Title

Ecologies of Gold: Understanding the social, political, and ecological impacts of mercury use in informal, small-scale gold mining in Madre de Dios, Peru

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by

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Abstract

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Informal, small-scale gold mining is a complex, entangled social-natural system that is also the principal livelihood for greater than 40 million individuals residing across more than 70 countries in the global South. While informal gold mining provides extensive socio-economic benefits to people in rural, underdeveloped areas of the globe, there are significant environmental and public health impacts from the use of toxic elements like mercury and cyanide in gold production. Like most mining, informal gold mining all too often degrades and contaminates land and in the absence of remediation this land is rendered unsuitable for production of consumptive goods.

In the Amazonian region of Madre de Dios, Peru, miners use elemental mercury to concentrate fine particles of gold in informal, small-scale mining. This dissertation uses an interdisciplinary, political ecology approach to examine the multiply scaled and multi-layered issues surrounding the use of mercury in informal, small-scale gold mining in Madre de Dios. The overarching claim of this dissertation is that mercury pollution is a phenomenon emerging out of and coproduced by the interrelation between both social and biophysical factors at particular spatial scales and in particular historical moments. Through the three chapters that form the body of this dissertation, I show how an understanding of a particular place as 'polluted' must be historicized in relation to past iterations of resource extraction and land use management. In Madre de Dios, the Peruvian central state once sold mercury to gold miners as part of a larger program to spur rural economic development via gold extraction. These past legacies of state-sanctioned mercury use have not been publicly addressed and yet they contribute to present narratives and policies regarding widespread mercury contamination in the region. In addition, the toxic legacy of nearly 300 years of extraction of mercury from cinnabar mines in the Andean highlands is almost never mentioned in relation to what is commonly understood as a recently emerging issue of mercury pollution in Madre de Dios. It is only when history, politics, culture, and ecology are

taken together and considered in relation with one another that the causes and consequences of mercury pollution can be fully understood and adequately addressed.

This dissertation is divided into three stand-alone chapters, meant to be read in order, and a brief conclusion. In Chapter One**,** I historically contextualize the problem of mercury pollution in small-scale gold mining, examining the long history of state promotion of gold mining in Madre de Dios. In the Amazonian region of Madre de Dios, Peru, ever-larger and prolonged military-led interventions claim to ameliorate the environmental and social impacts caused by the expansion of illegal, small-scale gold mining by forcibly displacing miners from certain lands designated as zones of mining exclusion. Central to state and extra state actors' justification for these coercive interventions is the need to protect sensitive Amazonian ecosystems from environmental degradation caused by illegal gold mining. Chapter One engages with these contested politics, ultimately arguing for a need to re-imagine both the history of mercury pollution associated with illegal gold mining in Madre de Dios and to reconsider the negative effects of militarized containment strategies. I argue that coercive containment solutions negate the biogeochemical complexity of mercury cycling, ultimately failing to contain or control mercury or the miners that rely on it. Further, I demonstrate how the framing of the problem of mercury pollution - as solely associated with illegal gold mining - both belies the histories of Peruvian state support of small-scale gold mining and justifies the criminalization of small-scale miners operating in certain places. Ultimately, in ignoring the ways in which mercury is used in small-scale gold mining throughout Madre de Dios – whether 'legal' or 'illegal' – and also moves freely through the environment on currents of air, water, and in the bodies of wildlife, the act of policing miners to reduce mercury pollution ends up exacerbating the risk of mercury exposure for both humans and wildlife by diffusing mercury to ever more remote corners of the forest.

In Chapter Two, I trace the use of mercury in gold mining to mercury pollution in abandoned gold mines, by examining how differences in gold production practices mediate mercury's accumulation and magnification in aquatic food webs. I push back against the notion of a permanently polluted world by demonstrating how pollution is uneven and mediated by both ecological food web structure and anthropogenic mercury loading in abandoned mines. I demonstrate that the level of pollution as measured in the bodily burden of mercury in individual organisms is connected in part to the social histories of these abandoned mines and also to site-specific gold production and processing practices as well as differences in ecological food web structure.

In Chapter Three, I delve further into the heterogeneity in gold production practices in Madre de Dios, focusing on characterizing the differences in extraction technologies used in Madre de Dios, by examining how different modalities of gold production have evolved over time and contribute to the socio-economic differentiation of the small-scale gold mining economy.

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ACKNOWLEDGMENTS

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This dissertation was more than an intellectual project, it was also a deeply personal journey. In many ways it was my own version of a hero's journey; I was finally able to return home and I am forever changed for it. In returning to Peru after so long and spending time living in my home country for the first time in my life, I found what I had been searching for my entire life – belonging. Not just belonging to a place but to a people, a culture, and to my own sense of self. I still can't quite articulate all the ways that returning home has changed me, but I am sure that one day I will permanently return to Peru and settle into the landscape of my childhood imagination.

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INTRODUCTION

1. Opening

Standing in a desert in the middle of the Amazon rainforest, I was deeply disoriented. All around me were sand dunes, mounds of gravel, and rocky plains; a landscape completely transformed by the search for gold dust buried beneath the forest floor. Naively, I had dressed for fieldwork: long pants, a long-sleeved shirt, and black rubber rainboots for wading through muddy sections of trail. It was my first full day in Madre de Dios and my attire was as ill-suited for the landscape before me as my pre-conceptions were for the reality of what a gold mine looked like. I could feel the heat reverberate through my boots as I walked across the sandy landscape, sweat beading on my forehead from the exposure. I ambled around a mosaic of abandoned gold mining pits, some as small as ponds, others as large as lakes, and I took in a kaleidoscope of colors emanating from this unfamiliar scene. One pit was covered by a dense mat of almost fluorescent green floating algae. A few hundred meters away another pit looked like an oasis with cerulean blue water, so clear you could see to the bottom. Steps away was another pit, its turbid muddy-red waters signaled the recent presence of miners. Old rubber boots, Styrofoam take-out containers, rusted pieces of machinery, and discarded oil drums littered the sandy floor around these mines; the remnants of the labor that created this new landscape. As I stood at the eroding edge of a pit and watched dragonflies skim the surface of the water, a tiger heron perched on a broken tree trunk surveyed the movement of jumping fish.

Figure 1. One of the mining pits I came across on my first day in the field.

I had been told by American colleagues, most of whom were tropical ecologists, that these abandoned mines were wastelands, lifeless zones where ancient forests once stood. Repeatedly, I had heard the story of how *miners* had 'ravaged' the Amazon, turning pristine jungles into toxic landscapes poisoned by mercury. I was told that these were uninhabitable places - completely devoid of life. What appeared before me was not a wasteland, but a space filled with life - albeit not to the same degree or in the same configuration as before. All around me was life: in the vines of ground tomatoes radiating through patches of gravel, the arrow-straight balsa wood trees growing tall in mounds of tailings, and the mats of floating macroalgae overtaking the surface of mining ponds. There was vitality in the flock of white egrets feeding on fish from the ponds, the small caiman poking its snout out from the still surface of the water, and the screeching cackles of hoatzin. It was this resilience of life that surprised me more than the absence of what was once a tropical rainforest. Still, I was deeply unsettled by this scene.

As I continued trudging through the sand, I passed a set of paw prints, the evidence of a large cat making use of these new hunting grounds. The sun began to set and in the reprieve from the intense heat, a new chorus of sounds emerged: the haunting calls of a pootoo and the melodic thrumming of cicadas just audible over the mechanical drone of motors. As the moonlight illuminated the new ecologies forming in this created landscape, I asked myself how it was that these spaces came into being and what futures they might hold.

