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RESEARCH SUMMARY

RESEARCH SUMMARY SERIES

AMAZON FORESTS NEAR SMALL-SCALE AND ARTISAN GOLD MINING CAPTURE HIGH LEVELS OF MERCURY ATMOSPHERIC POLLUTION

Research Summary No. 8 | February 2022

Key words: Artisanal gold mining, soil contamination by mercury, pristine forests

Key points:

⇒ Intact protected forests near artisanal and small-scale gold mining receive extremely high inputs of mercury via throughfall and litterfall that far surpass deforested areas and remote intact forests.

⇒ Mercury is accumulating in the soils of intact forests near artisanal and small-scale gold mining and getting into terrestrial wildlife such as songbirds.

⇒ The highest levels of methyl mercury – the form of mercury that is toxic to people and wildlife and the form that bioaccumulates – were found in forest soils near artisanal and small-scale gold mining, reflecting the high input of total Hg found in these soils.

⇒ It is important to protect intact forests near artisanal and small-scale gold mining since deforestation leads to the release of mercury into aquatic ecosystems, which are even more prone to mercury accumulation in the food web.

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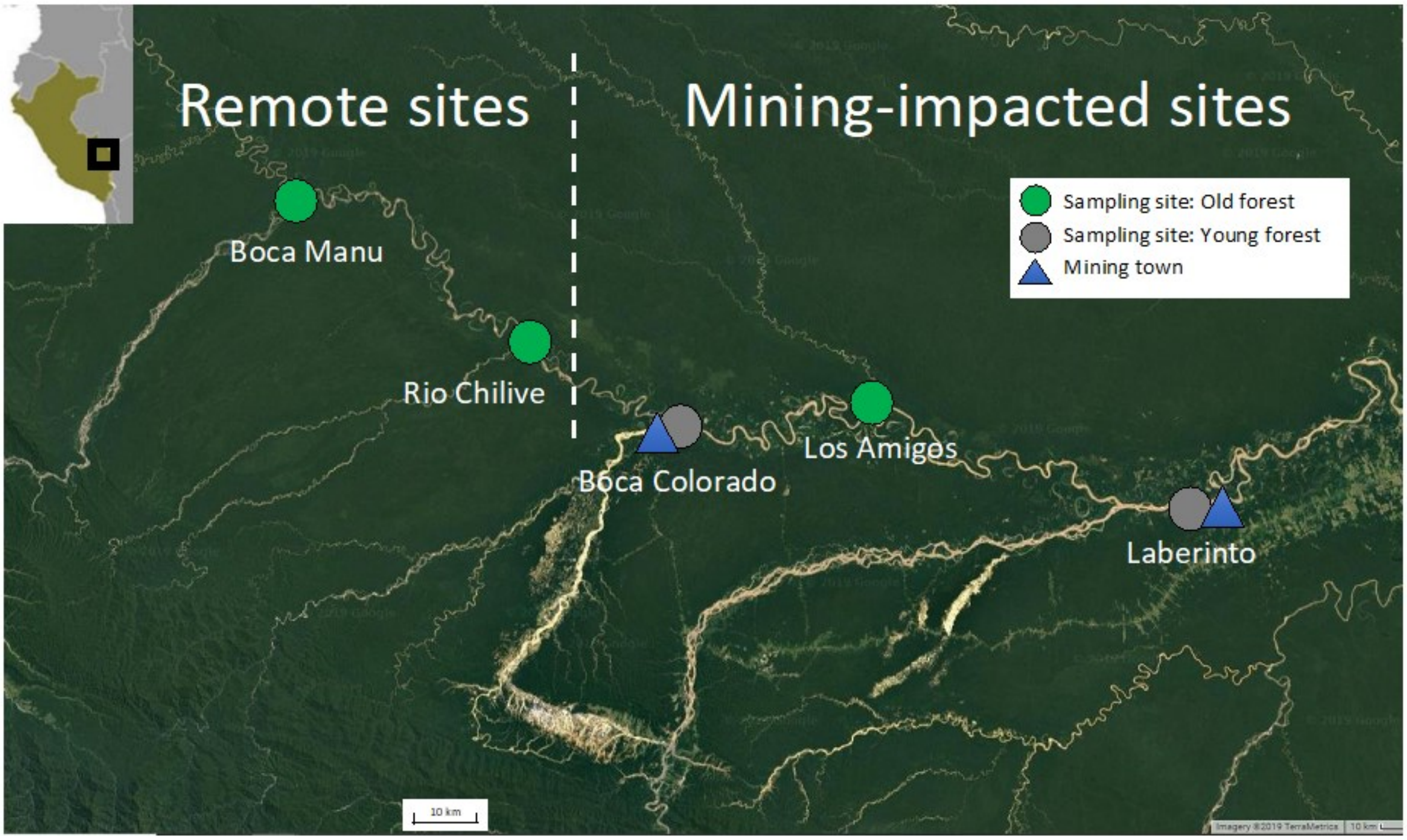

