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Disarmament Is the New War, Gold Is the New Opium, and Ecohealth Is the Historic Victim

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ABSTRACT: In Colombia, the convergence of drug trafficking, illegal armed groups, and gold production and trade threatens peace and stability in the post-FARC (Revolutionary Armed Forces of Colombia) era, as had the narcotics trade previously. Armed groups and criminal organizations have increased and consolidated their influence over illegal mining and may be diverting US$5 billion from Colombia's annual economy. As of 2014, 46% of the total area (78 939 ha) exploited for alluvial gold was in the Afro-Colombian Pacific States, in which unregulated mining was the main driver of deforestation. The informal job market represents 49% of the workforce and absent other economic alternatives, this workforce of ex-guerrillas, organized crime groups and corrupt officials will sustain the black markets that permeate gold mining. Human health consequences of unregulated gold mining are largely unrecognized, but include the spread of malaria and other insect-borne diseases, and we suggest diseases such as babesiosis.

KEYWORDS: Mining, gold, alluvial, malaria, babesiosis, Colombia

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Introduction

Previously, we examined the real cost of "mining as the 'locomotive' of the Colombian economy."[1] The focus was on the consequences that the open economic mining policies of Colombia's governments of the last 2 decades had on internal forced displacement; persecution of social leaders; opening of protected, public, and Amerindian territories to legal and illegal gold mining; increased imports of elemental mercury and sodium cyanide for gold extraction; and exponential expansion of contamination. We now examine aspects of the costs of mining to ecological and social systems, which are considered together as "ecohealth." We begin with an overview and a definition of ecohealth that encompasses various themes of this article:

> Ecosystem approaches to health (or ecohealth research) formally connect ideas of environmental and social determinants of health with those of ecology and systems thinking in an action-research framework applied mostly within a context of social and economic development. Ecosystem approaches to health focus on the interactions between the ecological and socio-economic dimensions of a given situation, and their influence on human health, as well as how people use or impact ecosystems, the implications for the quality of ecosystems, the provision of ecosystem services, and sustainability.[2]

Waltner-Toews and Kay[3] depicted the ecosystem and societal components as "stacked decks" interacting with each other and the overall environment. Paraphrasing, each deck is made up of layers. In their depiction, the layers of the local landscape include the species that define an ecological community and the aggregate of the ecological communities that define the local landscape. Their societal layers include the family, neighborhood, and municipality. Their connection between the decks with each other and with their interaction with the physical environment is the individual.

In our depiction (Figure 1), layers in the societal stack involve criminal and warring rebel factions controlling illegal (and legal) gold miners; politicians enabling international mining companies without requiring due compensation to Colombia's government; adversity in indigenous populations and local communities; and accumulation and control of wealth by a few compared with the hardship of artisanal gold miners, their families and neighbors. To summarize the societal stack, we quote Abraham Lincoln: "Nearly all men can stand adversity, but if you want to test a man's character, give him power." Layers in the ecological stack include physical loss and persistent poisoning of terrestrial and aquatic habitats; species extirpation, emigration, and invasion; unsustainable changes in the behavior and niche roles of species and communities; unremediable destruction of biological support systems that include soil bacteria, fertility, depth, mineral composition, and water retention; and contagion and spread of disease within and between species involving insect vectors, mammalian hosts, and humans. To summarize the ecological layer, we paraphrase the Colombia Attorney General[4]: "I am Nature, I am a subject of rights." The arrows identify the interrelations of variables in a system (causal loops). A detailed model of the causal loops in the mining sector layer "can be calibrated to test a set of alternative scenarios for the future of mining in Colombia."[5] A model of the interaction of the ecological, mining, and health layers examined the relationship between area (hectares) of

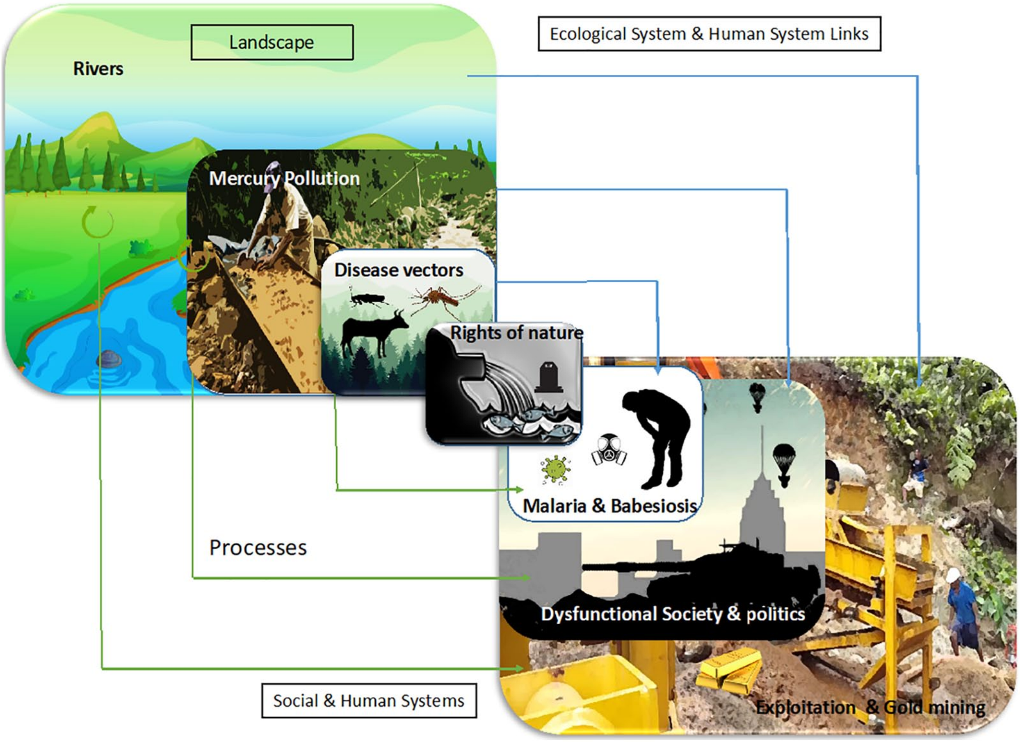

Figure 1. "Ecohealth" depicted as selected layers of the "stacked decks" of the ecological and societal domains affected by war, gold mining, and disease (by the authors, after Waltner-Toews and Kay[3]).

illegal mines (from satellite data) and the numbers of malaria cases in municipal governmental health reports.[6]

Both authors have contributed to both decks as teachers, ecosystem toxicologists, and interfacing with farmers, government, and the public. For the ecosystem deck, D.J.S. has contributed to development of "ecosystem health" as a medical science and illustrated a rigorous, formal mathematical procedure for using ecosystem "patient" history data (anamnesis) to perform the deductive process of health determination. Deductive elimination of spurious signs and diseases will imply the types of detailed studies that are required to identify the combination of diseases (disease complex) occurring in a given ecological system.[7] At the interface of the decks, D.V. studies *Babesia* ("piroplasm"), a malaria-like parasite that infects red blood cells, and implements on-farm methods for the prevention and treatment of tick cattle fever (babesiosis).