2. Overview and Background

> Peru was, is, and will be a mining country. Saying no to mining is an illusion.
> -Antonio Brack, Peru's First Minister of the Environment

Peru has long been known as a mining country (*pais minero*) – a country whose history and culture has been shaped by centuries of colonial rule that decimated bodies and environments in service of the accumulation of mineral wealth (De Echave and Torres 2005; Graulau 2008; Moore 2010; Bauer 2018). Today, the mining of metals, minerals, hydrocarbons, and precious gems is as much a part of national identity as the Incan ruins for which Peru is internationally renowned. Peru's position within the global extractive environment has been produced not through the preponderance of geological wealth but instead through the intentional restructuring of laws, institutions, and frameworks to facilitate and encourage foreign direct investment in mining industries (De Echave and Torres 2005; Bebbington and Bury 2009; also see Chapter One). In 2019, Peru was the second largest producer of silver, copper, and zinc in the world and Latin America's largest producer of gold (MINEM 2019). But the environmental and social costs of this mining bonanza cannot be overstated. Social conflicts surrounding mega-mining projects, heavy metal pollution, environmental degradation, increased poverty, and livelihood loss have gone hand-in-hand with the expansion of mining investment since the 1990s (Bridge 2004; Bury 2004; Bebbington et al., 2008;). This dissertation examines the social and environmental impacts of the expansion of an increasingly important type of gold mining in Peru – informal, small-scale gold mining. While small-scale gold mining is reconfiguring nature-society relations and ecosystems throughout Peru, the focus of this dissertation is on the Amazonian region of Madre de Dios, where gold mining is scrutinized for its outsized social and environmental impacts.

In the Amazonian region of Madre de Dios (Figure 2), mercury and gold are entangled in a metallurgic bond that stretches across centuries of knowledge and practice. It continues to this day as gold miners perform an everyday alchemy by adding liquid mercury to concentrate fine flecks of gold. Mercury envelops diffuse gold particles because of its strong chemical affinity and is only separated from this bond through the application of direct heat (Swain et al., 2007; Esdaile and Chalker 2018). Mercury's melting point is lower than that of gold allowing miners to concentrate gold by roasting an amalgam, releasing thick white clouds of mercury vapor that sinew through the air. What remains is value in its purest form – a sponge-like disc of solid gold to be sold to any one of the plethora of local gold buyers. Just like magic, miners turn dirt into gold by us

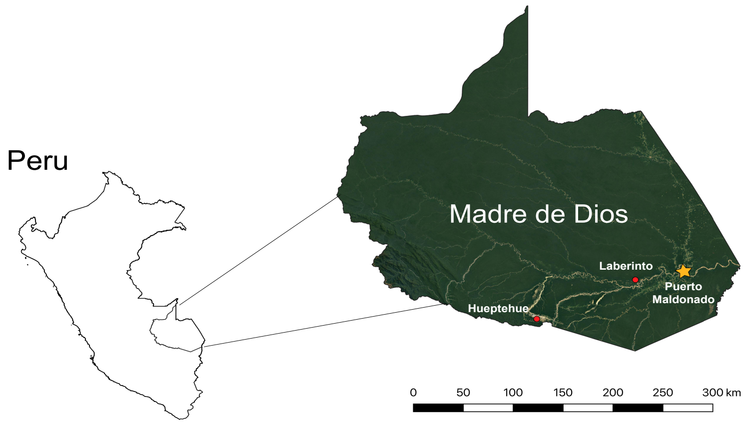

Figure 2. Map of the region of Madre de Dios, located in southeastern Peru bordering Brazil and Bolivia. The map highlights the regional capital (star) and major mining centers (red dots).

While mercury amalgamation has been used in mining for thousands of years, only recently has this practice become an object of global environmental concern and subject of joint policy initiatives at an international scale (Rubiano Galvis 2019). The principal reason for this heightened attention lies in the passage of an internationally binding, global treaty called the Minamata Convention on Mercury; ratified in 2013 by more than 70 nations, including Peru. Under the Minamata Convention on Mercury, anthropogenic mercury releases - from what is commonly called, artisanal and small-scale gold mining (ASGM) - are targeted in national and international abatement programs (UNEP 2020; Rubiano Galvis 2019). Mercury emissions from ASGM are estimated to account for 35 percent of all global annual anthropogenic mercury emissions, surpassing releases from industrial activities such as coal combustion and plastics manufacturing (UNEP 2020).

To begin to unpack the multiply scaled and multi-layered issues surrounding mercury use in small-scale gold mining in Madre de Dios, I first wish to clarify the terminology and definitions that I use throughout this dissertation. Most commonly, the term artisanal and small-scale gold mining or ASGM is used to refer to all the types of mining that I describe in Madre de Dios. But it is difficult to make any generalizations about ASGM as a whole given that the organization and arrangement of labor, as well as gold production methods used in any one particular mining locality are site-specific and embedded in and influenced by distinct political-economic, social, and environmental contexts. Nonetheless, generalizations are often made about ASGM by development practitioners and policymakers who most often define artisanal and small-scale mining as a labor intensive, low technology activity carried out by individuals largely outside formal economies (Hilson 2002). I aim to move away from the use of the term ASGM, by taking into account critiques of this term by scholars like Lahiri-Dutt (2018), who has argued that:

> This definition, with clear indication to its sectoral belonging, leaves unanswered questions about its [ASGM's] relationship with rural transformation, with globalization and development processes, with the advent of large-scale extractive operations, and extractivist economic policies (p.11)

In consideration of the ways in which the term ASGM obscures more than it clarifies and in the context of my locally situated understanding of gold mining in Madre de Dios, I use the term, "informal gold mining" (which can be large-scale and industrial) or "small-scale gold mining" interchangeably to encompass the full range of gold production practices employed in Madre de Dios. Further, I characterize informal gold mining in Madre de Dios as labor-intensive and mechanized gold production practices that often occur without formal government authorization and use historically adapted extraction technologies to concentrate and process gold-bearing material extracted from secondary gold deposits. My use of the term small-scale gold mining (SSGM) is not meant to ignore or make light of the extensive environmental and social effects of mining but instead to differentiate between the diversity of gold production practices carried out by individuals engaged in SSGM and those of corporate, formalized, industrial mega-mining projects that dominate the extractive landscape in Peru. I recognize that SSGM and informal gold mining are still inadequate terms to fully encompass the range of production practices that are present within Madre de Dios, but these terms are better suited to the local context in Madre de Dios, wherein artisanal mining or mining with non-mechanized technologies is mostly absent.

In the push to eliminate mercury use in informal and small-scale gold mining, proposed interventions and policy solutions have largely relied on top-down, state-driven approaches that center on three strategies: formalization of titles to mineral concessions and extraction permits, development of mercury-free technological alternatives, and technological knowledge transfer of mercury-free mineral processing and concentrating methods (UNEP 2020). These policy instruments, as I argue in Chapter Three, often obscure the complexities of small-scale gold mining on-the-ground. As a result, in the past 30 years, many of these interventions have failed to generate any meaningful reforms of small-scale gold mining (Veiga and Fadina 2020). In response to the myriad social and environmental challenges presented by the use of mercury in small-scale gold mining in Madre de Dios, my research delved deeply into the "mercury problem" by interrogating not only the claims of widespread contamination often attributed solely to mercury use but also by analyzing the entanglements between mercury pollution, environmental politics, land use history, ecotoxicology, environmental health, and extraction-based economic development paradigms dominant at both national and subnational scales in Peru.

Across the Global South, informal and small-scale gold mining is a major driver of rural transformation and is the principal livelihood for an estimated 40 million individuals and an additional 150 million dependents (Peluso 2016, 2017, 2018; IGF 2017; Hilson et al., 2019). Many scholars have noted an expansion of informal gold mining in the past thirty years following structural adjustment policies that heralded in neoliberal economic reforms in many countries (Peluso 2017; Lahiri Dutt 2018; Verbrugge and Geenan 2020). Many of these reforms affected mining laws and land tenure, promoting foreign direct investment in extractive industries and a contraction of government subsidies for inputs used in subsistence and smallholder farming (Lahiri Dutt 2018; Verbrugge and Geenan 2020). In some places the deagrarianization (Bryceson 1996) of rural landscapes was met with an expansion of informal and small-scale mining as a poverty driven pursuit (Bryceson and Jønsson 2010). This expansion of informal mining has been accompanied by well-documented livelihood benefits, including increased upward economic mobility, increased potential for poverty alleviation, revitalization of agrarian livelihoods, increased access to wealth generation opportunities for women, and emerging forms of frontier democracy (Hilson 2002; Bryceson and Jønnson 2010; Verbrugge and Besmanos 2016; Peluso 2017; Verbrugge and Geenan 2020). The synergisms between agrarian and mining livelihoods in rural regions has created new pathways for rural economic development in many underdeveloped regions of the global South (Verbrugge and Geenan 2020).