Figure 1: Map of five study sites, divided into remote sites and mining-impacted sites. Sites containing old, intact forests are shown in green. Sites containing young forests on disturbed sites are shown in gray. Locations of mining towns where Hg-gold amalgams are burned are shown in the blue triangles.

INTRODUCTION

Mercury (Hg) is a potent neurotoxin that can have harmful effects on both people[1] and wildlife[2]. The largest source of atmospheric mercury pollution globally is artisanal and small-scale gold mining (ASGM)[3]. ASGM also leads to high amounts of deforestation[4], creation of thousands of ponds across the landscape[5], and loss of biodiversity[6]. An estimated 180 tons of Hg have been emitted annually, concurrent with the clearing of over 100,000 hectares of forests in the past 35 years in the Madre de Dios region of the Peruvian Amazon, according to a recent report[7].

During ASGM, miners dredge gold-laden sediments from rivers, lakes, and floodplains. They then add Hg to the sediment, allowing the Hg to selectively bind to the gold and create a Hg-gold alloy. This amalgam is easily separated from the sediment, and the Hg is later burned off to isolate the gold. In this process, excess Hg is dumped as tailings into forests and water bodies, while amalgam burning releases large quantities of Hg into the atmosphere.

Once released into the atmosphere, Hg can re-enter the landscape via three pathways. First, Hg can attach to small particles present in the atmosphere. These particles can be intercepted by leaves in trees and then wash down to the forest floor when it rains ("thoughfall"). Second, Hg in the atmosphere can be taken up directly by vegetation, incorporated into their leaves, and then enter the forest floor when the leaves fall ("litterfall"). Third, Hg in the atmosphere can dissolve in raindrops, bringing Hg to forests, deforested areas, and water bodies when it rains ("wet deposition").

This research brief summaries a study that examined (1) how distance from ASGM activity affects the amount of Hg entering the landscape, and how this differs between forested

Figure 2. Collection of leaves from the tree canopy using a Notch Big Shot ®

and deforested areas; (2) the relationship between inputs of Hg to the ecosystem and storage of Hg in soils; and (3) whether Hg from ASGM is entering into animals inhabiting these forests.

METHODS

This study established five sites along the Madre de Dios River, with each site approximately 50 km apart (Figure 1). Three sites were designated as "mining sites" located within the mining zone (Boca Colorado, Los Amigos, and Laberinto), and two sites were designated as "remote sites" without mining activity that served as control locations (Boca Manu and Chilive, approximately 100 km and 50 km from gold mining, respectively). The vegetation at Boca Colorado and Laberinto sites consists of disturbed and recovering forests, with generally younger trees and less dense canopy compared to the old, intact forests at Los Amigos and Boca Manu. The Los Amigos site, while near mining activity, actually occurs within the Los Amigos Conservation Concession. At each of these five sites, we collected samples from under the forest canopy and from a clearing that did not contain overhead trees to exclude throughfall and litterfall.

Samples were taken in the 2018 dry season, 2018 wet season, and 2019 dry season. At each plot, we collected rainfall (rainwater) in the clearing (n=3 per season per site), rainfall under the tree canopy (throughfall; n=4 per season per site), leaves (Figure 2) (n=8 types of leaves per season per site), and soil (n=3 per season per site) (Figure 4). We also put out passive air samplers to collect gaseous elemental Hg (GEM) in the atmosphere in the clearings at all five sites (n=1 in the dry season, n=2 in the wet season per site). In the 2019 dry season, we collected throughfall from six additional forested plots (n=4 per plot) at the Los Amigos site and collected LIDAR data for leaf area index estimate using the GatorEye Uninhabited Flying Laboratory. Feathers from birds were collected at the Los Amigos site and at Cocha Cashu Biological Station (a remote site) in the 2019 dry season.

