	< 0,01	0.0002
In	0.01	-	< 0,01	< 0,01	<0.01	<0.01	< 0,01	< 0,01	N/A
Li	0.03	-	< 0,01	< 0,01	<0.01	26.00	< 0,01	< 0,01	N/A
Mn	0.15	-	0.08	0.07	259.00	<0.01	0.06	0.02	100
Ni	< 0,01	-	< 0,01	< 0,01	<0.01	1.00	< 0,01	< 0,01	25
Pb	< 0,01	-	< 0,01	< 0,01	N/A	N/A	< 0,01	< 0,01	1
Se	< 0,01	-	< 0,01	< 0,01	<0.01	<0.01	< 0,01	< 0,01	1
Si	6.19	-	14.17	12.87	-	-	10.93	20.31	N/A
Sr	0.06	-	0.24	0.22	2.00	3.00	0.18	0.31	N/A
Te	< 0,01	-	< 0,01	< 0,01	<0.01	<0.01	< 0,01	< 0,01	N/A
Tl	< 0,01	-	< 0,01	< 0,01	<0.01	<0.01	< 0,01	< 0,01	N/A
V	0.02	-	< 0,01	< 0,01	2.00	6.00	< 0,01	< 0,01	N/A
Zn	0.11	-	0.44	0.04	N/A	N/A	0.31	0.97	30

Supplementary Table 3. Physic/chemical properties of water matrix by site (Primary Forest Area: EPF-TBS sites; Forest Patches Area: LOMA-SJAC sites), including referential values to detect irregularities. Red numbers refer to values above reference (MAATE, 2015).

	NEAR THE OIL PLATFORM				FAR FROM THE OIL PLATFORM				REF
	EPF		**LOMA**		**TBS**		**SJAC**		
WATER MATRIX									
Physico-chemical properties									
	Mean	sd	Mean	sd	Mean	sd	Mean	sd	
Electric conductivity (uS/cm)	101.55	1.48	73.35	1.76	23.53	0.74	115.35	3.60	N/A
pH	7.31	0.04	6.87	0.02	6.00	0.00	6.71	0.12	6.5 - 9
Temperature (C°)	18.20	0.42	22.4	0	26.10	0.00	22.4	0	N/A
Turbidity (NTU)	25.13	0.51	16	0.31	19.83	1.04	10	0.41	N/A
Alcalinity (mg $CaCO_3$/L)	50.50	0.00	48.48	2.85	7.60	-	56.56	5.71	N/A
Amonuim (mg NH_4^+/L)	0.00	0.00	0.07	0.009	0.08	0.05	0	0	Total amonium (25ºC): pH 7: 3.37 mg/L; pH 8.5: 0.125mg/L
Nitrate (mg NO_3^-/L)	4.43	0.00	5.31	0.62	4.57	1.11	3.09	0.62	13
Fosfate (mg PO4/L)	0.22	0.01	0.22	0.005	0.17	0.03	0.235	0.035	N/A
Sulfate (mg SO_4^{2-}/L)	0.00	0.00	0	0	2.00	0.00	0	0	N/A
DQO (mg/L)	0.00	0.00	8	3	<LD	0.00	0.5	0.5	40
Total solids (mg/L)	11.200	-	98	-	92.00	-	130	-	N/A
Total disolved solids (mg/L)			-	-	15.60	0.00	-	-	

Supplementary Table 4. Concentration values of chemical elements of soil matrix by site (Primary Forest Area: EPF-TBS sites; Forest Patches Area: LOMA-SJAC sites), including referential values to detect irregularities. Red numbers refer to values above reference (TULSMA, 2009).