While the livelihood benefits of informal mining are substantial, they are also not without problems. In particular, one major critique of informal mining by development practitioners and scholars is that it occurs outside of the formal economy and as a result is plagued by poor occupational health and safety practices as well as negative environmental impacts (Hinton and Veiga 2002; Swain et al., 2017; IGF 2017). Critics claim that informal miners do not attend to health and safety precautions especially in the use of hazardous substances such as mercury and cyanide (Hinton and Veiga 2002; Swain et al., 2007; Zolnikov and Ortiz 2018). Moreover, in popular media, small-scale mining zones are frequently associated with a host of societal ills such as alcoholism, drugs, prostitution, human trafficking, and sex trafficking. Such portrayals contribute to the drive for policies aimed at criminalizing and cracking down on small-scale mining throughout the globe (Tscahkert and Singa 2007; Libassi 2020). In some regions, like Madre de Dios, there have been successful efforts to criminalize small-scale mining by introducing a definition of illegal mining into the penal code and constructing a legal framework for the prosecution of individuals caught mining in off-limits areas (see Chapter One). The movement towards more coercive approaches to mining governance appears to be gaining traction despite a dearth of evidence to support the effectiveness of these approaches in curtailing the expansion of informal mining into environmentally or culturally sensitive areas (Dezecache et al., 2017).

More often than not the livelihood benefits of informal mining are overlooked due to the environmental impacts caused by mining in biologically and culturally diverse rural landscapes (Alvarez Berrios et al., 2015; Hilson et al., 2019). Some of the most commonly listed environmental impacts from small-scale gold mining resemble those that are documented for industrial mining including: land degradation, deforestation, sedimentation, hydrological alteration, heavy metal pollution, siltation, lentification (creation of still waters), habitat fragmentation, and acid mine drainage (Martinez et al., 2018; Dethier et al., 2019; Diaz Leiva et al., 2021). While I show in Chapter Two that these impacts are mediated by the degree of mechanization of mining operations and site-specific gold production practices in particular environmental settings – the reality is that gold mining is a form of land use that physically disturbs environments and can preclude future productive uses of land in the absence of remediation and reforestation or without changes in land use.

In Madre de Dios, most informal mining operations rely on the use of dredges powered by small car motors or heavy machinery to suction or extract gold-bearing material. Gold production in inland forest areas requires the removal of surface vegetation, resulting in deforestation. Dredging and excavation of gold-bearing material creates open pit mines. These pits are filled with water from nearby rivers during the rainy season, rainfall, or by water pumped into a pit. While an individual mining pit may only span an area the size of a small pond, since 1985, the extent of these abandoned mining pits on the landscape has grown by more than 670 percent; they now cover approximately 16 kilometers[2] (Gerson et al., 2020). These new networks of aquatic habitat - as described in the opening of this introduction, are colonized by wildlife but are also increasingly understood as hotspots of mercury methylation and bioaccumulation in mining impacted landscapes (see Chapter Two). The result of this lentification of the landscape is an increased risk to humans and wildlife of mercury exposure from abandoned mines contaminated by mercury-laced tailings as well as an increased exposure to mosquito-borne illnesses such as dengue and malaria from the creation of still waters where mosquitos can reproduce (Sanchez et al., 2017).

The livelihood benefits realized by the millions of individuals whose socio-economic wellbeing is dependent on the extraction of gold stands in tension with the stark reality that the environmental impacts caused by gold mining in places like the Amazon rainforest appear outsized and unevenly distributed. Holding in tension these socio-economic benefits and environmental impacts, my dissertation aims to nuance and complicate mainstream understandings of both the social and the environmental impacts of small-scale gold mining in Madre de Dios. My interdisciplinary approach explicitly recognizes small-scale gold mining as a coupled social and natural system and uses a political ecology approach to examine these coupled dynamics. This dissertation demonstrates how a disciplinary understanding of small-scale gold mining from the perspective of the natural or social sciences alone can shroud the important interrelations and multi-scalar dynamics that must be clearly understood before any meaningful policy reforms of small-scale mining will be devised or successfully achieved. Before introducing my arguments and concepts from the three chapters of this dissertation, I first provide some context on the environmental and socio-political landscapes in my study region of Madre de Dios.

Mercury Pollution in Madre de Dios: what's known and unknown?

When scientists and policymakers speak of mercury pollution as a global environmental concern, they are referring to the dangers posed by *methylmercury*, a "potent neurotoxin that affects human and wildlife development and health (Selin 2009)." Mercury is a naturally occurring element that exists in three different chemical forms or species (Selin 2009). Mercury used in small-scale gold mining is in its elemental form (Hg^0). The elemental form, naturally found in cinnabar and refined into quicksilver, is both less chemically reactive (meaning less likely to form chemical compounds) and far more abundant than other forms (Ullrich 2001; Selin 2009; Driscoll et al., 2013). These inorganic forms of mercury are not inherently toxic, meaning that they pose little risk to the health of humans and wildlife (Ullrich 2001; Selin 2009). The transformation of mercury from its elemental or reactive inorganic (Hg^{2+}) forms to methylmercury is dependent on groups of sulfur-reducing or iron-reducing bacteria that add carbon atoms to inorganic mercury atoms forming an organic compound ($CHgH_3$). This biologically-mediated transformation largely occurs in the bottom sediments of waterbodies like lakes and wetlands, where certain abiotic conditions must be favorable to promote bacterial activity (Ullrich 2001; Hsu Kim et al., 2018). Even if the conditions are favorable, the biogeochemical cycle of mercury is so complex that there exist processes of demethylation that can turn methylmercury back into one of its inorganic species (Selin 2009; Driscoll et al., 2013). These mobilities of different species of mercury, transforming from one chemical form to another and back are central to understanding the relative risk of exposure from mercury released from small-scale gold mining. Unfortunately, the toxicity of methylmercury and quicksilver are often wrongfully equated, obscuring the important interactions between biogeochemical conditions and anthropogenic mercury releases that mediate exposure risk for humans and wildlife (Hsu Kim et al., 2018; Eagles Smith et al., 2018).

In Madre de Dios, it is well understood that the burden of mercury pollution is not evenly distributed among the diverse groups of inhabitants. In particular, indigenous tribes disproportionately bear the burden of methylmercury exposure due to their dependence on wild caught fish-based diets (Diringer et al., 2015; Fernandez et al., 2019; Gonzalez et al., 2019). Recent studies have found that indigenous tribes located *upstream* of mining activity, carry the greatest bodily burdens of methylmercury exposure measured in hair samples (Fernandez et al., 2019). This uneven burden is largely due to the fact that these tribes subsist primarily on wild fish, consuming greater quantities than those consumed by downstream, urban populations in the capital of Puerto Maldonado (Fernandez et al., 2019; Gonzalez et al., 2019). The disproportionate burden borne by a population that has been historically marginalized and structurally dispossessed of their ancestral lands by the government, adds another dimension of complexity to the problem of mercury use in small-scale gold mining. Because of these uneven effects, the mercury problem in Madre de Dios must be understood not only as an environmental or public health issue but also as an issue of environmental *injustice*. As such, solutions to these problems should center the most vulnerable and marginalized communities in the region and recognize the multiple historical and structural factors compounding the risk of exposure for these populations.

