International Journal of Health Sciences
September 2021, Vol. 9, No. 3, pp. 1-12
ISSN: 2372-5060 (Print), 2372-5079 (Online)

Published by American Research Institute for Policy Development
DOI: 10.15640/ijhs.v9n3a1
URL: https://doi.org/10.15640/ijhs.v9n3a1

Using Satellite Data to Estimate Risk of Mercury Exposure in the Amazonian Wayana Language Territory between Suriname, French Guiana, and Brazil

Daniel Peplow[1]

Abstract

There is a need for methods that measure public and environmental health risk due to mercury from small-scale gold mines (SSGMs) at a regional scale in tropical forests. The synoptic regional-scale perspective of overhead remote imaging technology was used to supplement previous ground-level community risk and health assessment studies. The objective was to evaluate the usefulness of remote sensing as a method for measuring mercury impacts over large areas and test whether regional-level vegetation index values are lower in a test area where mercury contamination from SSGMs are known to impact human health compared to index values in a pristine reference area. Low vegetation index values were obtained in the test area compared to the high index values at the pristine reference location where vegetation stress is low suggesting remote sensing is a useful method for measuring mercury impacts, and the risk to human and environmental health, over large areas.

Key Words: Remote Sensing, Risk Assessment, Mercury Contamination

1. Background

As of 2008, environmental contamination by mercury from Small Scale Gold Mining (SSGM) activities was occurring in at least 77 countries (Pirrone et al, 2009; Street et al, 2013; Telmer & Veiga, 2009). In the indigenous Wayana Language Territory (Figure 1), a trans-border Maroni River region between Suriname, French Guiana and northern Brazil, studies show that mercury contamination is significant suggesting there is a widespread global health issue due to its impact on human health among both mining and non-mining communities (Legg et al, 2015, Peplow & Augustine, 2010; Peplow & Augustine, 2012; Peplow& Augustine 2015). It is assumed that mercury pollution is a management problem involving three main groups of stakeholders: the private sector, government, and civil society (Healy et al, 2005; Veiga 1997). Despite governments in the region becoming parties to the Minamata Convention on Mercury (Hg), they have not yet implemented measures that effectively address a health and environmental crisis due to mercury poisoning that is produced by gold mining in the region (Sullivan, 2021).

Mercury dispersion from SSGM operations is very heterogenic and depends on many factors (Barbieri, 2009). Spatial trends are not obvious and many areas in the Amazon have never been studied. The effects of mercury contamination occur at different scales and levels of biological organization and there are potential opportunities for intervention at each level (Peplow & Edmonds, 2005). Since toxicity is a mechanism that operates at the molecular level, the degree to which cause and effect are related (i.e., specificity), the knowledge of the mechanisms of toxicity and apparent opportunities to design and implement appropriate and effective intervention measures is greater at lower levels, e.g., the individual and community.

When studies focus on the toxicity of environmental toxins at higher levels and compare populations and regions, the direct links between cause-and-effect and the knowledge of the mechanisms of toxicity and apparent opportunities to design and implement appropriate and effective intervention measures are often tenuous.

Despite the greater mechanistic understanding and endpoint-response specificity, the effects of environmental toxins at the individual or community level of organization may be limited. In situations where the contributing factors responsible for exposure lie outside the health sector and are socially, politically and economically formed, hey may not be easily identified at this level. The examination of Hg risk at multiple levels of social and biological organization are, therefore, needed to identify the full range of mechanisms of exposure and toxicity and to more completely identify apparent opportunities for intervention (Peplow & Edmonds, 2005; Peplow & Augustine, 2017).

[1] University of Washington, School of Public Health, Seattle, Washington, USA. dpeplow@uw.edu (509) 930-7247

In this study, the synoptic perspective of overhead remote imaging technology was used to supplement traditional ground-level community risk and health assessment studies. Visible and near-infrared reflectance spectroscopy, which is noninvasive, cost-effective, socially and environmentally friendly, was performed to supplement Hg risk previously measured among people living in the dense, tropical forest habitat in the Wayana Language Territory between Suriname, French Guiana, and Brazil. The overarching goal of this study was to evaluate the usefulness of remote sensing as a method for measuring Hg impacts over large areas to support the economic development policy process. Specific hypotheses tested in this study were:

H_0: Regional-level vegetation index values are not lower in a test area, where there is Mercury contamination from SSGMs, when compared to a pristine reference area.

H_a: Regional-level vegetation index values are lower in a test area, where there is mercury contamination From SSGMs, when compared to a pristine reference area.

2. Methods

2.1 Study Area.

This study was conducted in an area with boundaries that identify where the Wayana language is spoken by the majority culture. This region is part of the Guiana Shield, the largest contiguous region of exposed Precambrian (>0.6 Ga old) rock in South America, covering more than 2 million square km of northeast Amazonia (Goodwin, 1996). Its equatorial location and historic absence of large-scale deforestation render it the largest repository of tropical forest vegetation worldwide (34%). The Guiana Shield shares significant geological features with other former components of the paleo-continent Gondwana, including West Africa, Western Australia, and south-central Amazonia. It is characterized by widespread plant endemism and high species diversity affected by relatively few large-scale natural disturbances (Duplaix, 2002). The region ranks as the third fastest-growing region with tropical forest cover for gold production after Peru and Indonesia. Major factors promoting the widespread boom in mining are international initiatives, such as the World Bank and the Institute for the Promotion of Investments in Suriname (Hammond et al, 2007).

Although projects that facilitate the expansion of gold-mining in the Guiana Shield are administered by national governments, considerable weight is given to the influence of programs designed at the G7 and G20 level and implemented by international financial institutions that promote foreign direct investment by multinational enterprises. In 2006, the Inter-American Development bank funded the World Wildlife Fund to establish and administer the Suriname Gold Mining Association (WWF, 2006).

Two study sites were identified for comparison: A Test site (Kawemhakan, also known as Anapaikë) that lies between 03°28'49.07"N to 03°23'11.29"N and 54°03'01.99"W to 54°01'21.82"W and a Reference site (Upper Coppename river) that lies between 04°12'54.13"N to 04°09'51.98"N and 56°xx33'26.34"W to 56°37'11.73"W (Figure 1). These two sites were selected to compare forest health at the Test site, where Hg levels from abandoned alluvial gold mines would be elevated, to levels in an undisturbed forest in the Upper Coppename river Reference site.