	NEAR THE OIL PLATFORM								FAR FROM THE OIL PLATFORM								REF
	EPF			$\bar{x}$	**LOMA**			$\bar{x}$	**TBS**			$\bar{x}$	**SJAC**			$\bar{x}$	
SOIL MATRIX																	
Major Elements (mg/kg)																	
Ca	846.55	800.05	2473.87	1373.49	1483.22	2341.48	1082.92	1635.87	56.19	174.73	181.09	137.33	1418.25	1451.19	735.52	1201.65	N/A
K	474.6	812.44	566.54	617.86	262.55	247.7	445.57	318.60	871.56	4559.97	823.11	2084.88	188.47	607.39	400.81	398.89	N/A
Mg	1145.45	1271.55	1207.82	1208.27	903.89	1179.782	1763.448	1282.37	981.43	2637.57	1075.49	1564.83	939.554	2106.755	1523.06	1523.12	N/A
Na	229.14	174.18	236.04	213.12	311.61	346.81	446.53	368.31	167.09	775.77	153.42	365.42	301.92	192.32	127.8	207.34	N/A
P	433.60	359.26	1440.14	744.33	2344.97	1779.35	574.16	1566.16	152.27	617.52	196.73	322.175	755.97	1169.55	1260.47	1061.99	N/A
Minor elements (mg/kg)																	
Ag	91.37	45.92	56.22	64.50	78.51	90.43	12.41	60.45	8.77	19.97	8.47	12.40	> 100	> 100	> 100	N/A	20
Al	4556.45	2775.18	4155.63	3829.08	3554.34	2806.05	2495.16	2951.85	2813.39	6589.06	3682.85	4361.76	2779.13	5577.39	2828.11	3728.21	N/A
B	19.06	16.6	16.54	17.4	9.88	12.17	13.12	11.72	10.66	34.16	15.59	20.13	13.32	34.3	25.79	24.47	1
Ba	161.43	106.89	102.72	123.68	84.03	82.15	163.96	110.04	43.84	250.75	41.12	111.90	159.27	343.7	323.63	275.53	200
Be	<0,01	<0,01	<0,01	N/A	<0,01	<0,01	<0,01	N/A	<0,01	<0,01	<0,01	N/A	<0,01	<0,01	<0,01	N/A	N/A
Bi	<0,01	<0,01	<0,01	N/A	<0,01	<0,01	<0,01	N/A	<0,01	<0,01	<0,01	N/A	<0,01	<0,01	2.72	2.72	N/A
Cd	0.05	0.02	0.17	0.08	0.14	0.07	<0,01	0.105	<0,01	0.09	0.04	0.065	0.19	0.07	0.1	0.12	0.5
Co	19.67	18.06	14.83	17.52	7.92	10	13.18	10.36	5.35	14.77	15.42	11.84	13.16	34.21	26.75	24.70	10
Cr	30.61	27.58	26.33	28.17	16.83	20.29	23.1	20.07	26.16	81.5	37.77	48.47	25.45	75.75	55.22	52.14	20
Cu	27.13	20.04	21.08	22.75	25.4	22.58	24.45	24.14	7.6	22.2	15.42	15.07	15.73	49.2	41.74	35.55	30
Fe	20000.59	16621.29	13928.06	16849.98	10025.93	13246.84	17843.15	13705.30	12021.92	30973.89	16394.49	19796.76	14218.39	34408.49	26297.63	24974.83	N/A
Ga	5.8	5.9	6.65	6.11	4.16	3.91	3.92	3.99	5.31	16.96	5.93	9.4	5.81	15.44	13.56	11.60	N/A
Hg	<0,01	<0,01	<0,01	N/A	< 0,01	< 0,01	< 0,01	N/A	<0,01	<0,01	<0,01	N/A	< 0,01	< 0,01	< 0,01	N/A	0,1
In	41.96	32.27	30.44	34.89	10.46	15.94	30	18.8	3.86	23.43	28.33	18.54	25.87	76.65	58.98	53.83	N/A
Li	128.37	115.99	101.78	115.38	70.8	86.12	120.83	92.58	83.26	213.14	110.09	135.49	95.54	235.48	202.32	177.78	N/A
Mn	745.87	605.59	510.37	620.61	75.7	177.88	390.96	214.84	53.87	437.06	593.58	361.50	338.39	1000.96	744.92	694.75	N/A
Ni	11.9	10.06	10.06	10.67	7.77	8.16	10.41	8.78	9.33	31.71	10.88	17.30	9.14	23.65	19.07	17.28	20
Pb	45.79	42.91	43.7	44.13	28.14	28.71	32.31	29.72	32.55	95.96	36.48	54.99	35.23	86.57	78.55	66.78	25
Se	1.11	2.23	<0,01	1.67	1.331	1.217	3.841	2.12	1.04	7.97	2.59	3.86	1.29	7.99	8.477	5.919	1
Si	138.04	58.63	141.77	112.81	89.74	113.39	42.07	81.73	52.95	163.91	74.75	97.20	43.66	93.3	53.75	63.57	N/A
Sr	35.14	22.15	35.05	30.78	27.18	38.56	64.17	43.30	9.8	51.1	10.23	23.71	47.49	107.15	56.16	70.26	N/A

Te	<0,01	<0,01	<0,01	N/A	< 0,01	< 0,01	< 0,01	N/A	<0,01	<0,01	<0,01	N/A	< 0,01	< 0,01	< 0,01	N/A	N/A
Tl	50.29	34.07	35.68	40.01	< 0,01	< 0,01	< 0,01	N/A	37.19	122.63	41.73	67.18	< 0,01	< 0,01	< 0,01	N/A	1
V	87.66	73.27	87.09	82.67	60.47	71.08	76.82	69.45	69.82	246.59	75.11	130.50	88.76	218.27	182.82	163.28	25
Zn	50.29	34.07	35.68	40.01	51.65	45.76	55.66	51.02	37.19	122.63	41.73	67.18	37.03	79.76	64.68	60.49	60