While the populations most at risk for mercury exposure are well documented, the relative contribution of mercury releases from small-scale gold mining to the problem of mercury pollution in the region is not as well understood. Increasingly, scientists acknowledge that in the Amazon, large quantities of atmospheric mercury are stored in trees that absorb gaseous elemental mercury through the stomata in leaves (De Oliveira et al., 2001; Lechler et al., 2015; Crespo Lopez et al., 2020). This mercury makes its way into soils through the decomposition of leaf litter and through rainfall (Selin 2009; Pirrone and Mason 2009; Driscoll et al., 2013). Because forest and soils act as stores of mercury stocks in the Amazon, any activity resulting in the removal of vegetation, either through deforestation or burning will result in mercury releases into the atmosphere (De Oliveira et al., 2001; Lechler et al., 2015; Crespo Lopez et al., 2020). Moreover, runoff caused by land use activities or natural hydrological cycles can also contribute to mercury releases in waterways as mercury bound to fine particulate organic matter is carried downstream (Adler Miserendino et al., 2018; Schudel et al., 2018). These factors complicate causal claims that solely link mercury use in small-scale mining to mercury pollution in the region.

Tracing the source of mercury pollution in the Amazon has become more feasible with the use of mercury stable isotopes (Bergquist and Blum 2009). These chemical 'tracers' allow for an examination of the origins of mercury in different biological or biophysical matrices such as fish tissue, soils, sediments, and even air. Recent research using mercury stable isotopes to trace the source of mercury in air samples in Madre de Dios (Szponar et al. 2021, *in review*) demonstrates that small-scale gold mining does in fact contribute the majority of mercury releases to the *atmosphere* in Madre de Dios. However, even in forested areas proximate to mining activity, there are a mixture of sources that do not bear the isotopic signature of mercury used in small-scale gold mining alone, further reinforcing the notion that mercury releases from natural stores in soils and trees must also be considered as a significant source of mercury pollution in the region. Moreover, as I demonstrate in Chapter Two, in densely forested, unmined areas, fish captured in oxbow lakes have high concentrations of mercury despite being far from any direct mercury inputs from tailings from mining operations. While deposition of inorganic mercury in the atmosphere may contribute to mercury loading into these natural lakes, these emissions are more likely to be taken up by vegetation in a densely forested area. This finding is supported by a recent study carried out in Madre de Dios that found that the methylation potential of oxbow lakes was higher than that of any other aquatic environment in the region, including abandoned mines (Gerson et al., 2020). Considered together, these data suggest three key points: 1) there are high background levels of mercury in Madre de Dios, likely driven by the mercury captured and released from natural stores like trees and soils, 2) there are high levels of anthropogenic mercury loading from small-scale gold mining, and 3) a substantive proportion of the combined natural and anthropogenic mercury stocks are being methylated due to the favorable environmental conditions present in certain aquatic habitats in Madre de Dios. This trifecta of factors exacerbates mercury pollution in the region and also calls into question many of the singular causal claims between mercury releases from mining and mercury concentrations in humans and wildlife in the region.

The dangers of politicizing mercury science have become increasingly apparent in Madre de Dios in light of recent events. In 2016, for example, a sanitary state of emergency was declared in response to ‘widespread’ mercury pollution (see Chapter One). The state of emergency was legitimated by research findings from American scientists who claimed in their publications, research presentations, and public outreach that there was a causal relationship between high mercury concentrations in indigenous communities upstream of mining activity and mercury released into the environment from small-scale gold mining (Fernandez 2009, 2012; Diringer et al., 2015; Pan 2016). The exposure pathway that these scientists signaled out as that by which humans were exposed to mercury released from mining was through the consumption of fish that had become contaminated with mercury released from gold mines (Diringer et al., 2015; Pan 2016). While it is likely that direct mercury releases from mining were contributing to the pool of bioavailable mercury in these riverine environments, the authors of these studies did not nuance their claims and instead signaled out mining as the *sole* culprit of mercury pollution in the region.

This political misuse of mercury science negates the complicated nature of mercury cycling in the Amazon. In particular, these findings obscure the dynamics of mercury bioaccumulation and biomagnification. Biomagnification is an increase in the concentration of mercury up the food chain which occurs because of the efficiency with which methylmercury is transferred and stored in the fatty tissues of organisms (Weiner 2001). Biomagnification of heavy metals can lead to mercury concentrations in organisms at the top of the food chain, orders of magnitude higher than concentrations in water or sediments (Ullrich 2001; Driscoll et al., 2013; Eagles Smith et al., 2018). The diversity of freshwater species in the Amazon basin, provides a unique ecological context for mercury to bioaccumulate and biomagnify especially in so-called mega-fish species like the arapaima (*Sudas gigas*) and doncella (*Pseudoplatystoma spp.,* He et al. 2019). These large-bodied and long-lived predatory fish would tend to accumulate high concentrations of mercury regardless of the source (Eagles Smith et al., 2018). Thus, one way of understanding high mercury concentrations in upstream populations relies on a series of causal chains implicating mercury released from small-scale gold mining, while another way of understanding this finding could situate the result in the broader ecological context of Amazonia where many factors complicate causal associations between mercury releases from mining and the bodily burden of mercury exposure in humans and wildlife.

In recognition of these complex and nuanced social, political, and environmental factors, this dissertation project takes an interdisciplinary approach to studying the impacts of informal mining. My approach answers the call for better integration of social and biophysical sciences in service of a deeper understanding of what is in this case an environmental conflict around the right to use land for informal mining. This conflict, however, must also be understood as inseparable from larger questions regarding the right use of nature, the relationship between extractivist state policies and civil society, and the long legacy of colonial models of resource exploitation rearticulated in different socio-political and environmental contexts. In this dissertation, I show that mercury pollution is an uneven and place-specific phenomenon, coproduced by both social and ecological factors. I offer an alternative to the totalizing and homogeneous view of mercury pollution as an inevitable outcome of all gold mining. I further explore my approach to this research in the following sections but first begin by outlining my motivation for this work.

3. Research Motivation

The impulse for this research began in the landscapes of my imagination. When my parents left Peru in 1993, I was just a year old. Memories of my home country weren't inscribed in recollections of past events but in stories and sounds: the *huaynos* from the mountainous Andean city that my mom grew up in, the rhythmic beats of the *cajon* in my father's beloved collection of Afro-Peruvian music, the pan pipe flutes playing in *El Condor Pasa*. I savored these sounds and developed a love for my home country through family gathering featuring platters of *aji de gallina* and *papa rellena*, birthday cakes of *torta helada*, and pisco sours on Peruvian Independence Day. These traditions formed the backdrop by which I began to explore and understand my own place in the world.

My rich cultural upbringing formed the roots of my aspirations - I wanted to return to Peru one day to have the chance to create memories of my own instead of jealously listening to those of my older siblings. Over time, this desire to return to Peru morphed into something deeper - a longing for connection to a sense of place and a need to belong (to) somewhere. Fatefully, in second grade, a teacher of mine taught us about the Amazon rainforest and deforestation. I was as enraptured by his lesson as a religious devotee sitting in a Sunday sermon. Here was a problem that connected me both to a place that only existed in my dreams and that also ignited my burgeoning love of nature. At the age of seven, I decided to devote my life to "saving the Amazon rainforest."

Fast-forward to 2014, I had just graduated from Dartmouth College with a double major in Environmental Studies and Ecology. My senior thesis was on brook trout movement ecology and modelling the impact of climate change on stream temperatures under different emissions scenarios. I was an ecologist with an affinity for freshwater and I believed that the best way to solve the socio-natural problems that interested me was with the tools and epistemological framework of the natural sciences. My disciplinary devotions began to change when I started working in the headwaters of the Madre de Dios River, at the outskirts of Manu National Park.

Shortly after graduation, I was awarded a postgraduate fellowship with unrestricted funding to put towards a research project anywhere in the world, working with an organization or institution of my choice. I chose to work with an American-Peruvian NGO, the Amazon Conservation Association, on a freshwater monitoring project in the southeastern Peruvian Amazon. Finally, I would get to return home.