Rainwater and throughfall samples were analyzed for total Hg content using EPA Method 1631 revision E on a Tekran 2600 Automated Total Mercury Analyzer. Leaf, soil, and bird feather samples were analyzed for total Hg content using EPA Method 7473 on a Milestone Direct Mercury Analyzer. Mercury Passive air samplers (UofT-PAS) were analyzed for total Hg content using a vapor atomic absorption spectrometry (CV-AAS, USEPA Method 7473). We analyzed rainwater and throughfall samples from all three seasons, leaf samples from the 2018 dry season, and soil samples from all three seasons for methyl Hg (the form of Hg that is toxic and bioaccumulates) using EPA Method 1630 on a Tekran 2500 spectrometer.

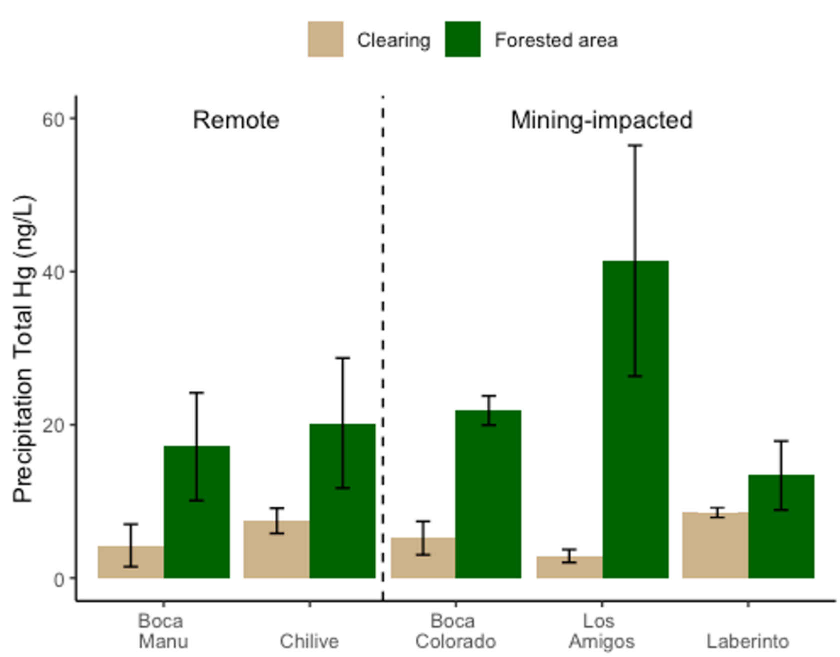

Figure 3A): Total Hg concentrations in rainfall at the two remote and three mining-impacted sites. Values shown represent the average and standard error. Brown bars are rainwater samples from clearings. Green bars are throughfall (rainfall that passes through the trees) samples from forested areas. Inputs of Hg via throughfall were highest in the forested area of Los Amigos Conservation Concession. There was no difference in Hg inputs via rainwater in clearings.

RESULTS

Atmospheric Hg concentrations were related to proximity to mining.

Concentrations of gaseous elemental mercury (GEM) were 2-14 times higher at the mining sites compared to the remote sites. Concentrations of GEM were highest at the two sites near mining towns (Boca Colorado, Laberinto) with values up to 10.9 ng m^{-3}. Mercury values in mining sites were above the global Southern Hemisphere average background concentration and were similar to, and sometimes exceeded, concentrations found in urban and industrial parts of the United States, China, and South Korea which receive Hg inputs from coal combustion. In contrast, GEM concentrations at the two remote locations were low with values below the global southern hemisphere average background concentration. It is therefore likely that burning of Hg-gold amalgams is the main source of elevated atmospheric Hg concentrations in Madre de Dios.

Total Hg concentrations in throughfall were dependent on both the proximity to mining and the presence of intact, old-growth forests.

The highest concentrations of Hg were found in the intact, old-growth forests within the mining zone at the Los Amigos site (Figure 3A). We measured total Hg concentrations in throughfall at Los Amigos that are among the highest ever reported in the world (range: 18-61 ng L^{-1}). These concentrations were at a similar level to, and sometimes exceeded, Hg concentrations in throughfall from areas heavily contaminated by mercury mining and industrial coal combustion in China. In contrast, concentrations of Hg in throughfall at the two other mining sites did not differ from the two remote sites (range: 8-31 ng L^{-1}). When these throughfall concentration data were used to estimate the total amount of Hg entering the landscape via throughfall over the year, we found that Los Amigos had the highest annual throughfall rates of Hg inputs ever reported globally (71 µg m^{-2} yr^{-1}).

Total Hg concentrations in forests leaves were highest near mining activity.