Several decades of legislative enactments had promoted large-scale mining as the "engine for growth and development of the country."[1] However, and as will be further elaborated, the lack of environmental protection by the government was brought to light by the Colombia Attorney General.[4] Within our aforementioned framework, we examine some aspects of prolonged insurgency, drug and gold cartels, and politics (section "Initial Ecological System Anamnesis ("Patient History"): Gold Mining in the Post-Revolutionary Conflict Context") on Colombia's ecological habitats (section "Ecological System Diagnostic Testing Tiers and Test Batteries: Environmental Effects in Gold Mining Territories in and out of Protected Areas"), spreading of mercury (section "Mercury Contamination Effects on Community Health"), and stimulation of vector-borne and other mammalian diseases (sections "Mercury Contamination Effects on Community Health" and "Malaria in Gold Mining Areas"). Section titles follow Gastó[8] and Schaeffer.[7]

Initial Ecological System Anamnesis ("Patient History"): Gold Mining in the Post-Revolutionary Conflict Context

On paper, Colombia exports more gold than it produces. Colombia is the fourth largest gold producer in Latin America by volume, and about 80% (54/68 tons) of the gold produced in 2016 was mined and sold illegally by transnational organizations or artisanal small-scale miners who did not have a mining title.[9] Several investigations revealed that most of this outlaw gold was exported to the United States.[10-12] In 2015, the Comptroller General of the Republic (Edgardo Maya Villazón) reported that illegal miners produce close to 80% of Colombia's gold.[13]

Illegal gold mining is now the main source of income for criminal organizations, surpassing cocaine trafficking. In 2015, the Colombian Ministry of Finance estimated that illegal mining could generate as much as US$5 billion in revenues per year.[14] Unlike cocaine, in which every step of the chain is illicit (from growing, processing, to moving and selling it), whether legally or illegally mined, "gold is gold" and is a legal product. A recent review examined the political economy of gold mining and armed conflict in Colombia since 2000.[15] Our focus in the sequel is at the confluence of the health of social systems and

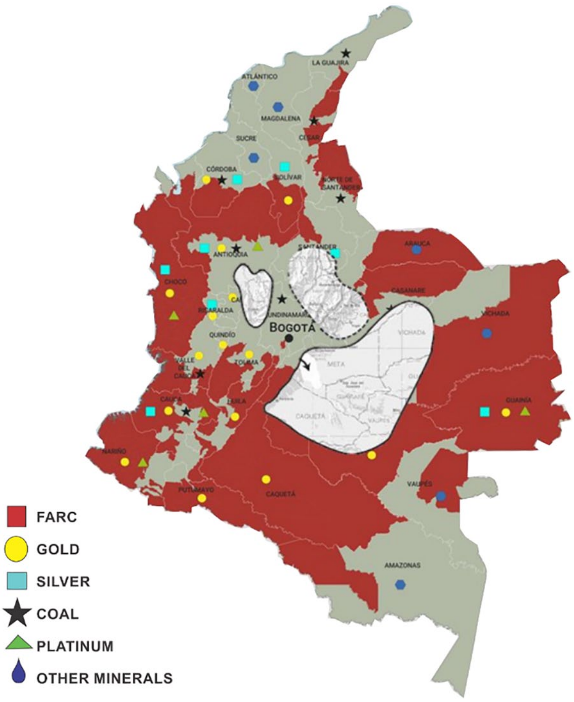

Figure 2. Former areas occupied by FARC and mineral exploitation. Today, links between gold and armed groups (demobilized FARC units, ELN, and criminal organizations) remain high in Antioquia, Choco, and Cauca. ELN indicates National Liberation Army of Colombia, FARC, Revolutionary Armed Forces of Colombia.
Source: Adapted by the authors from Colombian Mining Information System (SIMCO).

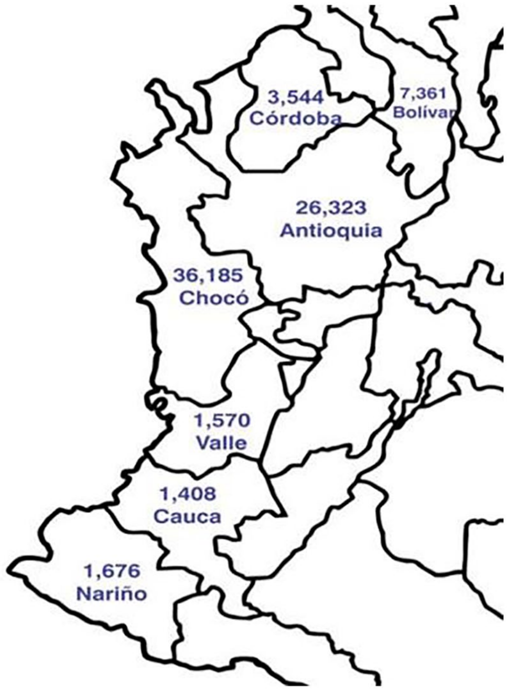

Figure 3. Hectares of land affected by alluvial gold exploitation per States of Colombia as of 2014. Notice that 79% of the mined area is concentrated in the states of Chocó and Antioquia.[16]

the health of ecosystems in the "stacked decks" conceptualization of ecohealth in Figure 1 in the departments of Colombia identified in Figures 2 and 3.

The peace accords with the Revolutionary Armed Forces of Colombia (FARC) was intended to end a 5-decade civil war by a group that controlled 170 million acres of coca and had displaced more than 6 million people. Rather than reintegrating into society, many FARC groups joined organizations that illegally control gold mining.[17] By late 2012, Colombia's Attorney General's Office estimated that, out of the 489 municipalities with illegal mining, 40% had the presence of the FARC, National Liberation Army of Colombia (ELN), or other armed groups.[14] The FARC were thought to have presence in more than 100 municipalities with illegal mining (Figure 2). Before demobilization (about 6000 troops and 5000-7000 militias), the FARC's income from extortion of illegal miners in the Department of Antioquia was as high as US$2 million/month,[18] serving to diversify its sources of income from activities related to illegal drug production and trafficking, extortion of banking, transport, electricity, and oil companies, in addition to more traditional sources like kidnapping and cattle theft. The Organisation for Economic Co-operation and Development (OECD)[19] reported that some criminal networks in South West Colombia involved "small-scale miners and prospectors, national trading companies, local municipal authorities, former civil servants from the National Mining Agency [SIMCO], corrupt law enforcement agents, and illegal armed groups."