It was in Pilcopata, Peru that I first learned about small-scale gold mining in Madre de Dios. One day while talking to my field assistant, Leonidas, who also worked as a day laborer at the research station, he asked if I had heard of the gold rush happening in the neighboring region of Madre de Dios. He recounted how some of the young men from Pilcopata were moving to Madre de Dios to work in the gold mines, making hundreds of times what they would make in a year in just one week. Leonidas said that the work was dangerous, that many of these young men never returned either because they died in accidents in the mines or because they fell into the habit of drinking away their earnings and spending them on women. He said that many of the mines bosses that hired these men were exploitative. Leonidas told me the story of the wealthiest and most famous mine boss in Madre de Dios - an elderly and illiterate woman, who with her husband, helped found the mining town of Huepetehue in the 1950s. Gregoria Baca was said to have made her fortunes exploiting laborers - stealing their wages and allegedly even performing human sacrifices or payments to the earth (*pagos a la tierra*) in an effort to ensure her continued prosperity by paying tribute to the spirit of the earth (*Pachamama)*. These stories piqued my curiosity, but it wasn't until I saw images of the open pit gold mines that I decided that I would pursue a graduate degree so that I could study the social and ecological impacts of gold mining in Madre de Dios.

Initially, I sought to understand the social and ecological implications of the creation of abandoned mining landscapes. As I describe in the opening of this introduction, it was evident from the first mine I visited on my second day in Madre de Dios, that these were not the wastelands portrayed in media reports and popular narratives. Instead, these mines were complex socionatural formations that seemed to be evolving before my eyes. As I walked around that first mined landscape, I noticed newer pits with little or no riparian vegetation and what looked like pits that had long been abandoned and resembled manmade ponds with complex habitat structure and trees beginning to colonize the margins. I was excited by this natural experiment that provided a chronosequence in which to study mercury bioaccumulation and biomagnification under different environmental conditions.

Since each pit looked a little different: different sizes, the presence of absence of certain vegetation, different colors of water - I wondered how the different environmental conditions might affect mercury concentrations in the wildlife in these pits. I also thought about how each pit was formed by people working to extract gold and wanted to know if the actual labor of gold mining had any effect on the trajectory of ecological succession in these created landscapes. I also wondered if these differences in physical habitat structure and diverse ecologies, might indirectly influence the potential of these pits to support methylmercury production given the importance of aquatic environments as the principal sites of mercury methylation. This interest led me down the road of understanding how it is that gold is actually produced and to frame this inquiry in relation to the biogeochemistry of mercury, its environmental fate, and movement through webs of ecological interactions.

In following mercury from the hands of miners using quicksilver to produce gold, to the insects and fish in abandoned mining pits, and finally out of the pit into long-jawed orb weaving spiders, I traced both the ecological relations that mobilize mercury and the social relations in which mercury is embedded. But I couldn't ignore the political context in which my work was occurring and increasingly I was preoccupied by the way I heard government officials, local leaders, and ordinary citizens talk about mercury pollution and gold mining. My first summer in Madre de Dios, I was pulled over on the way to a field expedition, carrying diesel to give to a boat driver. The officer that stopped our taxi informed me that transporting diesel was against the law as most of this diesel was being trafficked into 'illegal' mining camps. As we were pulled over by the side of the road, an SUV with a modified fuel tank drove by without notice. These SUVs were ubiquitous, known as *lecheros* or milk trucks, they trafficked diesel to mining camps located along the Inter-Oceanic Highway. A strip of black rubber sheeting attached to the back bumper of the car, barely hid the modified fuel tank, but also clearly marked these vehicles' purpose. That day, as the officer tried to extract a bribe from us, I realized the first of many contradictions in the governance of small-scale mining. Official government discourse proclaimed zero tolerance for 'illegal' gold mining and government policy regulated the sale and distribution of critical inputs into gold mining, signaling a desire to control the expansion of 'illegal' mining – and yet on the ground, in Madre de Dios, state actors whether police officers or average citizens were benefitting from mining in visible ways that flew in the face of this push towards criminalization.

These contradictions were one among many that I realized along the way. Each of these contradictions has come to inform not only the questions I asked in my research but also my research approach. Above all else, I wanted to ensure that the work I was doing wouldn't reproduce or exacerbate existing inequities within small-scale gold mining or contribute to the further portrayal of gold miners as environmental criminals. In my time in Madre de Dios, I was careful about who I was seen with and who I associated with. Once, while I interviewed the former President of the Regional Small Miners Federation (FEDEMIN), I was accused of being an environmentalist because my University department's name includes the word 'environmental.' The ex-President threatened me and told me that if I was secretly working with 'American NGOs,' I would be found out and would be blacklisted from ever speaking with any miner ever again. This was one of many moments that began to shape my understanding of my research, its political importance, and the extent of my ignorance at having entered into a region where science, particularly mercury science, has been weaponized and politicized by powerful interests. These interactions shaped me in ways that I am still trying to understand and I am grateful that they have forced me to be more reflexive and intentional about the ways in which I represent my research goals and findings.

I came into this project with a certain worldview; one where I understood environmental problems to be the result of human greed and individual action. The first time I stepped foot into a mined landscape, I mourned the loss of non-human life and couldn't resolve where I stood on the issue of mining. I wasn't anti-mining, but I certainly didn't believe that there was a future where gold mining could co-exist with environmental conservation in Madre de Dios. Now, five years later, I find myself seeing these environmental problems in a different light; my worldview has shifted as has my understanding of the ways in which environmental problems are connected to much larger issues that implicate a broader network of actors and touch on structural inequities with long histories of previous manifestations. For example, I can now see the connections between gold mining today in Madre de Dios and rubber tapping that occurred in the region at the turn of the 20th century and led to the enslavement, dispossession, and extermination of indigenous tribes. I understand how Peru's long history as a *pais minero* is related to the government's approach to promoting the development of a small-scale gold mining economy in Madre de Dios during the latter half of the 20th century (see Chapter One). And I now know that gold miners are not villains 'savagely' destroying the world's largest remaining rainforest driven by greed and a desire for quick profits, but instead that these individuals diverse and nuanced motivations are embedded in historical legacies of marginalization and underdevelopment in the Andean regions from which most migrate from. With this heightened understanding, I also now know where I stand on my work and my position on gold mining in Madre de Dios – in particular, this research should be understood not as an indictment of small-scale gold mining but as a call for more socially and environmentally just approaches to mining governance that begin from the understanding that mining in Madre de Dios is heterogeneous and individuals participate in gold mining for diverse reasons. It should also be clearly understood that mercury pollution is a serious problem unevenly affecting the region's most vulnerable and historically marginalized populations. As such, I think that solutions should be designed in a participatory manner and should center the wellbeing of these communities while also acknowledging that there are indigenous tribes that both participate in mining and indirectly benefit from it.

Finally, missing from popular discourse on mining governance in Madre de Dios, are the life stories of miners and their motivations for engaging in the dangerous work of gold mining. The stories of many of these ordinary individuals are lost in the politicized and reactionary narratives around the environmental impacts of gold mining. Yet these life stories are crucial to frame this environmental problem around livelihoods and the underlying drivers of mining expansion which implicate the underdevelopment of rural regions of Peru. In Madre de Dios, there are upwards of 50,000 miners. The population of this least densely populated region of Peru, increased from around 30,000 at the beginning of the 2000s to now more than 130,000, driven largely by in-migration from individuals from Andean regions searching for work (Valencia 2016). Most individuals work informally but this is not exceptional for Peru where more than 72 percent of the population labors informally (Llosa and Panizza 2015). The story of the places from which these people migrate reveal some of the entanglements between small-scale mining and industrialized mining in Peru.

In the past 30 years in Peru there has been an opening-up of the economy to foreign direct investment in extractive industries (Bebbington et al., 2008; Bebbington and Bury 2009). Oil, natural gas, minerals, and metals drive capital accumulation in the hands of a few corporations but has not brought economic development to the country's rural populace. Moreover, many of

Peru's largest mining operations occur in the Andean regions where most gold miners in Madre de Dios migrate from. When asked why they migrated to Madre de Dios, nearly every single one of the miners I've interviewed stated that they came in search of jobs. The search for work and for *livelihoods,* is what drives gold mining in Madre de Dios and Amazonia more broadly. For this reason, the growth of small-scale mining and clandestine economies like illicit timber harvesting and drug smuggling must be understood as a failure of development more than the greed of individuals.