All three mining sites had higher average total Hg concentrations (0.080-0.22 µg g^{-1}) in leaves than in the two remote sites. These concentrations exceeded leaf Hg concentrations from

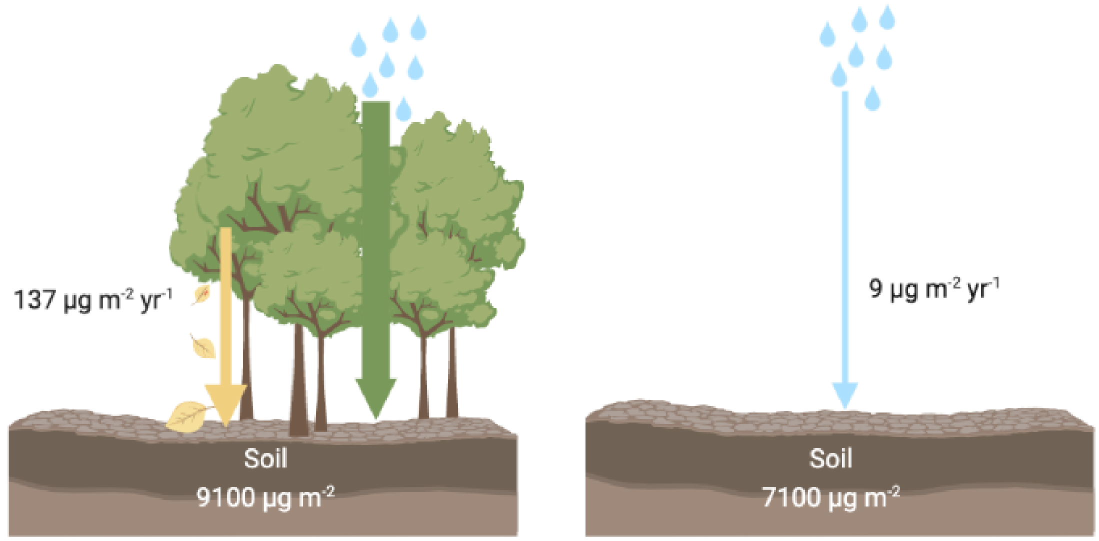

Figure3B): Total Hg inputs and storage in a forested area and clearing at Los Amigos Conservation Concession, a protected intact forest located near ASGM. In forested areas, Hg enters the forest floor and soil through throughfall (rainfall that passes through trees) and leaves falling. In clearings, Hg enters the soil through rainwater. Inputs and soil storage of Hg was much higher in the forested area than the clearing.

remote sites and Hg point source locations in North America, Europe, Asia, and Amazonian forests in South America, but were comparable to subtropical mixed forests in China and Atlantic forests in Brazil. The highest annual input of Hg via litterfall was at the Los Amigos Conservation Concession (66 µg m^{-2} yr^{-1}), since it is the mining site with the highest number of leaves falling to the forest floor each year. These results show that leaves are an important source of Hg in these artisanal gold mining-impacted terrestrial ecosystems.

Inputs of total Hg to forested areas at the Los Amigos Conservation Concession (located near mining activity) were more than 15 times greater than the surrounding deforested areas.

We found that atmospheric inputs (including both dry and wet deposition) of total Hg to forested areas of the Los Amigos Conservation Concession were 137 µg Hg m^{-2} yr^{-1} compared to 9 m^{-2} yr^{-1} in deforested areas (Figure 3B). This number exceeds values for North America and Europe near coal combustion and is similar to levels measured in industrial areas in China. We also found that, among the six plots measured with LIDAR at Los Amigos, the extent of canopy cover (measured as leaf area index) was associated with higher amounts of Hg inputs. These results highlight that tree cover is important to the scavenging of atmospheric Hg released by ASGM and for transferring this atmospheric Hg into the terrestrial ecosystem.

There was no difference in Hg inputs to non-forested areas (clearings) at all sites, regardless of proximity to mining.

Total Hg concentrations in dry season rainwater in all non-forested sites (clearings) was comparable (1.5-9.1 ng L^{-1}). All clearing sites had low Hg concentrations, below that found in remote areas of the Amazon. Rainwater inputs of Hg in clearings are therefore uniform across the region and do not reflect mining activity. Nevertheless, areas that are deforested by mining could still have mercury contamination that originates from direct Hg releases from the mercury-gold amalgamation process used in ASGM.

Surface soils (top 0-5 cm) at the Los Amigos Conservation Concession forested site had the highest levels of total Hg in our study.