Although the Colombian authorities are now managing illegal gold mining using strategies similar to narcotics, mining is lucrative, hard to prosecute, and simplifies moving and laundering money.[20] The 2001 Mining Code established that "the right to explore and exploit mines that are state property can only be granted through a concession title registered in the National Mining Registry" (Law 685, art. 14, 2001). However, exceptions are used by unregistered actors to violate environmental legislation such as the ban on using mercury by 2018 (Law 1658 of July 15, 2013). In particular, traditional small-scale mining reserve areas and *barequeros* (miners who employ only manual means like panning) who are registered in their municipality's mayor's office can produce gold without a title (Decrees 276 of February 17, 2015; 0933 of May 9, 2013; and 2390 of October 24, 2002). However, about a quarter of these 85 000 registered *barequeros* employ unpermitted bulldozers and dredges and about half employ unpermitted generators and pumps.[21] These exceptions to registration are the loophole used by most of the unlicensed mining activities to pass ill-gotten gold into legal bullion of central banks and jewelry.[11,12] Decree 2637 (December 2012) requires all gold sold by marketers to come from miners holding titles. However, the mechanism of *barequeros*, which legalized participation of small-scale miners in the national gold trade, is used to launder illicit gold.[22] In many cases, the *barequeros* were not aware that a merchant was doing business in their names.

In mid-2015, the government created a new Police Directorate and a specialized Army Brigade of more than 1000 men combined that were dedicated to fight illegal mining.[22] Authorities also introduced normative changes that allow law enforcement agencies to better deter armed groups from controlling illegal miners. These new efforts to tackle the criminal influence over mines have started yielding results. For example, in January 2018, the government launched the Joint Task Force for Stabilization and Consolidation, "Hércules," comprising a 9800-strong division of law enforcement and military forces, to reestablish the Social Rule of Law, create border stability, protect the population, and maintain sovereignty in the Department of Nariño. The effectiveness of the task force is evidenced by its drug seizures.[23-25] The Twenty-Third National Army Brigade, enforcing the Victoria Plus Stabilization and Consolidation Plan after an alleged attack on the electoral system in the Department of Nariño by ELN guerrillas or FARC dissidents, captured and destroyed stockpiled explosives.[26] Dismantling of these criminal networks by the government revealed that the organizations have *resource portfolios* or can shift benefits interchangeably between different resources. Unfortunately, public attention to drugs dominated exposure to the extent to which illegal organizations permeate other economic spheres. Studies that have compared drug trade with illegal gold mining have even concluded that gold mining might be as pervasive in causing violence, criminality, and links to armed conflict.[20]

Ecological System Diagnostic Testing Tiers and Test Batteries: Environmental Effects in Gold Mining Territories in and out of Protected Areas

Diagnostic tests of stressed ecological systems can be organized into batteries, and batteries into tiers of response variables, namely, nutrient pool in systems, primary productivity, size distributions, species diversity, and system retrogression. Within a tier, batteries characterize exposure, response, recovery, and anthropogenic stress.[7]

Articles 79 and 80 of the 1991 Colombian Constitution establish the principles on which to base protection of the diversity and integrity of the environment, and preservation of areas of special ecological importance. Notwithstanding, the reality of degradation from mining is detached from the goals of protection and preservation. Mining activities perpetually affect the national heritage from indigenous cultures, the physical environment (water, air, sediment and soil chemistry, microclimate, landscape), and biological webs. For example, a 2005 fact sheet from the US Geological Survey starts: "Mercury contamination from historical gold mines [in California] represents a potential risk to human health and the environment."[27] Air pollution from Roman era mining and smelting has been documented using lead and antimony concentrations in basal ice dated to −5000 ± 600 cal years BP using radiocarbon dating of particulate organic carbon in the ice.[28]

The magnitudes of adverse environmental effects from gold mining are speculative because of a lack of rigorous studies of ecosystem health.[8,7] and also the discord between the numbers of actual mining operations and those officially registered. For example, between 2010 and 2011, the Colombian General Comptroller's Office reported the absence of a reliable mining cadaster: 12 977 mining titles were issued although only 6653 were officially reported. A United Nations Office on Drugs and Crime report estimated that alluvial gold exploitation in 2014 was 78 939 ha and was a main driver of deforestation in Colombia.[16] About half of the territory was in the Chocó Department, which encompasses biodiverse and highly valued ecosystems and includes Forest Reserve areas within the National System of Protected Areas (*Sistema Nacional de Áreas Protegidas* [SINAP]). The estimates do not include the surface areas of altered river courses and dredged riverbeds, which are more difficult to estimate regarding surface area impacted, and for which both mercury and cyanide are typically employed to remove gold from river sediments. The bulk of tailings from such informal mining are discharged directly into the Colombian rivers,[29] completely changing their natural hydromorphology and increasing the load of sediments downstream. Biological communities that require clear water may disappear due to water contaminated with suspended solids and sediment pollution. Gold production parallels the imports of elemental mercury and cyanide in the country, and on a per-capita basis Colombia is the most polluted country worldwide.[1] As of 2014, 78 939 ha of land was affected by alluvial gold mining (Figure 3). A second United Nations Office on Drugs and Crime (UNODC) report, comparing 2016 with 2014, revealed an increase of 6% (4681 ha) and the dynamics of the territories affected into stable areas, new areas, expanding areas, and areas with indicators of pastures and grasslands.[30,31]

Colombia hosts 59 designated protected areas in the National System of Protective Areas (SINAP). Sistema Nacional de Áreas Protegidas was established through Law 165 of 1994, when Colombia signed the Convention on Biological Diversity that was conceived as a United Nations Environmental Program (UNEP). As of 2018, these 59 protected areas covered 169 545 km^2 (65 462 mi^2; about 14% of Colombia's area). However, half of these areas are in a critical state of deterioration,[32] and according to the UICN methodology of the Red List of Ecosystems out of 81 assessed ecosystems, 46% were classified within the status of endangered or critically endangered.[33] Approximately 47% of Colombia's illegal alluvial gold exploitation occurs on such protected lands.[30,31] Alluvial gold extraction is taking place in at least 5 national parks and in 9 others it is recorded in buffer zones.[16,31] The studies also show the vulnerability of the parks by being directly connected through some rivers or its tributaries to areas of alluvial gold mining. For example, in cases like the Ayapel Wetland Complex, which constitutes an area of great ecological interest because of its aquatic and terrestrial biotopes, about 92% of its hydrographic basin has been impacted by alluvial gold mining. The discord between the National Mining Agency and the Ministry of the Environment is notorious in that between 16%

and 32% of the land titled for mining in 2010 overlapped with protected areas.[34] This is exemplified by the number of legal mines that have been intervened by the Prosecution Unit Crimes created in 2011 (*vide supra*).