4. Research Approach and Literature Review

This dissertation project is interdisciplinary and as such engages with multiple theories, frameworks, and methodologies across fields that include both the natural and social sciences. While many of these theories and methods are discipline-specific, my approach to the overall dissertation project integrates the natural and social sciences. This approach is best situated within the field of political ecology. My political ecology of the mercury problem in small-scale gold mining combines an understanding of ecotoxicology and mercury biogeochemical cycling with methods and approaches from the field of political ecology which aims to uncover the origins of environmental problems (Blaikie 1985). My approach relied on semi-structured interviews with miners, local experts in mining policy, government officials, and conservation actors within and outside the government to contextualize and deepen my understanding of the 'mercury problem' in small-scale gold mining. I also collected and analyzed biological and biophysical samples from gold mines to trace the movement of mercury in these impacted landscapes. I employed methods in freshwater ecology and ecotoxicology, integrating the use of carbon and nitrogen stable isotopes with mercury concentration data to construct an estimate of the rate of mercury biomagnification in abandoned mines. I also compared biomagnification and bioaccumulation in wildlife found in mines worked with different extraction technologies to better understand how the interaction between the social relations of gold production and the biophysical context of mining landscapes mediates the movement of mercury. Finally, I contextualized my findings within the political-ecological landscape of small-scale mining governance, proposing alternatives to dominant policy and governance approaches (see Chapter Three).

In what follows I outline the overall approach that I employed in the three chapters that form the body of this dissertation. After doing so, I turn to the broader debates within the fields of political ecology, ecotoxicology, and critical science and technology studies that structure my analyses, providing a brief overview of the contributions that my three chapters make.
An approach rooted in political ecology seeks to understand the social and environmental impacts of small-scale mining by explicitly rejecting the notion of humans as external drivers of environmental change and instead disentangling the ways that humans act as a force *within* socio-natural systems, shaping and responding to a changing biophysical environment (Lave et al., 2014). For political ecologists, combining the frameworks of human geography and biophysical sciences better accounts for the multitudinous and nuanced ways in which human-environment interactions *together* shape the landscapes of scientific inquiry. As Urban (2018) states:

> we are no longer simply trying to understand and explain a humanized Earth but rather define landscape dynamics where human agency is mediated by systemic feedback and intentionality (p.60)

Political ecology is a field and an approach that puts into conversation and gives equal footing to social relations of power, politics, values, and culture – and biophysical processes and factors that together produce the particular contours of the problems which we seek to understand. This dissertation uses a political ecology approach to disentangle the interrelations at the multiple scales in which issues surrounding mercury use in small-scale gold mining manifest. The overarching goals of my dissertation project support a political ecology approach by demonstrating how biophysical science or social science alone would be insufficient to understand the complex suite of issues surrounding mercury pollution, the environmental politics of mercury science, small-scale gold mining, and the long histories of mercury use in gold mining in Peru more broadly. My interdisciplinary, political ecology approach to understanding the webs of social and natural relations entangled in ecologies of gold production, has given me greater insight into interactions occurring at multiple scales which better explain the origins of the problem of mercury use in small-scale gold mining.

Political ecology is a critical perspective that does not take surficial relations or evidence at face value. Instead, political ecology takes a critical approach - bringing the politics and power relations underlying the knowledge and meaning making practices that policy, formal institutions, and state practices attempt to normalize to light. Political ecology also considers different levels of analysis, to understand, for example, how international environmental governance of mercury emissions or even different national development goals might have influenced miners' access to mercury. Further, political ecology seeks to not only disentangle the ways that power relations manifest in the ongoing politics of environmental change, but to also identify the root causes of these environmental problems in service of more just and equitable outcomes for people and nature (Perreault et al., 2015; Robbins 2011; Blaikie and Brookfield 1987).

My methods and approaches for understanding mercury pollution in the context of small-scale gold mining also drew from freshwater ecology and ecotoxicology. I began from the observation that abandoned mining pits form new networks of aquatic habitat and that these living laboratories allow for a study of primary ecological succession in real time in the context of an understudied and novel environmental disturbance. These networks of abandoned mines form new hydroscapes that are not well understood and yet are seemingly one of the biggest environmental impacts of mining in this area (Araujo-Flores et al., 2021; Gerson et al., 2020). In terms of mercury's biogeochemical cycling, I wondered whether these ponds were hotspots of methylation on the landscape, and this is why I wanted to use some sort of indicator species to measure whether methlymercury was being exported from these pits.
My initial entry into this question was through the lens of spatial subsidies defined by Polis et al. (1997) as:

> a donor-controlled resource (food, detritus, nutrients) from one habitat to a recipient (plant or consumer) from a second habitat which increases population productivity of the recipient, potentially altering consumer-resource dynamics in the recipient system (p. 290)

I thought of how energy is passed between ecosystems in the form of subsidies from emergent insects, salmon carcasses, and terrestrial leaf litter (Kraus 2019; Cristol et al., 2008; Sabo and Power 2002; Nakano and Murikami 2001; Nakano et al., 1999; Polis et al., 1997). I considered how contaminants and in particular methylmercury is also passed along in consumptive interactions as methylmercury readily accumulates in the fatty tissues of organisms. This negative or dark side of subsidies (Walters et al., 2008) was a productive and novel entry point into the problem of mercury pollution in mining impacted landscapes.

In the end, I chose to examine cross-ecosystem linkages in the context of abandoned mines because they represented for me, the unexplored and invisible impacts of mining and mercury release. These were the invisible pathways by which mercury entered into terrestrial food webs and they begged the question for me, of how far does the impact of mercury released from a single mine travel? Mining was not only reconfiguring landscapes but was also creating a historical record written in the releases of mercury that persist in the landscape for generations. These invisible impacts of mercury become 'visible' in the bodily burdens of certain humans like the indigenous tribes upstream of mines who bear the uneven impacts of gold mining even as they don't participate in the extraction of gold. These complex interrelations and hidden linkages motivated my interdisciplinary approach because I felt that it was fruitless to try and understand how mercury moved in these landscapes without also understanding the motivations and socio-political context in which these mobilities were embedded.

Isotopes and bioindicators as tracers of mercury's movement

The existence of multiple species of mercury in the environment and the interaction between these chemical species and biotic and abiotic processes make it difficult to map out where in the landscape mercury may be converted into its biologically available form or where it may become stored in an inorganic form which does not pose a risk of exposure to humans or wildlife (Hsu Kim et al., 2018; Eagles Smith et al., 2018; Driscoll et al., 2013; Pirrone and Mason 2009; Ullrich 2001). One way of understanding the fate of mercury in the environment and its potential impact on organisms is by studying food web interactions. The concept of 'resource sheds' provides a spatially-explicit conceptual framework to understand how primary consumers utilize energy (carbon) from source areas and how predator-prey interactions can later transport these resources far from their source area (Power and Rainey 2000). Integrating a resource shed framework with stable isotopes of ^{15}N and ^{13}C - used to measure trophic position and basal carbon sources, respectively – allowed me to trace mercury's movement through food webs integrated in time and space (Azevedo-Silva et al., 2016; Chumchal et al., 2015; Clayden et al., 2015; Lavoie et al., 2013; Kidd et al., 2012; Chasar et al., 2009; Kidd et al., 1995).

Moreover, I also leveraged the use of bioindicators which are organisms that act as indicators of contaminant presence and provide a means to measure mercury flux in mining impacted landscapes (Gerhardt 2002). One family of species that acts as a novel indicator of the bioaccumulation of pollutants are long-jawed orb-weaving spiders (Family: Tetragnathidae). These spiders have been used to assess contaminant bioavailability from coal ash spill sites, PCB releases from industrial sources, and the bioaccumulation of heavy metals from atmospheric deposition (Chumchal et al., 2015; Otter et al., 2013; Walters et al., 2008). These spiders are valuable tools in understanding spatial patterns in contaminant bioavailability across aquatic and terrestrial ecosystems. Long-jawed orb-weaving spiders are obligate consumers of emergent aquatic insects and are consumed by a diversity of terrestrial prey (CITES, Power and Rainey 2000). These riparian consumers thus link aquatic and terrestrial ecosystem through the transfer of energy and also contaminants. Particularly for mercury which is used in small-scale mining and may run-off into the sediment of mining pits or be deposited in tailings directly into these pits, spiders act as an important assessment tool to understand whether mercury methylation and bioaccumulation is occurring inside these pits. In Chapter Two, I examined whether mining pits export mercury to terrestrial ecosystems via contaminated prey that are then consumed by long-jawed orb-weaving spiders.