2.2 Test Site

Kawemhakan, also known as Anapaikë, is an indigenous Wayana village located on the west bank of the Lawa river (Figure 1). Lawa River is a tributary of the Maroni River in the north Amazon Natural Region that flows north to the Atlantic Ocean. The Lawa and Maroni rivers represent provisional borders to some collectives, but to the Wayana they are avenues of transportation, contact zones, and social spaces where conflicting interests meet in a context characterized by highly asymmetrical relations of power (Brightman, 2014).

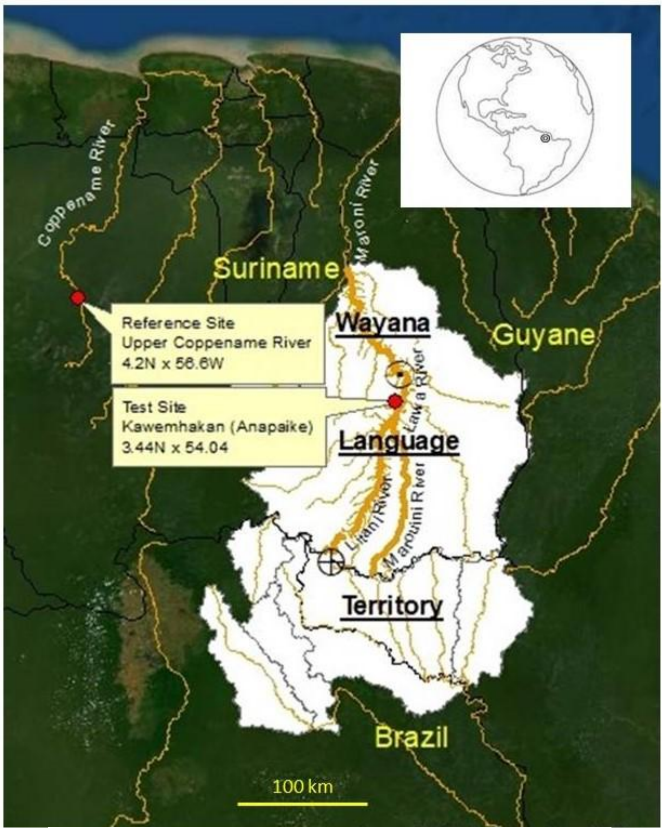

Figure 1.Map showing the Wayana Language Territory, Test site and Reference site.

Although the study region may be described in different ways using different political and historical perspectives, the focus of this study is apolitical and defined as a single Wayana Language Territory. The Wayana Language Territory is a frontier region between Brazil (East Paru River, state of Pará), Suriname (Tapanahoni and Paloemeu rivers) and French Guiana (upper Maroni River, Lawa River and its tributaries and the Tampok and Marouini). The Wayana Language Territory surrounding the Maroni River is an area characterized by multiple frontiers where native Amazonians, tribal people of African descent, migrant Brazilian gold prospectors, and metropolitan state functionaries interact.

2.3 Indigenous People Living in Area Surrounding Test Site

The Wayana are indigenous to the northern Amazon Region, which is now claimed, but has not been ceded, to Suriname, French Guiana and Brazil. The region is significant due to the long-term uncontrolled release of mercury from SSGM that is causing an environmental and public health crisis (de Kom et al, 1998; Gray et al, 2002; Legg et al, 2015, Mohan et al, 2005; Peplow & Augustine, 2010; Peplow & Augustine, 2012; Peplow & Augustine 2015; Veiga, 1997). While this study refers to the people in the region as Wayana, in many villages, Indigenous Peoples from different groups appear to be living peacefully together. In contrast, outside the Wayana Language Territory, the region is divided by long running border disputes making this an area of conflict where there is clear opposition between competing international interests over natural resources led by actors who want to maximize their advantages on a global market (Hammond et al, 2007; Healy et al, 2005; Veiga, 1997). Understanding the environmental health issues in this territory means viewing the conditions from the perspective of the population of indigenous Wayana people who have been living in the area and are being impacted by foreign direct investment projects.

2.4 Reference Site

Upper Coppename River, now part of the Central Suriname Nature Reserve, is considered pristine and virtually undisturbed (Duplaix, 2002) (Figure 1). The biodiversity is exceptionally high with many rare species represented. There is no adverse human activity except for occasional fishing and hunting expeditions by local people. As a result, many large vertebrates are quite common including Giant otters, jaguar, puma, tapir, peccaries, Dwarf caiman, harpy eagle and capybara (US EPA, 2001).

2.5Geospatial Technology and Geographic Information Systems

Imagery and geospatial data collected from space showing details with a resolution of less than 1-meter were used to monitor the effects of mercury from gold mining operations on environmental health.

GIS software tools were used for mapping and analyzing geospatial data which is georeferenced (assigned a specific location on the surface of the Earth). This study used ENVI version 5.6 (64-bit) from L3 Harris to detect geographic patterns in forest health resulting from mercury.

2.6 Normalized Difference Vegetation Index (NDVI)

L3 Harris' ENVI 5.6 (64-bit) software was used to analyze WorldView2 satellite data and calculate the Normalized Difference Vegetation Index (NDVI). NDVI was used as an indicator of forest health and, by extension, was used as a bio-indicator of risk to human health caused by mercury contamination from gold mining operations in the region.

2.7 Satellite Data Specifications:

2.7.1 Test Site (Kawemhakan/Anapaikë)

WorldView-2 High-Resolution, 8-Band Multi-Spectral Imagery
Datum: WGS84
Date Collected: 09-25-15 and 10-09-18
Projection: UTM Zone 21 North
Resolution: 0.58m
Pixel Size: Multispectral - 2 meters, Panchromatic - 0.5 meters

2.7.2Reference Site (Upper Coppename River)

WorldView-2 High-Resolution, 8-Band Multi-Spectral Imagery
Datum: WGS84
Date Collected: 07-30-20
Resolution: 0.58m
Projection: UTM Zone 21 North
Pixel Size: Multispectral - 2 meters, Panchromatic - 0.5 meters

Data Processing Order of Operations

Table 1 gives an overview of the order of operations used starting from high-resolution, 8-band multi-spectral imagery, masking to exclude border and parts of raw data from Atmospheric Correction analysis, and the creation of raster color slices to highlight vegetation index results of Test and Reference area images.