In 2016, Colombia's Constitutional Court ruled (Sentence T-622 of 2016) that Federal authorities neglected to protect one of the most contaminated and long rivers in the country, the Atrato River in Chocó, and ordered a series of measures to protect the river and combat illegal mining in the region. The court mandated (a) restoring the river course to its original state, (b) removing all sediment banks created from dredging the riverbanks, (c) reforesting areas left bare from gold mining, (d) urging the Ministry of Defense to neutralize and eradicate illegal mining in the Atrato River watershed and Choco, (e) designing a scheme for restoring the traditional and sustainable livelihoods of the Afro-Colombian communities that have been reshaped by mining activities, and (f) conducting toxicological and epidemiological studies to assess the extent of contamination by mercury and other toxic substances associated with gold mining. This ruling constitutes a precedent toward recognizing and enforcing the rights of nature to be protected and preserved.

The panel was formed in October of 2017.[4,35] On July 10, 2018, the Minister of the Environment, Luis Gilberto Murillo, participated in the forum "I am Atrato, I am a subject of rights." The Ministry page (MinAmbiente) listed the actions taken including creation of the Commission of Guardians of the Atrato River; construction of action plans such as for decontamination of water sources and eradication of illegal mineral extraction; prohibition of mining on the Quito River; and reduction of deforestation in the Chocó and in the Atrato river basins. In addition, actions were different with different entities and with the communities. Some carefully planned projects that had shown success were presented at the forum. Notably, deforestation along the Rio Atrato basin had been reduced by banning gold mining activities on the Quitio River and forest conservation or reforestation programs in other areas were progressing. On June 4, 2018, the government established the "Intersectoral Commission to ensure coordination between different institutions and address the humanitarian crisis in the Department of Chocó."[36] Involvement by the courts and various ministries, institutions, and communities is providing options to control the environmental effects of alluvial gold mining that do not solely focus on the eradication of mining activities. As in the Peruvian Amazon,

> exclusive use of "command and control" policies are not effective in developing countries, especially in areas which are prone to high corruption, lack of efficient law enforcement due to the cultural imperative, as well as the inherent difficulty of enforcement in a very low density area and a highly centralized nation.[37]

Mirroring the Atrato River decision and Colombia's National System of Protective Areas (SINAP), a Brazilian federal court judge issued an order that "suspends possible administrative acts based on the decree" signed by the President that would have opened a 46 000 km^2 (17 800 mi^2) Amazonian reserve to mining for gold, iron ore, copper, and other minerals[38] A new decree restricts mineral exploration to areas with no protected areas, indigenous lands, or border strips.

Diagnosis

Mercury contamination effects on community health

The toxic effects of mercury have been known for millennia. It has been proposed that Emperor Qin Shi Huang (259 BCE - 210 BCE), the first emperor of a unified China and creator of the "Terracotta Army," had clinical findings consistent with mercury-induced neurotoxicity, and his son, Qin Er, "was mentally ill . . . [and] his strange behaviours were . . . consistent with low does mercury poisoning."[39] It has been suggested that Saint Ioannis Lampadistis, a Cypriot saint who lived during the 11th century, was blinded by ingesting fish contaminated with methylmercury from the copper mines of Galata.[40] Present generations still consume fish and shellfish contaminated with methylmercury (Minamata disease, first reported in 1956). In Colombia, fish from areas affected by gold mining are also potential sources of mercury contamination for the population. For example, piscivorous fish of commercial importance [such as the Atlantic tarpon (*Megalops atlanticus*) and crevalle jack (*Caranx hippos*)] and captured downstream from the most contaminated gold mining rivers, like in the Atrato River Delta, have been recently shown to have concentrations (median of 3.48 ppm for crevalle jack and 1.1 ppm for Atlantic tarpon) exceeding the maximum 0.5 ppm established by the World Health Organization (WHO) for safe consumption.[41] Another study, which conducted a risk-based analysis based on Acceptable Daily Intake (ADI) of approximately 7 µg/day of methyl-Hg, found that systemic effects may occur by ingestion of more than 3 meals a week for any of 13 of the 16 commercially available fish species from the Atrato River.[42]

Spatial relationships of mercury contamination and children's cognitive deficits. Several recent toxicology studies update the health effects of heavy metal pollution downstream from gold mining in Colombia.[41-43] We summarize the effects of *in utero* exposure to mercury on children's IQ, as identified from modeling data-rich datasets.[44-48]

Mercury absorbed from maternal circulation by the human fetus and by infants from breast milk may affect infant neurodevelopment. Romero and Saavedra[44] modeled APGAR (Appearance, Pulse, Grimace, Activity, and Respiration) scores using micro-data of all births to mothers living in Colombian municipalities within 25 km of a mine permit at some time from 1999 to 2012. Nearly 4.6% of the newborns had a low

Figure 4. Illegal gold mining in southwestern Colombia. The stagnant and brackish pools created by mining are breeding grounds for several species of mosquitoes that transmit malaria and other diseases.
Source: Miami Herald investigation by Wyss and Gurney.[22]

APGAR score measured 1 minute after birth. To estimate the contribution of mining to low APGAR scores, they compared scores from births near mines with those from 5, 10, and 20 km downstream buffers. They found that

> mothers living in the vicinity of a mine have a 0.51 percentage points lower probability of having low APGAR score births (from a basis of 4.5%). [M]others living in municipalities located downstream from a mine experience an increase of 0.45 percentage points in the probability of having low APGAR score births.

The difference was attributed to increased consumption of contaminated fish by the downstream mothers during Holy Week. This is a good example of the levels of detail of the data and analyses required to model the interacting layers within and between the societal and ecological decks in Figure 1.

Another data-rich model used micro-data from about 800 mines in 44 developing countries.[45] Possibly contrary to expectations, "gains in asset wealth (0.3 standard deviations) coexist with a higher incidence of health conditions linked to heavy metal toxicity: anemia among women (10 percentage points) and stunting in young children (5 percentage points)." Observed health impacts were only near mines that could cause metal contamination. For example, blood hemoglobin levels in women after childbirth had "a characteristic signature of lead toxicity."