We measured 140 ng g^{-1} total Hg at the Los Amigos Conservation Concession forested site in the dry season and found that soils at Los Amigos had high Hg levels even at depth (up to 45 cm). The only site to have higher Hg concentration in surface soils was one sample from Boca Colorado, which may be related to local contamination during the Hg amalgamation process. In general, surficial soil Hg concentrations were correlated with total Hg concentrations in throughfall in forested sites, suggesting the importance of throughfall inputs of Hg to soil storage of Hg.

The highest concentrations of methyl Hg – the toxic and bioavailable form of Hg – were found in soils near gold mining.

Most research on Hg from ASGM has focused on Hg contamination in aquatic ecosystems since Hg is more readily converted into methylmercury (MeHg) in these environments. However, we found that terrestrial ecosystems near ASGM also had elevated concentrations of Hg, suggesting that the impacts of ASGM extend beyond just rivers and lakes. We measured the highest concentrations of MeHg in soil at two of the mining sites (Boca Colorado and Los Amigos; 1.4 and 1.1 ng MeHg g^{-1}, respectively). We also found that the percent of Hg present as MeHg – calculated as (MeHg concentration / total Hg concentration x 100%) - at these two sites was comparable to other sites throughout the world (1.4% and 0.8% Hg as methyl Hg, respectively).

These findings indicate that the high concentrations of methylmercury in these soils are likely due to high Hg inputs to, and high Hg storage in soils, rather than efficient conversion of inorganic Hg to MeHg in these soils. While Hg is converted into MeHg within forests near artisanal gold mining, it is important to note that the relative efficiency of this process (the percent of Hg present as MeHg) is still much lower in terrestrial ecosystems than in aquatic ecosystems.

Levels of Hg in songbirds near mining areas were elevated compared to remote forests.

We found that songbirds from the Los Amigos Conservation Concession (near mining sites) had concentrations of Hg up to twelve times higher than songbirds from the Cocha Cashu Biological Station (remote site) (Figure 6). This pattern was seen for all three bird species examined (understory insectivore *Myrmotherula axillaris,* ant-following insectivore *Phlegopsis nigromaculata*, and frugivore *Pipra fasciicauda*) regardless of feeding habits. Seven of ten *Phlegopsis nigromaculata* individuals sampled from Los Amigos had levels of Hg above those known to affect reproductive success, while none from Cocha Cashu had levels exceeding these standards. These results suggest that Hg from ASGM is entering into the terrestrial food web and may be negatively impacting the reproductive success, and thus the viability of bird populations.

CONCLUSIONS

We found that inputs of mercury to the terrestrial ecosystem are positively related to both the proximity to mining and to

Figure 4. Soil sampling

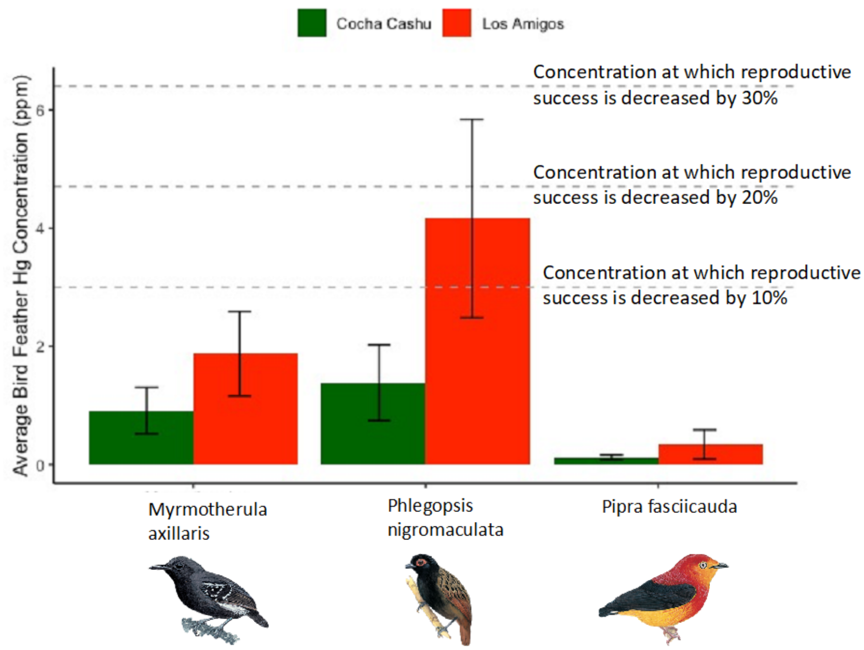

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Figure 5: Average concentration of total Hg in bird feathers at Cocha Cashu Biological Station (a remote site) and Los Amigos Conservation Concession (a mining-impacted site). Hg concentrations were measured in Myrmotherula axillaris (an understory invertivore), Phlegopsi nigromaculata (an ant-following invertivore) and Pipra fasciicauda (an understory frugivore).