Table 1.Order of operations for use of L3Harris' ENVI 5.6 software for analyzing WorldView2 Data including tools used and critical setpoints.

Order of Operations	Tools Used	Inputs
I) Raw data	Main menu, open data files that support analyses across spatial scales.	WorldView2 Fuzzy Logic knowledge base file with a TIL extension
II) MASK	The Masking tool was used to Exclud clouds, shadows, large black borders from analysis.	Data Ignore Value Enter set to **0** (ENVI assigned a value of **"0"** to masked pixels and displayed them as "No Data")
III) Radiometric Calibration	The Radiometric calibration tool, also known as radiometric correction, was used to convert raw digital image data to a common physical scale based on known reflectance measurements taken from objects on the ground's surface.	On 'Calibration Type' drop down list, selected: Radiance, BSQ, Float, Scale Factor 1.0
IV) Atmospheric Correction	The QUick Atmospheric Correction (QUAC) method was used to 1) corrected for atmospheric effects, and 2) express data in terms of "Apparent Surface Reflectance".	Used default settings
V) Rescale Data	The 'Apply Gain and Offset' tool'was used to rescale data to Top of Atmosphere (TOA) reflectance.	Used a 'gain' value of 0.0001 for each of 8 of 8 bands which was divided into the Quac results to rescale the pixels to floating point values between 0-1.0.
VI) Vegetation Analysis	The Normalized Difference Vegetation Index (NDVI) was used to quantify vegetation health by measuring the difference between near-infrared (which vegetation strongly reflects) and red light (which vegetation absorbs).	Used default settings
VII. Raster Color Slice Analysis	The Raster Color Slices tool was used to select data ranges and colors to highlight areas of intrerest and data features in an image.	Reduced number of raster color slices from 16 to nuber desired to compare NDVI measurements between Test and Reference areas.

Statistical Analysis

NDVI values were scaled between 0 and 1, representing bare soil (0) and 100% cover with maximum canopy assimilation, plant transpiration, and photosynthetic capacity. To determine which range of NDVI values showed the highest level of significant difference between the Reference area and the Test area, raster color slices were configured to display the number of pixels for each NDVI value at both the Test and Reference sites. The color slice table was reduced to a single slice and different 'Slice Min' and 'Slice Max 'values were edited to reflect the upper and lower values of the NDVI ranges being tested. The data were recorded as the percent pixels at each NDVI value out of the total for both Test and Reference sites. If low NDVI values are lower due to a greater frequency of unhealthy trees then pixels with low NDVI values would occur at a greater frequency in the Test area than the Reference area.

Statistical analyses were performed using the Mann-Whitney test and Minitab 20 statistical software to compare the means of two small sets of observations. The basis of the null hypothesis is that, for randomly selected values X and Y from two populations, the probability of X being greater than Y is equal to the probability of Y being greater than X. If the sum of the ranked Test area data is too large then the null hypothesis is rejected and the mean higher incidence of low NDVI values for the Test Area will indicate forest health has been reduced compared to the Reference area. P-value criteria were defined as p-value < 0.0001 (highly significant), p-value < 0.0001 (highly significant), p-value < 0.005 (highly significant), p-value < 0.01 (very significant), p-value < 0.05 (significant), p-value $\geq$ 0.05 (not significant).

3. Results

Mean NDVI Values Test vs Reference

Table 2 shows the overall calculated NDVI values for the Test area (Mean 0.38) were lower than the Reference area (Mean 0.78). Because this study showed that regional-level vegetation index values are lower in the test area contaminated by mercury from SSGMs compared to the pristine reference area, the null hypothesis is rejected.

Table 2. NDVI values for Test Area to Reference Area.

	NDVI	Std Dev	Min.	Max.
Reference	0.78	0.33	-1.00	1.00
Test	0.38	0.45	-1.00	1.00

In Table 3, the results for Data Set 4 showed that the percent pixels for NDVI values between 0.1 and 0.6m was approximately 10 times higher for the Test compared to the Reference areas with a p-value < 0.005 (highly significant). For data set 3, which tested NDVI values between 0.1 and 0.7, the fraction of pixels that recorded NDVI values at that level was significant at less than 3 times higher in the Test Data with a p-value <0.003. The differences between the Test and Reference Data Sets 1, 2, and 5 were not significant.

Table 3.Raster color slice analysis of NDVI data comparing Test area and Reference area results.

	Data Set 1		Data Set 2		Data Set 3		Data Set 4		Data Set 5	
NDVI	Test (Kawemhakan/ Anapaike): % Pixels/NDVI Value	Reference (Upper Coppename River): % Pixels/NDVI Value	Test (Kawemhakan/ Anapaike): % Pixels/NDVI Value	Reference (Upper Coppename River): % Pixels/NDVI Value	Test (Kawemhakan/ Anapaike): % Pixels/NDVI Value	Reference (Upper Coppename River): % Pixels/NDVI Value	Test (Kawemhakan/ Anapaike): % Pixels/NDVI Value	Reference (Upper Coppename River): % Pixels/NDVI Value	Test (Kawemhakan/ Anapaike): % Pixels/NDVI Value	Reference (Upper Coppename River): % Pixels/NDVI Value
0.1			0.17	0.03	0.17	0.03	0.17	0.03		
0.2			0.18	0.03	0.18	0.03	0.18	0.03		
0.3			0.16	0.03	0.16	0.03	0.16	0.03		
0.4			0.18	0.05	0.18	0.05	0.18	0.05		
0.5			0.25	0.06	0.25	0.06	0.25	0.06		
0.6			0.40	0.10	0.40	0.10	0.40	0.10	0.40	0.10
0.7			1.46	0.26	1.46	0.26			1.46	0.26
0.8	11.18	3.75	11.18	3.75	11.18	3.75			11.18	3.75
0.9	84.82	91.45	84.82	91.45						
1	1.21	4.23	1.21	4.23						
CI 95%	P=0.877		P=0.081		P=0.020		P=0.003		P=0.349	
a = 0.05	$\eta_1 - \eta_2 = 0$		$\eta_1 - \eta_2 = 0$		$\eta_1 - \eta_2 > 0$		$\eta_1 - \eta_2 > 0$		$\eta_1 - \eta_2 = 0$	
CI 99%	P=0.877		P=0.081		P=0.020		P=0.003		P=0.349	
a = 0.05	$\eta_1 - \eta_2 = 0$		$\eta_1 - \eta_2 = 0$		$\eta_1 - \eta_2 > 0$		$\eta_1 - \eta_2 > 0$		$\eta_1 - \eta_2 = 0$	

Figure 2 is a graphic visualization comparing NDVI index values for the Test site to the Reference site. The mean NDVI values for the Test and Reference sites suggest a difference in overall forest heath. To determine which NDVI values are associated with forest health and which are associated with unhealthy forests, the NDVI data were divided into five subsets and each subset was analyzed statistically (Figures 3 and 4).