The effects of prenatal exposure to mercury and methylmercury on children's cognition may differ depending on the source of the maternal exposure or possibly asset wealth. The nutritional benefits of fish in the diet were determined for 282 school-age Inuit children in Arctic Québec. The maternal data were a rich set of demographic characteristics and socioeconomic status variables, pregnancy history, and heavy metal concentrations (lead, mercury, selenium) in maternal hair. The cord blood data were concentrations of 14 polychlorinated biphenyl (PCB) congeners, 10 organochlorine pesticides, heavy metals, and the fatty acid profile (phospholipids). Children with cord mercury $\geqslant 7.5\ \mu g/L$ were 4 times as likely to have an IQ score < 80, the clinical cut-off for borderline intellectual disability. Regression modeling showed that *in utero* co-exposure to docosahexaenoic acid (DHA) and selenium decreased the negative cognitive effects of methylmercury but co-exposure to PCBs did not modify the IQ decrements from mercury.[46] Conflicting findings were obtained in a study of 872 children in Massachusetts. Maternal prenatal fish intake (averaging about 1.5 weekly servings) of mercury, selenium or fatty acids, was not associated with verbal or non-verbal intelligence, visual motor function, or visual memory at a median of 7.7 years of age.[47] Another study reported an Hg-related decrease in cognitive score at 18 months of age only in children carrying at least 1 apolipoprotein E (*Apoe* $\varepsilon 4$) allele and that the decrease in fine motor scores was independent of the *Apoe* genotype.[48]

By way of shifting focus, a conceptual model has proposed that the terrestrial food web might be contaminated by methylmercury produced in aquatic ecosystems *via* insects emerging from small ponds.[49] Pond permanence and the level of Hg contamination of the food web were proposed as controlling the emergent insect-mediated flux of methylmercury. If this model of food chain contamination from small human-made ponds is substantiated by research at the regional, watershed, and pond scales, we expect it to hold for insect emergence from mercury-laden water from alluvial gold mining (Figure 4). Next, we consider evidence that alluvial gold mining affects the incidence of malaria in humans.

Malaria in gold mining areas

Malaria is a devastating human disease in tropical and subtropical areas worldwide, and there is ample evidence showing that informal gold mining favors the spread of malaria. Alluvial gold mining promotes the transmission cycle of the malaria agents by perpetuating the continuous presence of human reservoirs and providing new breeding sites for the mosquito vectors. Outbreaks of malaria have been documented in parallel to increases of informal gold mining activities in different parts of South America, including Madre de Dios in Peru,[50] Mato Grosso State in Brazil,[51] French Guiana,[52] and throughout Colombia.[53] Cases of malaria in areas of high mining activity in Colombia had increased by more than 31% in recent years.[53] Reported data are unavoidably biased because most gold mining operations are not registered and approximate locations are generally used for the areal scale.

During the 1980s, the invasion of alluvial gold miners in the Yanomami Indian territories of Northern Brazil was attributed as the cause of spiking of malaria, influenza, tuberculosis, and sexually transmitted diseases among the Indian population, to the point of decimating their tribes.[54] About 40 000 gold miners had invaded the Yanomami territory and about 20% of the Yanomami died in just 7 years. The conflict between indigenous tribes of Brazil and gold miners perpetuated due to inadequate federal law protection,[55] whereas malaria and other diseases spread because medical supplies did not reach the Yanomami Indians due to a chaotic health care system.

Correlative studies. We distinguish studies of correlation between gold mining and malaria incidence and studies of causality discussed subsequently. In the Mato Grosso State of Brazil, individuals directly involved in gold mining activities had a higher malaria prevalence than those in other occupations in the same community.[51] A strong positive association was found between the amount of gold extracted and the malaria incidence rates from 1985 to 1996, after allowing for financial investments in malaria control activities.[56] A study in French Guiana using highly sensitive nested polymerase chain reaction (PCR) reported a malaria prevalence of 22.3% (94/421) among alluvial gold miners, of whom 84% were asymptomatic carriers.[57] Asymptomatic patients can infect mosquitoes with an infection rate of 1.2% versus 22% for symptomatic carriers.[58] A 1-year follow-up of asymptomatic carriers found that *Plasmodium falciparum* persisted in the circulation an average of 194 days.[59] We confirmed a significant correlation between malaria cases per 100 000 men (Secretaria Seccional de Salud y Protección Social de Antioquia, 2019) and gold production (grams) in Antioquia using public data for municipalities from 2012 to 2017.[60] The log-log linear correlation for the 124 pairs, for which there was at least 1 malaria case, was $R = 0.46$ ($P < .001$; Figure 5). Because production and malaria cases had to be greater than 0 to be included, this is a conditional analysis. The excluded data included 183 pairs that had 0 malaria cases in a year when gold was being mined in the municipality.

Studies of causality. The previous section established that malaria rates in gold mining areas correlate with gold production. In this section, we consider studies that tease out some of the causal factors and paths that result in correlations. The development of a causal model was published by Feged-Rivadeneira et al.[61] In a classic book, Li[62] introduces path analysis using a situation similar to the role of gold mining in malaria. We adapt his simple example of the difference between multiple regression and path analysis. For multiple regression, increases in malaria cases (*Y*) are expressed as functions of "all other variables, regardless of their meaning, so that a close prediction of *Y* may be made." In a path diagram, the number of malaria cases and other vector-borne diseases (*X*) "are regarded as the consequences of the same set of variables *W*," where *W* includes gold mining and also, for example, deforestation. We concur with Li (p. 4)[62] that "we shall be contented with intuitive understanding of the visual differences between the 2 diagrams" (Figure 6).

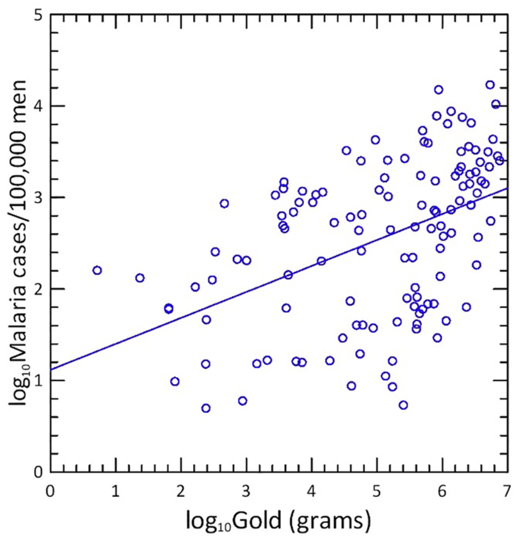

Figure 5. Log-log plot of annual malaria cases against annual gold production in various municipalities from 2012 to 2017.

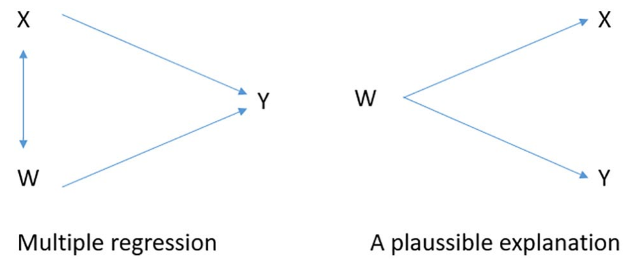

Figure 6. The visual difference between multiple regression and a plausible explanation (redrawn from Li, 1975).