elements of forest structure. We found that intact, protected forests near mining have the highest inputs of mercury. The total mercury concentrations and annual total inputs of mercury to forested areas in the Los Amigos Conservation Concession were among the highest ever reported. We also found evidence of storage of mercury in forest soils, measurable levels of the toxic and bioavailable methylmercury in these soils, and elevated levels of total Hg in songbirds in intact and protected forests near mining. ASGM is likely posing a risk to the viability of the high biodiversity of animals living in these protected forests.

These results also imply that the continued protection of intact forests is an important aspect to managing the dynamics of mercury in Amazonian ecosystems. If these forests are clear cut or burned for additional mining activity or agriculture, the mercury that is currently stored in these soils could then be transported to nearby water bodies, where it can more efficiently be converted to more toxic and bioavailable methylmercury, become incorporated in the aquatic food chain, accumulate in fish and other aquatic animals, and increase negative health risks for fish-eating populations.

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AUTORES

Jacqueline Gerson, Natalie Szponar, Angelica Almeyda Zambrano, Bridget Bergquist, Eben Broadbent, Charles T Driscoll, Gideon Erkenswick, David C Evers, Luis E Fernandez, Heileen Hsu-Kim, Giancarlo Inga, Kelsey Lansdale, Melissa J Marchese, Ari Martinez, Caroline Moore, William Pan, Miles Silman, Emily Ury, Claudia Vega, Mrinalini Watsa, Emily Bernhardt.

RESEARCH PARTNERS

Department of Biology - Duke University, Duke Global Health Institute - Duke University, Department of Earth Sciences - University of Toronto, School of Forest Resources and Conservation - University of Florida, Department of Civil and Environmental Engineering - Syracuse University, Department of Molecular Microbiology - Washington University School of Medicine, Field Projects International, San Diego Zoo Wildlife Alliance, Biodiversity Research Institute, Centro de Innovación Científica Amazónica (CINCIA), Center for Energy, Environment, and Sustainability (CEES) - Wake Forest University, Department of Biology - Wake Forest University, Department of Civil and Environmental Engineering - Duke University, Environmental Science Program - Duke University, Department of Biological Sciences - California State University, Nicholas School of the Environment - Duke University, Universidad Nacional de Piura, Instituto de Investigación en Ecología y Conservación (IIECOO).

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The Amazon Center for Scientific Innovation (CINCIA) is a partnership between Wake Forest University and USAID. It was created in 2016 with the aim of generating scientific capacity to identify, recover and mitigate threats to ecosystems, biodiversity and health in Madre de Dios. CINCIA aims to strengthen research capacity and improve the application of scientific knowledge.

DISCLAIMER

This publication has been made possible thanks to the support of the People of the United States of America through the United States Agency for International Development (USAID), Wake Forest University, and the Amazon Center for Scientific Innovation. The opinions expressed herein are those of the authors and do not necessarily reflect the opinion of USAID, the United States Government, or the other institutions that contributed to the printing of this publication.

THANKS

We would like to thank the following people for their contributions and assistance in carrying out this research: Ramiro Cordova Salas, Francisco Phuno Soncco, Bryan Huamantupa Rivera, Cecilio Huamantupa, Arianna Basto, Kelsey Lansdale, Melissa Marchese, Arabella Chen, Christian Lara, Annie Lee, Fernanda Machicao, Tatiana Manidis, Laura Naslund, Centro de Innovación Científica Amazónica (CINCIA), Conservación Amazónico (ACCA), and Los Amigos Conservation Concession for field assistance; Brooke Hassett, Kim Hutchison, Gary Dwyer, Nelson Rivera, Faye Koenigsmark, Natalia Neal-Walthall, Austin Wadle, Rachel Coyte, Rand Alotaibi, and Arianna Agostini for laboratory assistance; and Jennifer Swenson for remote sensing advice.

Recommended citation: Gerson, J.R., Szponar, N., Zambrano, A.A. et al. (2022) *Amazon forests near small-scale and artisan gold mining capture high levels of mercury atmospheric pollution* (Research summary series CINCIA #8) Puerto Maldonado, Perú: Centro de Innovación Científica Amazónica.

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