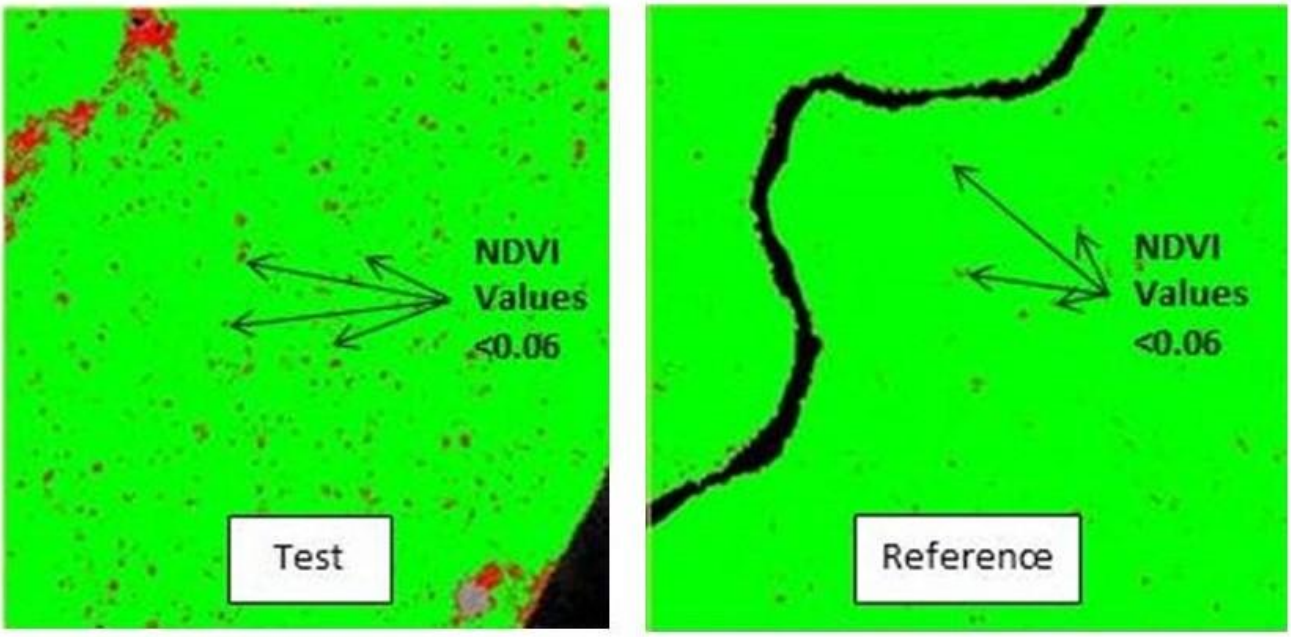

Figure 2. NDVI visualization comparing index values for Test site to Reference site. Dark spots on gray background (b&w) or dark red spots on green background (color) are pixels where NDVI values < 0.6. Image scale was increased creating images 1 km² to increase resolution. The units compared were pixels with low NDVI values (0.1 to 0.6) that equate to unhealthy trees and pixels with high NDVI values (0.7 to 1.0) that equate to healthy trees.

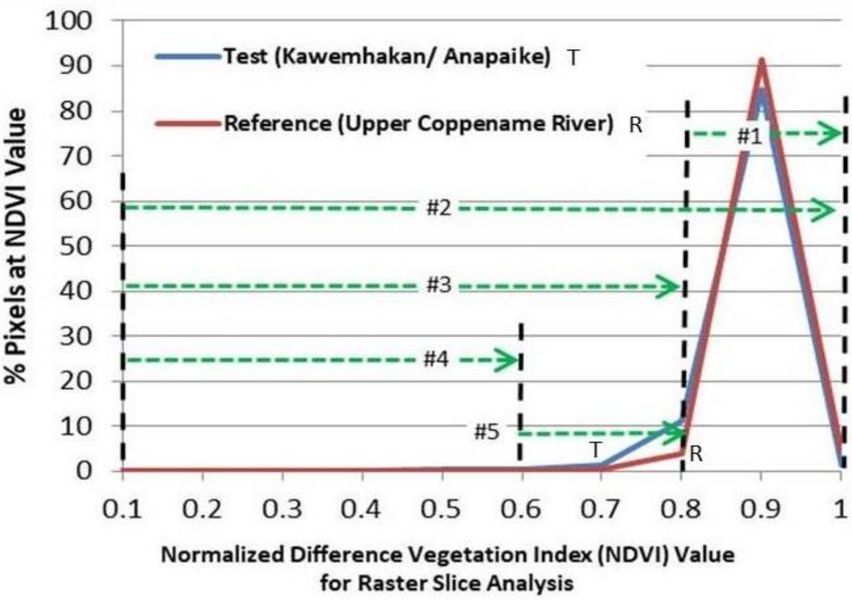

Figure 3. Percent pixels for NDVI valuesbetween 0.1 and 1 in Test site compared to Reference site. Five data ranges are identified for analysis using Mann-Whitney test.