Toxicity Politics

In understanding and theorizing the different social and environmental impacts of the use of mercury in small-scale gold mining, I spent quite a bit of time thinking about pollution and the layers of material and symbolic harm caused by contaminant exposure. The literature in the social studies of science on toxicity provided a fruitful jumping-off point with which to think about contaminated natures and the politics of contamination more broadly. Scholars have argued that we are living in a "permanently polluted world" (Liboiron et al., 2018), in a time where it is impossible to escape so-called "Anthropocenic exposure," brought on by the uncontrolled expansion of capitalism (Roberts 2017). These authors argue that toxicity is a ubiquitous and pervasive legacy, "reproduced by systems of colonialism, racism, capitalism, patriarchy, and other structures that treat land and bodies as sacrifice zones (Liboiron et al., 2018, p. 2)." I affirm these authors notions that toxicity cannot be understood simply as polluting molecules permeating bodies and environments, but instead must be understood as the consequence of entangled socio-political and biophysical relations that enable or constrain particular contaminant outcomes. My understanding of how pollution is produced followed from Liboiron et al. (2018) conceptualization of toxicity:

> toxicity is not given in advance by nature but is stimulated, constructed, rehearsed and contested through a myriad set of social, epistemological, historical, economic, material, biological, and governance systems and structures. Toxicity…has scales, sources, and consequences that manifest in situated ways (Liboiron et al., 2018: 334)

My dissertation argues that pollution is a phenomenon emerging out of and coproduced by the interrelation between both social and biophysical factors at particular spatial scales and in particular historical moments. I push back against the notion of a permanently polluted world by demonstrating how pollution is uneven and mediated by both ecological food web structure and anthropogenic mercury loading in abandoned mines (see Chapter Two). I demonstrate that the level of pollution as measured in the bodily burden of mercury in individual organisms is connected in part to the social histories of these abandoned mines and in particular to site-specific gold production and processing practices (see Chapter Three). Moreover, I show how an understanding of a particular place as 'polluted' must be historicized in relation to past iterations of resource extraction and land use management (see Chapter One). In Madre de Dios, the Peruvian central state once sold mercury to gold miners as part of a larger program to spur rural economic development via gold extraction (see Chapter One). These past legacies of state-sanctioned mercury use have not been publicly addressed and yet they contribute to present narratives and policies regarding widespread mercury contamination in the region. In addition, the toxic legacy of nearly 300 years of extraction of mercury from cinnabar mines in the Andean highlands is almost never mentioned in relation to what is commonly understood as a recently emerging issue of mercury pollution in Madre de Dios. It is only when history, politics, culture, and ecology are taken together and considered in relation with one another that the causes and consequences of mercury pollution can be fully understood and adequately addressed.

Chapter One

Mercurial Natures: Operation Mercury 2019 and the criminalization of small-scale gold mining in Madre de Dios, Peru

Abstract

In the Amazonian region of Madre de Dios, Peru, ever-larger and prolonged military-led interventions claim to ameliorate the environmental and social impacts caused by the expansion of informal, small-scale gold mining by forcibly displacing miners from lands designated as Zones of Mining Exclusion. Central to state and extra state actors' justification for these coercive interventions is the need to protect sensitive Amazonian ecosystems from environmental degradation caused by 'illegal' gold mining. In particular, the use of mercury in informal, small-scale gold mining is singled out as a threat to the ecological integrity of protected areas in Madre de Dios. This article engages with the debates surrounding mercury use in small-scale gold mining and the politics of coercive governance approaches that rely on spatialized containment strategies to displace gold miners from zones of mining exclusion. In this article, I argue for a need to re-imagine both the history of mercury pollution associated with small-scale gold mining in Madre de Dios and to reconsider the long-term negative effects of militarized containment strategies. I argue that these containment strategies negate the biogeochemical complexity of mercury cycling – particularly the mobilities of mercury and miners – in the end failing to contain or control mercury or the miners that rely on it. Further, I demonstrate how the framing of the problem of mercury pollution as one solely associated with 'illegal' gold mining, both belies the history of Peruvian state support of small-scale gold mining and has led to the criminalization of gold mining, rending gold miners as criminals. In ignoring the ways in which mercury is used in small-scale gold mining throughout Madre de Dios, whether 'legal' or 'illegal,' the act of policing miners to reduce mercury pollution ends up exacerbating the risk of mercury exposure for both humans and wildlife by diffusing miners and the mercury they rely on to ever more remote corners of the forest.

Keywords: mercury, state-led territorialization, small-scale gold mining, Madre de Dios, conservation

1. Introduction

On February 18, 2019, President Martin Vizcarra declared a 60-day state of emergency in three districts of the Amazonian region of Madre de Dios, Peru. The Peruvian National Police Force (PNP) with support from the armed forces, were tasked with 'maintaining internal order' in Madre de Dios, temporarily suspending some constitutionally assured rights (Article III, Diario El Peruano, 2019). Following this declaration, on February 19th, Minister of the Interior, Carlos Moran, stepped out of a helicopter onto the sandy soil of *La Pampa* with the Minister of Defense at his side, and proclaimed the beginning of *Operativo Mercurio* (Operation Mercury) 2019 - a coordinated multi-ministry security intervention composed of 1,200 PNP officers, 300 members of the armed forces, and 70 special environmental prosecutors (Ministry of Interior, 2019a). Operation Mercury is a multi-phase security intervention. Its formally stated objective is the eradication of "illegal" gold mining from Zones of Mining Exclusion, through military interventions known locally as *interdicciones* (interdictions or interventions). During an intervention, groups of officers accompanied by specialized environmental prosecutors conduct raids of mining camps, destroying mining equipment and arresting any miners found working in off-limits areas. Such large-scale military interventions are only the latest in a series of coercive, state-led interventions inside the gold field known locally as *La Pampa* – an 11,000-hectare area composed of hundreds of informal, small-scale gold mines and mining camps.

La Pampa is at the center of these military interventions largely because this area is located entirely within the buffer zone of the 274,690-hectare Tambopata National Reserve, a protected area established in 2000. State actors from the Ministry of the Environment – responsible for managing the Reserve and buffer zone - and extra-state conservation advocates and organizations claim that "environmentally sensitive" areas like the buffer zone, are under threat because of environmental degradation caused by small-scale gold mining. Yet, while mercury is used in virtually all small-scale gold mining operations throughout Madre de Dios, only "illegal" mining, or mining occurring within Zone of Mining Exclusion, like in *La Pampa,* has been called out as the source of mercury pollution (Fraser 2009; Brack et al., 2011; Ashe 2012). Framed as a problem associated with illegal gold mining alone, the solution to the problem of mercury pollution in Madre de Dios emphasizes spatialized containment of "illegal" gold mining through militarized intervention, even though the same mercury use characterizes mining outside of the Reserve and buffer zone's formal boundaries (Figure 2). The uneven focus on mercury emissions solely from 'illegal' mining obscures mercury releases from formally titled and legal mining operations, which dominate the extractive landscape in Madre de Dios (Valencia 2016). Moreover, this myopic framing also negates the long legacy of legal and state-supported mercury use in Peruvian mining, which dates back centuries to the exploitation of cinnabar mines in Huancavelica during colonial rule (Lohmann Villena 1949).