A multivariate geospatial model, using 2004-2008 malaria incidence across 6 Brazilian Amazon States, identified proximity to gold mining operations and higher forest cover as important risk factors.[63] For 9 Amazonian states of Brazil, there was a negative correlation between extraction forestry economics and malaria.[64] The study found that, between 2009 and 2015, areas affected by a 1-km square of deforestation produced 27 new cases of malaria. In the Madre de Dios region of the Amazon in southeastern Peru, health networks serving illegal

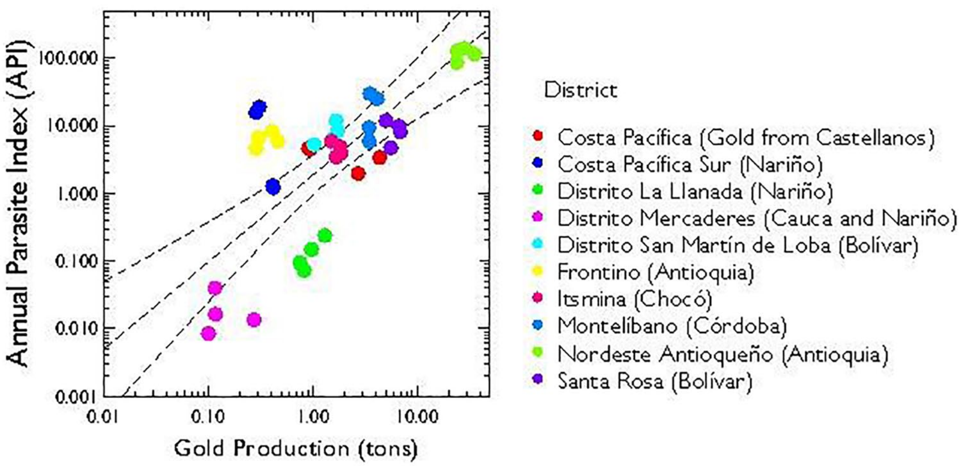

Figure 7. Correlation between the annual parasite index (API, cases per 1000 inhabitants) for malaria and the annual gold production (tons) for the highest producing districts of Colombia (Pearson $R = 0.75$, $P < .0001$). Each point represents data for a single year between 2010 and 2013. The center dashed line is the linear regression and the outer dashed lines are 95% confidence limits. Our figure separates the pooled data for Costa Pacífica (shown in Castellanos et al[53]) into the 3 Nariño districts and Istmina in Chocó.

gold mining camps reported at least 30 times more malaria cases than in low gold mining areas.[50] The association between gold mining and malaria was attributed to changes in the breeding sites of mosquitoes that favor vector abundance and immigration of non-immune workers from low-endemicity regions of Peru. The migrant behavior of the gold miner population has been deemed as a threat to the success of malaria elimination or control programs and to pose a serious risk of dissemination into non-endemic areas.[52,65]

A detailed, complex, spatial analysis reported that the areas in Colombia with the highest gold production also had the highest risk of malaria infection, and the 2 factors were strongly correlated.[61] Laboratory-confirmed malaria outbreak data, obtained weekly (2007-2015, 477 weeks) for 1122 municipalities ranging in area from 1 to 65 786 km^2, were geocoded to municipality level. Except for La Pedrera and Tarapacá in Amazonas, all clusters of *Plasmodium spp.* were in municipalities "located in the departments: Antioquia, Bolívar, Chocó, Córdoba Valle del Cauca, Cauca and Nariño, which are precisely where gold-mining is most prevalent." The variables considered included the age, sex, and ethnic membership of each case (comprising 3369 populations), land use patterns, development, deforestation, and type of malaria (*P falciparum, Plasmodium vivax*). Spatial and temporal analyses of malaria cases and locations where the proportion of cases of *P falciparum to P vivax* changed during the study period were presented in tables, maps, and histograms.

The annual parasite index (API) and gold production were reported for 8 districts of the main gold-producing states of Colombia.[53] In the municipality of El Bagre in Antioquia, there were 188 malaria cases per 1000 people, whereas the national average was 4.95 cases per 1000 people. Our reanalysis found that the annual incidence of malaria (API) was also associated with the year and district (Figure 7). Using satellite data to determine the location and extent of illegal mines,

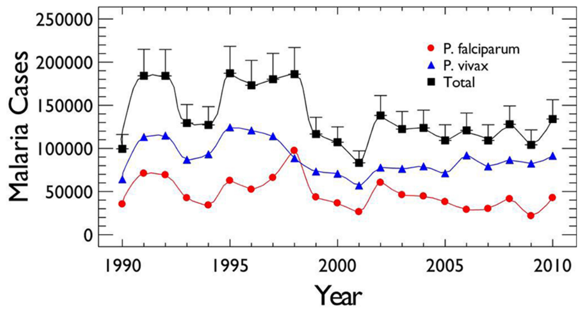

Figure 8. Number of malaria cases reported by the National Colombian Health Institute (SIVIDILA) for *Plasmodium falciparum* and *Plasmodium vivax* for the period from 1990 to 2011.[66] Error bars are estimated as 15% of the total cases (see text).

Rozo[6] estimated that for every increase of 1 ha of illegally mined area the API for malaria increased by 1.04 cases per 100 000 inhabitants, using two-stage least squares to adjust for covariates, $R^2 = 0.42$ (N = 1045).

From 1990 to 2011, malaria cases in the whole country (Figure 8) had fluctuated between 64 000 and 115 000 per year for *P vivax* (64.6% of total cases) and 22 000 and 97 000 (34.7% of total cases) for *P falciparum*.[66] In this period, the average API for 13 states (90% of cases) was 450.3 per 1000 inhabitants and 643.2 per 1000 inhabitants in 7 of them. A stratified capture-recapture analysis using 3 incomplete registers of malaria cases in the Netherlands in 1996 estimated that the detection rate of total cases was 84%.[67] A capture-recapture study using 2 malaria databases estimated a 15% underreporting of malaria cases in England.[68] The error bars in Figure 8 show our estimated minimum upper 95% limits of total malaria cases in Colombia for a 15% rate of underreporting. Causal (structural equation) models for ecological drivers of malaria have been proposed.[69,70]

Malaria transmission in Colombia is now decreasing in some areas and rapidly increasing elsewhere.[61] Reported cases nationally were 87 000 in 2016 and 82 600 in 2017. Of these totals, 40 000 cases per year were in Chocó, amounting to 8- to 10-fold annual rate increases from previous years.[71] The reasons for the increases are unknown. However, Chocó is the second largest gold-producing state in Colombia (behind Antioquia) and is also where deforestation is occurring faster than elsewhere. Declines and increases in malaria rates have also been observed for 6 states of the Brazilian Amazon.[63]