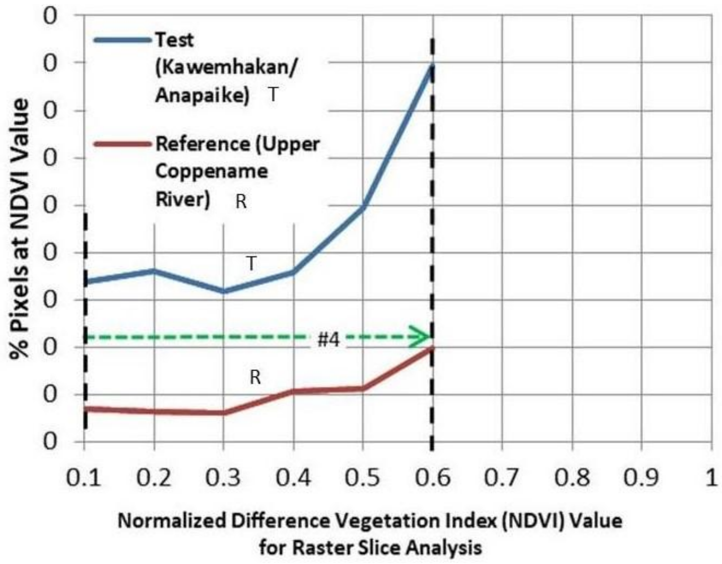

Figure 4. Percent pixels at NDVI values between 0.1 and 0.6 in Test site compared to Reference site.

4. Discussion

Mercury Link to Human and Environmental Health in the Wayana Language Territory

Previous community-Led risk and health assessment studies that combined clinical examinations and scoring of individual performance on a battery of neurological tests in conjunction with hair mercury data, showed that the Wayana people living in areas where there was legacy or ongoing SSGM were at a high lifetime risk of adverse effects from exposure to Hg (Legg et al, 2015, Peplow & Augustine, 2010; Peplow & Augustine, 2012; Peplow & Augustine 2015).

The organic forms of mercury are generally more toxic than the inorganic form to microorganisms, aquatic organisms, plants, birds, terrestrial wildlife and humans. Organic mercury compounds often cause the same level of toxicity at levels 10 times lower than the inorganic form (Ramírez, 2021). The elevated risk of exposure and toxicity to organomecury results from the conversion of inorganic mercury to methylmercury (MeHg), a process that occurs under reducing conditions in saturated soils, wetlands and sediments. The primary route of exposure to humans and wildlife is through the consumption of aquatic organisms including fish. MeHg bioaccumulates so exposure increases with consumption of organisms and it biomagnifies so that concentrations increase with trophic level. The origin of MeHg associated with tree foliage toxicity appears to be largely unknown.

In people, exposure to mercury causes serious health problems and it especially threatens the development of children in utero and early in life. For everybody who is exposed to toxic levels, mercury affects the nervous, digestive and immune systems and has effects on the lungs, kidneys, skin and eyes. For fetuses, infants and children, the primary health effect of MeHg is impaired neurological development (Legg et al, 2015).

Sources of Hg Inputs to Terrestrial Sites

There are three potential sources of Hg in the Test and Reference sites studied: endogenous Hg from geologic sources, atmospheric sources, and from point sources of human activity such as mining. The Test site in this study is a disturbed ecosystem contaminated by mercury discharged from decades of gold mining in the area. Current estimates are that between 80-120 tonnes of mercury are used and released in the Guianas region by the SSGM sector (Gray et al, 2002). The release and dispersion of inorganic Hg is a major health problem in the Wayana Language Territory. It is responsible for serious damage to human health (Legg et al, 2015, Peplow& Augustine, 2010; Peplow & Augustine, 2012; Peplow & Augustine 2015).

MeHg is the most abundant and toxic organic form of the metal. It bioaccumulates in individual organisms and biomagnifies along food chains. In the Bolivian Amazon, of six trophic chains identified the most important was based on periphyton (Molina et al, 2010). All macrophytes were found to transfer MeHg during all seasons, wet and dry.

Mercury Dispersion and Toxicity

The determination of Hg levels in soils of alluvial gold mine spoils and undisturbed forest soils in a region of Peru revealed that the major factors that determine Hg dispersion include vegetation cover, soil organic matter, soil pH and clay particle content (Ramirez et al, 2021; Bishop et al, 2020). A major pathway for the movement of Hg from gold mining sites into aquatic and terrestrial systems where they can bioamplify through trophic structures is the aquatic pathway (Boening, 2000; Driscoll et al, 2013; Frery et al, 2001; Glenn, 2008; Kwon et al, 2015; Roach et al, 2013). The dispersion process occurs due to runoff processes that move Hg-laden sediments downstream from mining operations. A pathway through which Hg is dispersed through the terrestrial ecosystem is when contaminated organisms, plants and animals are used as food. Plants and animals bioaccumulate Hg making contaminated food the dominant pathway for Hg exposure to humans. Several studies have reported the accumulation of mercury in plant roots, as well as its translocation within the plant to other parts including shoots and seeds (Boenig, 2000, Driscoll, 2013). Mercury is biomagnified by wildlife and birds in mining areas accumulating Hg levels that are a threat to their health and reproduction.

Observed Reference and Test Site NDVI Values.

While the Guiana Shield is considered to be one of the largest and still pristine tropical rainforest regions in the world, it also is a region being degraded by mining and mercury pollution (Ouboter, 2012; Legg et al, 2015). Although Duplaix reported in 2002 the Upper Coppename was pristine and virtually undisturbed, a 2021 report by Ouboter et al. presented contradictory evidence of high mercury levels in fish from the Upper Copename River (Ouboter, 2012). In this study, the NDVI value for the Reference site fell within the expected range for a wide range of natural stands of riparian species including Arroweed, Tamarisk, Willow Cottonwood, and Alfalfa. Stands at 100% cover ranged from 0.2 to 0.85 (Sellers, 1985).

Mercury harms plants by impairing the synthesis and metabolism of chlorophyll and inhibition of root shoot growth (Hoff et al, 2002; Sellers, 1985). These effects lead to visible symptoms of plant health, including leaf necrosis, necrotic leaves and leaf tips, and stunted growth. NDVI has been shown to be strongly correlated with nutrient deficiencies that alter foliar intercellular airspace. NDVI is near-linearly related to area-averaged net canopy plant transpiration, carbon assimilation and area-averaged photosynthetic capacity based on light absorption by chlorophyll.

NDVI as an Indicator of Mercury Impacts on Forest Health

Remote sensing tools have been shown to be an important method for detecting vegetation stress and the environmental effects of hydrocarbon contamination caused by the seepage of oil and gas from oil pools and tar deposits in California (Hoff et al, 2002). In mangrove forests impacted by oil production in the Niger Delta, pollution leads to changes in vegetation density and distribution of plants, as well as leaf deformation and defoliation where remote sensing of changes in Mangrove leaf spectral reflectance made it possible to use vegetation indices to diagnose the effects of oil spills. In this study, remote sensing was a noninvasive, cost-effective, socially and environmentally friendly method for measuring bioindicators of Hg pollution at large scales.

NDVI has been used previously to complete an ecological impact assessment of heavy metal pollution and measure different ecological risk levels depending on the relative proximity to human activity (Glenn, 2008). Using L3Harris ENVI software to analyze WordView2 satellite data, low NDVI values were shown to correlate with high heavy metal concentrations in the soil and elevated ecological risk assessment index values. Results similar to our study were obtained where low vegetation index values near the source of heavy metal contamination were obtained and high index values reflecting low vegetation stress were seen at more distant locations. In the Netherlands, grassland spectral signatures showed a negative correlation with heavy metal levels in floodplain soils (van der Meer, 2002).

Regional-Scale Monitoring of Hg Contamination for Health and Human Rights Impacts

Mercury is a potentially harmful trace element and one of theWorld Health Organization's foremost chemicals of concern (WHO, 2005). It is widespread in the environment, bioaccumulates in the food chain, and it is toxic to the central and peripheral nervous system of humans even at low levels of exposure. The principle target organs for the toxic effects of mercury are the central nervous system (CNS), the brain, and the kidneys.

Like many other toxic metals, the health risks of mercury, overall, are greater for fetuses and young children than for adults. Mercury can produce harmful effects on the nervous, digestive, and immune systems as well as the lungs and kidneys and may be fatal. Between 2005 and 2012, Peplow and Augustine showed mercury exposure was also occurring in the Test site at levels causing adverse neurological effects among the indigenous Wayana people who are highly dependent on fish in their diet (Dolbec et al, 2001; Legg et al, 2015, Peplow& Augustine, 2010; Peplow & Augustine, 2012; Peplow & Augustine 2015).

Acknowledging the extreme nature of the Wayana health crisis, global health practitioners are compelled to address the large-scale social forces at work. While the attention paid to technological and behavioral solutions at the individual level yields important health outcomes, attention should also be paid to structural causes of disease, disability and premature death (Peplow & Augustine, 2017).

Indeed, indigenous people living in the Wayana Language Territory who consume fish regularly and in large quantities (200-500 g/individual/day) for cultural and or socio-economic reasons, exhibit high consumption levels in both adults and children (Frery et al, 2001). Significant relationships were found between consumption levels and the presence of neurological and behavioral deficits in children (Heemskerk et al, 2007). These results are in agreement with other studies from the Brazilian Amazon basin (Boudou, 2005; Cordier et al, 2002; Dolbec et al, 2001; Frery et al, 2001; Grandjean et al, 1999; Label et al, 1996; Legg et al, 2015, Peplow & Augustine, 2010; Peplow & Augustine, 2012; Peplow & Augustine 2015; Peplow & Augustine, 2017). Nevertheless, mercury contamination in the fish eaten by people in the Wayana Language Territory was markedly lower than that measured downstream of the Petit-Saut hydro-electric reservoir: The average ratios were between 3 and 10 depending on the species considered. Hence, management policies should give careful consideration to all human activities likely to create environments favorable to Hg methylation.

Integrating Public Health and Economics.

In general, global health relies on intervention plans that embody a collaborative approach. An example of this approach is best represented in WHO's Health in All Policies (HiAP) framework for Country Action (WHO, 2005). The intention of HiAP is to integrate and articulate health considerations into policy making across sectors to improve the health of all communities and people. HiAP assumes that health is created by a multitude of factors beyond healthcare and, in many cases, beyond the scope of traditional public health activities. HiAP would be the correct approach to take in the Wayana Language Territory where Indigenous Peoples seek rights to the lands they traditionally live on, use for their subsistence, and consider as their customary territory. International law, however, does not allow for public consultations in the context of development projects (Peplow & Augustine, 2017).

A 2017 study presented a policy-oriented causal diagram that linked impaired health from exposure of the people in this region to Hg from internationally financed economic development projects and the role intergovernmental forums have played within the global economy (Peplow & Augustine, 2017). Specifically, the health and well-being of indigenous people in the Wayana Languange Territory could be understood in terms of the foreign investment programs and economic development policies traceable to the Inter-American Development Bank's Suriname Land Management Project (SLMP) and The Initiative for the Integration of the Regional Infrastructure of South America (*IIRSA*).

An approach that integrates economic development and human health would require a collaborative and multi-sector approach that integrates the goals of international financial institutions and the goals of global health. Global health practitioners seeking public policy solutions to health issues that accompany the extraction of natural resources from land held by indigenous people face a dilemma when, all other things being equal, they assume it is better to limit economic development to protect human life (MacKinnon, 1986).

On one hand, if the risks to human life and health are seemingly limitless, then the cost to society would also be limitless. To reduce risk to citizens, policy makers turn to economists to compare the economic costs of a global health solution to various measures of the economic value of life (MacKinnon, 1986). On the other hand, many people believe that although other things may properly be given an economic value, indigenous life may not when it is measured solely in economic terms and the contribution the population is making to the economy of an external culture. The legal framework that devalues indigenous life is discernible from a close reading of the United States Supreme Court case of Johnson v. McIntosh (Martin 1846; Miller, 1842). Under an element of international law referred to as *Terra Nullius*, which has been adopted into the civil law systems of many western nations, lands not occupied by any person or nation used in a manner that Euro-American legal systems have approved are considered empty and vacant or "terra nullius" rendering the lives and life-years-lost of the indigenous people living there without value and equal to zero (Miller, 2019).

5. Conclusion

This study shows it is possible to consider risk assessment across a range of scales. Regional-level vegetation index values indicate remote sensing can be a useful method for measuring mercury contamination impacts at scales that support the supranational policy development processes that address health issues caused by factors that lie outside the health sector and that are socially, economically and politically formed.

When direct observation is not possible due to limited access during global pandemics, limited time and money, or the potential scope of the suspected global health problem, large-scale remote sensing methods can provide an alternative to overcome the constraints and provide quick, non-invasive and quantitative analyses of environmental health issues.

While international financial institutions acknowledges that addressing the environmental, economic, and social components of ill-health contributes to human security, technological advancements have changed the face of the world of finance, the potential to address global health issues at the policy level is declining as the influence of globalized transactions of international financial institutions dominate international relations. While monitoring environmental health risk at the same level that economic development policies are developed becomes a prerequisite for addressing the structural causes of global health issues and for tracking progress towards health and human rights goals at the supranational level.