In a similar study in an endemic area of Colombia to the one conducted in French Guiana,[57] the prevalence of infection of *Plasmodium spp*. determined by quantitative polymerase chain reaction (qPCR) was 5% to 15% of the population.[72] The qPCR detection rate was 26 times higher than that by microscopy of thick blood smears, which is the current method employed for tracking the control of malaria. Because asymptomatic human reservoirs are unidentified and therefore are not treated, molecular assays to identify reservoirs are required if malaria is to be eliminated in Colombia. Of the 47 species of *Anopheles* in Colombia, the primary malaria vectors are *Anopheles nuneztovaria* (53.5%), *Anopheles darlingi* (34.5%), and *Anopheles albimanus*.[73] The former two also have the highest prevalence of human bites.[74] Ideal larval habitats for these 2 species are slow-flowing streams or rivers with submerged vegetation, and gold mine dugouts (Figure 4) and turbid polluted water bodies that are sun-exposed, suggesting good adaptation to altered deforested environments.[73,75,76]

The cited studies considered the contributions of gold mining activities to the direct spread and maintenance of malaria in endemic areas. Predisposing factors include failure to use insecticide-treated bed nets, wearing short-sleeve garments at night when mosquitoes are most active, scarcity of mosquito repellents, immigration from non-endemic areas, and lack of compliance with use of prescribed antimalarial agents. Gold mining may similarly contribute to other insect-borne diseases such as dengue, Zika, and chikungunya.[57,77] In summary, alluvial gold mining is a major large-scale driver of malaria.[6] The illegality of this sector, absence of quantitative transmission data between and within humans, and humans and mosquitoes, has hindered the success of official health policies to prevent and control malaria.

Babesiosis (Piroplasmosis)

Our interests in *ecohealth* encompass both ecological health and human health[7] and papers cited therein. Our research on cattle ticks[78-80] is (narrowly) issues of an ecosystem health problem that has crossed the boundaries shown in Figure 1 and is emerging as a societal health problem, babesiosis (piroplasmosis). This a tick-borne malaria-like disease that can be misdiagnosed as malaria due to similar clinical presentation and almost indistinguishable morphological similarities of *Babesia* and *Plasmodium* parasites. In addition to babesiosis, Rocky Mountain spotted fever, caused by *Rickettsia spp.*, is one of the main diseases transmitted by tick bites in Colombia.[81,82] The vectors of malaria (mosquitoes *Anopheles spp*.) and babesiosis (ticks *Ixodes spp*.) can share similar habitats and can be found in similar areas. *Aedes aegypti* and *Aedes albopictus* mosquitoes, which transmit yellow fever, dengue, chikungunya, Zika, and Mayaro, were found to breed in flooded gold mine shafts.[83,84]

Babesiosis is usually associated with cattle, but rates of human infection are rising worldwide. Most human cases have been in people working on cattle ranches or moist wooded areas.[85] In tropical countries like Colombia, cattle are an important reservoir of zoonotic *Babesia bovis* and *Babesia bigemina*. Bovine babesiosis is a prevalent disease in the malaria-endemic regions of Colombia[86] but "its relevance in national public health has not been determined"[87] and it is not a compulsory notifiable disease in Colombia. Babesiosis is a nationally notifiable condition in the United States.[88]

In Colombia, intense deforestation due to illicit agriculture and uncontrolled mining favor the establishment of mosquito breeding sites and the maintenance of high anopheline densities.[89-91] Malaria rates are associated with manual gold mining and decrease when this type of gold extraction is diminished.[56,92,93] It is unknown if gold mining, mercury, other habitat-destructive operations, or habitat restoration contribute to the spread of ticks infected with *Babesia* and if babesiosis in cattle and humans mirror changes in malaria rates.

The first case of human babesiosis in Colombia was reported in 2003 in the Puerto Berrío (Magdalena Medio region).[86] Serological tests of 194 people who worked at slaughterhouses or cattle ranches, or with malaria-type symptoms, identified 7 individuals who were serologically positive for *B bigemina* or *B bovis*. One patient was parasitologically and serologically positive for *B bovis* but negative for antimalarial IgM antibodies. This patient was presented at the local hospital with intermittent fever, chills, sweating, weakness, and joint aches. The seropositive rate reported for *Babesia microti* in the Department of Córdoba was 30.6% (23/80; 15 men and 8 women), suggesting that other domestic or wild animals are also reservoirs for *Babesia*.[87] A 2014-2015 study in Tanzania of 1030 children <5 years found that 186 (18.1%) were malaria positive using a rapid diagnostic test (RDT), of whom 70 out of 180 (38.9%) had blood smears positive for parasites. The median association between *Babesia* and malaria in RDT-negative samples (0.09) and RDT-positive samples (0.013) was statistically significant ($P < .001$).[94] Along the China-Myanmar border, monoinfections of *B microti, P vivax*, and *P falciparum* were 1.8% (8/449), 9.8% (44/449), and 0.2% (1/449), respectively. The rates of mixed infections of *P falciparum* or *P vivax* with *B microti* were both 0.2% (1/449).[95]

To our knowledge, there has been only 1 report that analyzed *Babesia* in humans, cattle, and ticks from the same environment. *B bovis* prevalence was 2% (6/300) in individuals involved in cattle raising, the infection rate for *B bovis* in cattle at these ranches was 14.4% (29/202), and the infection rate for *B bigemina* in collected ticks was 18.5% (30/162).[85] The study pointed out the importance of doing epidemiological

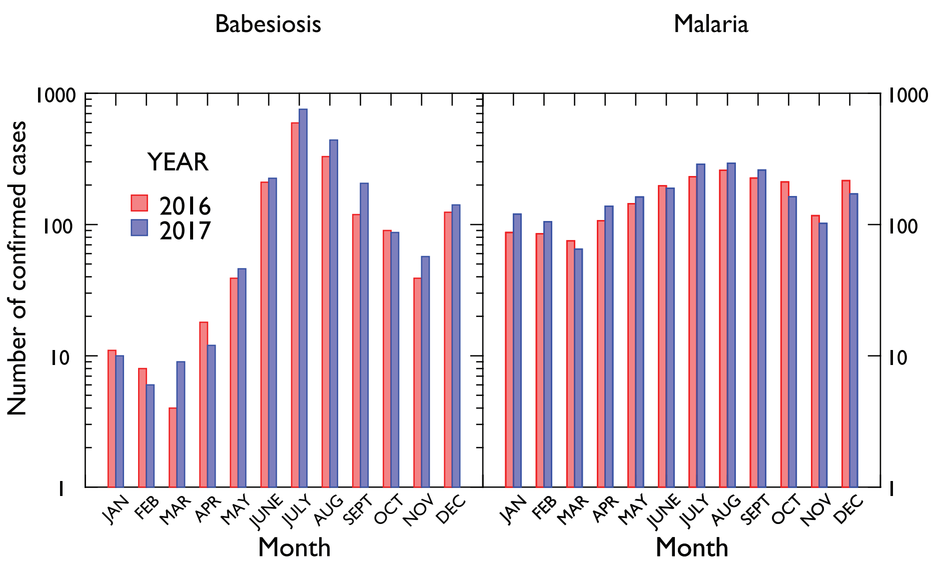

Figure 9. Numbers of confirmed cases of babesiosis and malaria in the United States by month for 2016 and 2017. Source: CDC.

surveillance of babesiosis as a non-malarial febrile illness in people. Killeen et al[96] used published human blood indices and ratios of cattle to humans to estimate the relative availabilities of humans, cattle, and other host populations to malaria vectors. We suggest that a similar model might be constructed using the ratio of babesiosis in humans to cattle or the ratio of malaria to babesiosis in cattle. However, the numbers of coinfections in humans might be too small for this purpose, and we did not identify reports of coinfection in cattle.