Abbreviations

SSGM:	Small-Scale Gold Mine
NDVI:	Normalized Difference Vegetation Index
Hg:	Mercury
MeHg:	Methylmercury
SLMP:	Inter-American Development Bank's Suriname Land Management Project
***IIRSA*:**	Integration of the Regional Infrastructure of South America

Declarations

Ethics Approval and Consent to Participate

Not Applicable

Funding

Financial support for this University of Washington project was provided through an award from the Suriname Indigenous Health Fund, fiscal sponsor the Alliance for Global Justice (Form 990, https://www.dropbox.com/s/6xkuk55smf1u8qq/RKW40052_2019_GovernmentCopyTaxReturn.pdf?dl=0).

Competing Interests

The author declares he has no competing interests

Acknowledgements

The Author wishes to thank the people of the Wayana Language Territory who provided the input that made possible the creation of the map (Figure 1) that was the basis for the study.

Author Information

Daniel Peplow is Clinical Assistant Professor in the Department of Health Services, University of Washington, Seattle, Washington, USA. He is a former advisor to the American Embassy in Paramaribo and since 2004 has been a member of an informal public private partnership (PPP) addressing global health issues in the trans-border region between Suriname, French Guiana and Brazil.

References

Barbieri, FL., Gardon J. (2009). Hair mercury levels in Amazonian populations: spatial distribution and trends. International Journal of Health Geographics. Available: http://www.ij-healthgeographics.com/content/8/71(Accessed 21 July 2021).

Bishop, K., Shanly, J.B., Riscassi, A. (2020). Recent advances in understanding and measurement of mercury in the environment: Terrestrial Hg cycling. Science of the Total Enviornment. 721:137-647.

Boening, D.W. (2000). Ecological effects, transport, and fate of mercury: a general review. Chemosphere, 40:1335-1351.

Boudou, A., Maury-Brachet, Coquer, M., Durrieu, G., Cossa, D. (2005).Synergic effect of gold mining and damming on mercury contamination in fish. Environmental Science and Technology*,* 39(8): 2448-2454.

Brightman, M. (2014). Securitization, alterity, and the state Human (in)security on an Amazonian Frontier. *RegCohes*, 4(3):17-38.

Cordier, S., Garel, M.,Mandereau, L., Morcel, H., Doineau, P., Gosme-Seguret, S., Josse, D., White, R.,Amiel-Tison, C., (2002). Neurodevelopmental investigations among methylmercury-exposed children in French Guiana.Environ.Res. 89,1-11.

deKom, F.M.J., et al. (1998). Mercury Exposure of Maroon Workers in the Small Scale Gold Mining in Surinam.Environmental Research, 77(2):91-97.

Dolbec, J., Mergler, D., Larribe, F., Roulet, M., Lebel, J., Lucotte,M., (2001). Sequential analysis of hair mercury levels in relation to fish diet of an amazonian population, Brazil. Sci. Total Environ, 271,87-97.

Driscoll, C.,T., Mason, R. P, Chan, H., M., Jacob, D. J., Pirrone, N. (2013). Mercury as a global pollutant: sources, pathways, and effects. Environmental Science and Technology, 47:4967-4983.

Dunagan, C., Gilmore, M.S., Varekamp, J. C., (2007). Effects of mercury on visible/near infrared reflectance spectra of mustard spinach plants (Brassica rapa P.). Environmental Pollution, 148:301-311.

Duplaix, N. (2015).Giant otter Final Report: Rapid River Bio-Assesment in Suriname and Guyana 2002: Upper Coppename River (Central Suriname Nature Reserve), Pages 48-50 of 120. All content following this page was uploaded by Nicole Duplaix on 19 February. Last viewed 21 June 2021: https://www.researchgate.net/publication/272492103_Giant_otter_Final_Report_Rapid_River_Bio-Assesment_in_Suriname_and_Guyana_2002.

Frery, N., Maury-Brachet, R., Maillot, E., Deheeger, M., DeMerona, B., Boudou, A. (2001). Gold-mining activities and mercury contamination of native Amerindian communities in French Guiana: key role of fish in dietary uptake. Environ Health Perspect, 109(50):449–56.32.

Glenn, E. (2008). Relationship between remotely-sensed vegetation indices, canopy attributes, and plant physiological processes: what vegetation indices can and cannot tell us about the landscape. Sensors, 8:2136-2160.

Grandjean, P., White, R. F., Nielsen, A., Cleary, D., de Oliveira Santos, E. C. (1999). Methylmercury neurotoxicity in Amazonian children downstream from goldmining. Environ. Health Perspect, 107, 587-591.

Gray, J.E., Labson, V.F., Weaver, J.N., and Krab-benhoft, D. P., (2002). Mercury and methyl-mercury contamination related to artisanal gold mining, Suriname. Geophysical Research Letters, 29(23):201-4.

Goodwin, A. (1996). Principles of Precambrian Geology. Academic Press, New York, 319 pp.

Hammond, D., Gond, V., et al. (2007). Causes and consequences of a tropical forest gold rush in the Guiana Shield, South America.Ambio, 36(8):661-670.

Healy, C., Heemskerk, M., Fontaine, M., Viera, R. (2005). Situation Analysis of the Small-Scale Gold Mining in Suriname: Reforming the Subsector to Promote Sound Management. Document of the World Wildlife Fund. 2005. http://awsassets.panda.org/downloads/2005_situation_analysis_small_scale__mining.pdf. Accessed 31 July 2021.

Heemskerk, M., Delvoye, K., Noordam, D., Teunissen, P. (2007).Wayana Baseline Study, Amazon Conservation Team, Paramaribo, Suriname.http://www.act-suriname.org/wp-content/uploads/2015/05/Wayana-Baseline-Study_2007.pdf (Accessed 29 July 2021).

Hoff, R., Hensel, P., Profritt, E., Delgado, P., Shigenaka, G., Yender, R., and Mearns, A. J. (2002).Oil Spills in Mangroves. Planning & Response Considerations. National Oceanic and Atmospheric Administration (NOAA_).EUA.Technical Report. https://www.google.com/books/edition/Oil_Spills_ in_Mangroves/ 49HC-gYagj8C?hl=en&gbpv=1&printsec=frontcover. Accessed 8 July 2021.

Kwon, S. Y., Blum, J. D., (2015). Nadelhoffer KJ, Dconch JT, Tsui MT. Isotopic study of mercury sources ad transfer between a freshwater lake and adjacent forest food web. Science of the Total Environment, 532:220-229.

Lebel, J., Mergler, D., Lucotte, M., Amorim, J., Dolbec, D., Miranda, G., Arantes, I., Rheault, I., Pichet, P. (1996). Evidence of earlynervous system dysfunction in Amazonian populationsexposedto low levels of methylmercury. Neurotoxicology, 17, 157-168.

Legg, E. D., Ouboter, P. E., Wright, M. A. P, (2015). Small-Scale Gold Mining related to Mercury Contamination in the Guianas: A Review. Prepared or WWF Guianas. Affiliations: 1. Halcyon Medical Writing; 2. Anton de KomUniversiteit van Suriname; 3. WWF Guianas.https://wwfeu.awsassets. panda.org/downloads/ mercury_contamination_in_the_guianas__2015.pdf. Accessed 21 July 2021.

MacKinn,on B. (1986). Pricing human life. Science, Technology, & Human Values, 11(2);29-39.

Miller, (1842). Native America, supra note 2, at 21–22, 24, 26–28, 56. See also Johnson, 21 U.S. at 595–97 (discussing the Crown's ownership of, and right to grant titles to, the vacant lands in America); Martin v. Waddell, 41 U.S. 367, 409 (1842) ("The territory occupied was disposed of by the governments of Europe at their pleasure, as if it had been found without inhabitants.").

Miller, R. (2019). The Doctrine of Discovery: The International Law of Colonialism. The Indigenous People's Journal of Law, Culture and Resistance, 5(1):35-42.

Mohan, S., Tiller, M., van der Voet, G., Kanhai, H. (2005). Mercury exposure of mothers and newborns in Surinam: a pilot study. Clinical Toxicol, 43(2):101–4.

Molina, C. I., Gibon, F. M., Duprey, F. M., Dominquez, E., Guimarães, R. M. (2010). Transfer of mercury and methylmercury along macroinvertebrate food chains in a floodplain lake of the Beni River, Bolivian Amazonia. Science of the Total Environment, 408:3382-3391.

Ouboter, P. E., et al. (2012). Mercury Levels in Pristine and Gold Mining Impacted Aquatic Ecosystems of Suriname, South America. ABIO, 41:873–882.

Peplow, D, & Edmonds, R. L., (2005). The effects of mine waste contamination at multiple levels of biological organization. *Ecological Engineering* 24:101–119.

Peplow, D. & Augustine, S.,(2007). Community-directed risk assessment of mercury exposure from gold mining in Suriname. *Pan American Journal of Public Health*.22(3):202-210.

Peplow, D. & Augustine, S. (2012). Community-led assessment of risk from exposure to mercury by native Amerindian Wayana in Southeast Suriname. *Journal of Environmental and Public Health*.2012:1-10.

Peplow D. & Augustine, S, (2015). Neurological abnormalities in a mercury exposed population among indigenous Wayana in Southeast Suriname. *Environ Sci Process Impacts*,16(10):2415-22.

Peplow, D. & Augustine, S, (2017). Intervention Mapping to Address Social and Economic Factors Impacting Indigenous People's Health in Suriname's Interior Region. *Globalization and Health*. 2017:13:11.

Pirrone, N., Mason, R. (2009). Mercury Fate and Transport in the Global Atmosphere: Emissions, Measurements and Models. Springer, London New York, pp 143-150.

Ramírez, M. G. V., et al. (2021). Mercury in soils impacted by alluvial gold mining in the Peruvian Amazon. Journal of Environmental Management. 288:112364.

Roach, K. A., Jacobson, N. F., Fiorello, C. V., Stronza, A. (2013).Gold mining and mercury bioaccumulation in a floodplain lake and main channel of the Tambopata River, Perú. Journal of Environmental Protection, 4:51-60.

Sellers, P. (1985).Canopy reflectance, photosynthesis and transpiration. International Journal of Remote Sensing, 6:1335-1372.

Street, I., Palmberg, J., Artigas, J. C., Grubb, M. (2013). Gold demand trends: full year 2012. World Gold Council, London, United Kingdom. https://www.exchangetradedgold.com/ media/ETG /file/ GDT_Q4_pdf. Accessed 21 July 2021).

Sullivan, A., Robertson, L., Baca, A. (2021). Report on the Republic of Suriname to the 39th Session of the Universal Periodic Review, Human Rights Council, Oct–Nov 2021. University of Oklahoma College of Law, [Available Online 13 November 2021].

Telmer, K.H., Veiga, M. M. (2009). World emissions of mercury from artisanal and small scale gold mining. In: Mason R., Pirrone N. (eds) Mercury Fate and Transport in the Global Atmosphere. Springer, Boston, MA. https://doi.org/10.1007/978-0-387-93958-2_6 Accessed 21 July 2021.

United States v. Rogers, 45 U.S. 567, 572 (1846) ("the whole continent was divided and [parceled out], and granted by the governments of Europe as if it had been vacant and unoccupied land").

van der Meer F, van Dijk P, van der Werff H, Yang H. Remote Sensing and Petroleum Seepage: A Review and Case Study. Terra Nova.2002; 14:1-17.

Veiga, M.M. (1997). Artisanal Gold Mining Activities in Suriname. United Nations Industrial Development Organization.http://artisanalmining.org/Repository/02/The_GMP_Files/raw%20files%20-%20globalmercuryproject.org/LatAmerica/Suriname/UNIDO%20Veiga%20Suriname1997-nomap.pdf. Accessed 26 May 2021.

WHO, (2005).Policy Paper: Mercury in Health Care. Geneva, World Health Organization (WHO/SDE/WSH/05.08).http://www.who.int/water_sanitation_health/ medicalwaste/mercury/en/index.html.

World Wildlife Fund (WWF), (2006). WWF to Train Gold Miners in Suriname in Sustainable Production. Document of the World Wildlife Fund.https://wwf.panda.org/wwf_news/?56360/WWF-to-train-gold-miners-in-Suriname-in-sustainable-production. Accessed 31 July 2021.