From the limited available data, co-occurrence of *Babesia* and *Plasmodium* species in both humans and cattle is currently <1%. In communities dominated by cattle raising and slaughtering, rates of occurrence of both diseases in the humans associated with cattle are also <1%.

In the United States, babesiosis is a voluntary reportable disease in cattle (National List of Reportable Animal Diseases-National Animal Health Reporting System [NLRAD-NAHRS]) and a mandatory reportable disease in humans (Centers for Disease Control and Prevention [CDC]). Confirmed cases of babesiosis and malaria in humans are available by month for 2016 and 2017. Figure 9 shows similar levels of confirmed cases in both years for each disease, and both diseases have similar patterns of seasonality, increasing in the spring and summer (April-August) and decreasing from September through the following March. We suggest that the co-occurrence of babesiosis and malaria in Colombia will be similar to that in the United States, but cannot test this because babesiosis is not a mandatory reportable disease in Colombia.

Possibly, the only serial data of *Babesia* spp. incidence in *Ixodes scapularis* and confirmed incidence of human babesiosis is a report of human babesiosis in Maine, USA (1995-2011).[97] We calculated a Spearman rank correlation of the incidence rates of 0.854 ($P<.001$). We fitted the ranks of *Babesia spp.* incidence (x) and of babesiosis incidence (y) to 65 models in

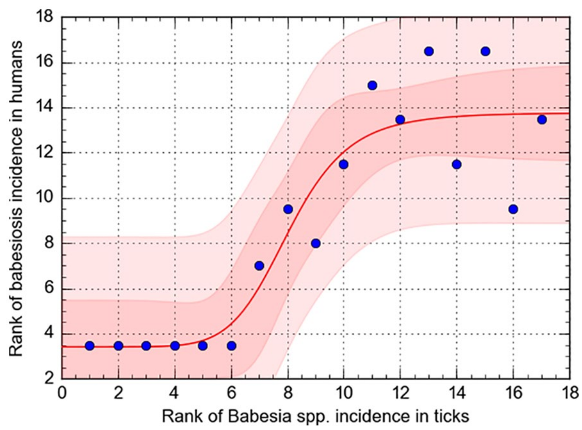

Figure 10. Ranks of babesiosis incidence in humans from Maine, USA (1995-2011) are correlated ($R=0.861$, solid red line) with the ranks of *Babesia spp.* incidence in *Ixodes scapularis* ticks (dots). The fitted line is the DR-Hill model and the shaded areas are 95% confidence bounds on the curve.

CurveExpert Pro (Hyams Development, https://www.curveexpert.net/products/curveexpert-professional/). For the DR-Hill model given by equation (1), $R^2=0.861$ (Figure 10)

$$y = 3.411 + \frac{10.35x^{7.53}}{8.09^{7.53} + x^{7.53}} \quad (1)$$

Conclusions

We introduced this article with a sketch of the ecological and social "decks" of *ecohealth* via their interaction with the broader environment. We showed that gold production stresses *ecohealth* at multiple levels and in unexpected ways. Adverse environmental changes from mining spatially couple decrements in human health and cognition with habitat expansion of disease vectors. We have used knowledge from diverse disciplines and found that most studies lacked data that were spatially and temporally coordinated. Thus, in Colombia, the reported gold production was tabulated by trimester for individual municipalities, whereas malaria cases were aggregated yearly by department and region, and information on babesiosis in cattle and humans was not systematically collected. Similarly, because much illegally mined gold is unreported, values may underestimate real production. Similarly, although malaria is a reportable disease, an unknown number of patients are not correctly diagnosed or seen by a doctor. Because of inaccurate reporting, models that use such data might be used to identify qualitative, but not quantitative relationships. We discussed modeling studies that quantified some of the uncertainties and these show the difficulties, costs, and range of expertise required to collect data for use in causal (path) analysis.

At present, we do not know if the vectors of these and other diseases are expanding their territories beyond, say, the spatial extent discernable from satellite images. We do not know the long-term societal consequences from *in vivo* infection of infants nor the effects on the animals in the wildlife and human food chains. Although databases for disease and mineral production are imperfect due to misidentification or non-reporting of disease in the former, and underreporting and non-reporting of legal and illegal production in the latter, the mandatory collection of data on a scheduled basis according to specified protocols is necessary to evaluate the current, and project the future, ecosystem health. The "rights of nature" include us, and we cannot know if, when, and how those rights are being violated or being met when data are, by design, not collected, not verified, and not readily available. We present a case in which the Colombia's Constitutional Court ruled that Federal authorities neglected to protect one of the most contaminated and long rivers in the country, the Atrato River in Chocó, and ordered a series of measures to protect the river and combat illegal gold mining in the region. The Colombian court has asked "what are the 'rights' of an ecosystem?" and answered that a river, a forest, an ocean, has rights unto itself, for which humanity is only the caretaker.

To end on a light note, we report 2 just-published studies that are marginally related to the main themes of this article. Paraphrasing Emily Conover's summary (*Science News*, May 8, 2019), astronomers have suggested that heavy elements such as gold might be formed in collapsars. These massive, rapidly spinning, massive stars collapse into black holes that can create the necessary conditions. She suggests that the "gold in your favorite jewelry could be the messy leftovers from a newborn black hole's first meal." As summarized by Kerry Grens (*The Scientist*, May 24, 2019), these "messy leftovers" are food to *Fusarium oxysporum*, a fungus found in Australia that can oxidize and dissolve the gold in deeper deposits in the Earth's crust and then precipitate the metal on their surfaces. Our concluding speculation is that someone will devise a process that uses this fungus, or other organisms, to "mine" gold and thereby relegate many problems associated with alluvial mining to history.

Author Contributions

DV conceived of this paper and wrote the first draft, prepared the graphical abstract, reviewed revisions, and handled submission. DS wrote subsequent drafts and did the statistical analyses. Both authors contributed to the literature research.

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