As has been true in small-scale gold mining frontiers around the world, formal attempts to contain mercury pollution have consistently created an 'emergency' or crisis out of the growth of small-scale gold mining (Tschakert and Singha 2017; Verbrugge and Geenan 2020). Such crisis narratives are commonplace in the performance of national emergencies that also claim that 'illegal' miners are creating 'wastelands,' and generating other undesirable social and ecological effects. These emergency politics are also substantiated by scientific studies, including those reliant on remote sensing techniques to track the "explosion" of 'illegal' gold mining with ever increasing precision and ecotoxicology studies that measure mercury concentrations in people and wildlife (Asner et al., 2013; Alvarez Berrios et al., 2015; Diringer et al., 2015).

This article engages with these evolving and contested politics, ultimately arguing for a need to re-imagine both the history of mercury pollution associated with illegal gold mining in Madre de Dios and to reconsider the negative effects of militarized containment strategies. In what follows, I demonstrate how the problem of mercury pollution and "illegal" mining are new representations of mining as a criminal activity. Such claims of mining's "newness" and criminalization mask the histories of Peruvian state support of small-scale gold mining. In fact, the Peruvian state facilitated the development of small-scale gold mining throughout the latter half of the 20th century as mining was proudly regarded as a demonstration of good use of national patrimony. Second, I show how coercive governance interventions against miners within the buffer zone arose out of international pressure to control and contain the growth of gold mining substantiated by narratives of environmental emergencies and misrepresentations of mercury science. Finally, I demonstrate how these spatialized strategies of governance do not "control" or "contain" either miners or the mercury they rely on for processing gold; rather, these interventions push small-scale miners ever deeper into the forest and through a series of food web interactions, have the unintended effect of diffusing mercury throughout the ecosystem.

My analysis draws on a close reading of government documents, media accounts, and existing analyses of gold mining and mercury pollution to understand how the mercury problem and solution have been framed and actualized in Peru and how they fit into longer histories of state-led strategies and practices of land use and land control. I also rely on quantitative data collected in abandoned gold mines (Diaz Leiva et al., 2021, *in review*), as well as ecological studies to document how small-scale miners and mercury itself have defied state attempts to impose top-down control on the area. My insights derive from nearly a year of field work in Madre de Dios including more than 40 semi-structured interviews with gold miners, government officials, and environmental NGOs.

Below, I begin by detailing the theories and approaches that guide my understanding of state territorialization (Vandergeest and Peluso 1995), then briefly provide a history of the development of the small-scale gold mining economy in Madre de Dios. I then shift to a discussion on the spatial strategies of governance of small-scale gold mining and the rise of coercive, spatialized governance approaches that aim to contain and control "illegal" gold mining. Finally in the conclusion, I revisit and reinforce my argument that coercive containment strategies have had the unintended effect of diffusing mercury further into the forest through the mobilities of miners and mercury together.

2. Theoretical Approach and Literature Review

In order to consider the potential effectiveness, or lack thereof, of the use of state violence to displace gold mining and miners operating inside Tambopata National Reserve and its buffer zone, I first analyze the origins of what I call "the mercury problem" - or the association between mercury pollution and illegal gold mining. My analysis of the mercury problem relies on a historical approach or a situated history that foregrounds the politics of knowledge deployment.

A historical perspective helps to reveal how current accounts of environmental relations and change exist in relation to their past incarnations and the previous events and interactions that shaped and changed them (Davis 2009; Robbins 2011; Peluso 2012; Perreault et al., 2015). Looking back over time, I analyze how state and extra state actors have framed the mercury problem as a problem of governance, arising out of the practice of illegal gold mining in certain state spaces. In this case, Peruvian authorities are selectively using mercury science to legitimate coercive approaches to environmental governance. However, what their "science-based governance" is unevenly applied, opening spaces for miners to evade enforcement, and thinly veiling the conflicts over land use and control that underlie these governance actions. Moreover, these unevenly applied actions obscure the very fact that mercury is used throughout Madre de Dios in both legal and illegal mining sites, thus the focus only on containment of mercury pollution in illegal mining sites only partially addresses mercury releases from mining.

Spatialized and coercive governance of small-scale gold mining is not unique to Peru but commonplace throughout the >70 countries where small-scale gold mining is prevalent (IGF 2017). In fact, in Amazonia, coercive and spatialized approaches to mining governance have a long history of deployment across the eight countries that make up the Amazon basin (Cleary 1990). As Damonte (2015) posits in his analysis of the increase in the use of violent militarized interventions to eradicate informal, small-scale gold mining in Amazonia:

> In countries like Brazil and Colombia, for example, the use of force is included in legislation pertaining to crime reduction, whereas in Bolivia and Peru the use of force is classified as a 'sanction' (loss of rights). This difference in legal terminology reflects the different objectives of the interventions (Damonte 2015: 2).

The differences in policy objectives surrounding the deployment of coercive governance practices signal divergent motives across different countries but also emphasizes the fact that these policies have become accepted tools used across different countries and in radically different contexts to try and control and regulate informal gold mining. While the underlying motives for coercive governance approaches championed by state and extra state actors in Madre de Dios are likely varied and multiple, it is critical to understand how these policies and politics have shifted over time and what the consequences are today for the health and wellbeing of populations affected by mercury exposure and the violence of militarized campaigns.

To analyze the changing political relations and conflicts underlying the "mercury problem" in Madre de Dios, I consider how mercury used in gold mining relates to territorial relations, state zoning, and the competing claims of state agencies around the access and control of land for gold mining. In particular, I analyze the ways in which state actors play a central role in the ordering of space through processes of territorialization or the control of land, land-based resources, and resource users (Vandergeest and Peluso 1995; Kelly and Peluso 2015). Processes of territorialization can enable resource commodification when state actors and agencies formalize land and allocate property or use rights to land or land-based resources (Kelly and Peluso 2015: 473). Formalizing land or land-based resources and assigning private property rights makes land and resources not only taxable but also controllable by state authorities (Scott 1998). In Madre de Dios, the state-owned mining Bank mapped land, registered miners, and formalized mining concessions beginning in the latter half of the 20th century – these practices constituted processes of internal territorialization (Vandergeest and Peluso 1995) that facilitated the development of the gold mining economy as part of a broader national policy aimed at colonizing "uninhabited" rural Amazonian regions (Garcia 1982).

In sharp contrast to this past history of state promotion of gold mining, today, "new" gold mining areas such as those in *La Pampa*, are criminalized as sites of illicit activity that threaten the conservation of protected areas – particularly Tambopata National Reserve and its buffer zone. State actors in the Ministry of the Environment and Interior, describe *La Pampa* as an 'ungoverned' space, where the 'rule of law' (*estado de derecho*) is absent (Brack et al., 2011). These discursive framings invoke particular understandings and imaginaries of resource frontiers, situating *La Pampa* as a frontier of state control and authority (Salman and DeTheije 2018). Resource frontiers for scholars like Michael Watts (2018) are social spaces, "defined precisely in relation to the presence, capabilities, and interests of the state (p. 480)." I use the concept of the resource frontier, not as a space that emerges at the limits of state control, but instead as a relational space that forms in specific locations, at specific moments in time, through a suite of complex and multi-scaled interactions around the control of particular resources, land, and people (Barney 2009). These relational resource frontiers are always shifting, being reproduced, or even collapsing in relation to changing state and non-state actors' capabilities, interests, and practices of land control. In analyzing the historical development of gold mining in Madre de Dios, I try and unpack how changing relations of power have developed over time as state actors' have come to view certain areas like those within the buffer zone as sites of criminality and as a result have rendered miners operating in these spaces, criminals.

Moreover, the criminalization of small-scale gold mining in Madre de Dios is not only enforced through unevenly deployed territorial strategies of control, but also substantiated by narratives that associate mercury use in gold mining with environmental degradation and the poisoning of people and wildlife (Ashe 2009; Fraser 2009; Brack et al., 2011). But coercive governance interventions, when unevenly enforced only in certain Zones of Mining Exclusion, produce opportunities for gold miners to evade top-down impositions of control. The mobility of miners escaping these interventions and creating "new" mining territories along the way, further complicates the problem and creates the unintended effect of displacing mining to areas further inside the forest. A further layer of complexity is the nature of mercury itself – as a mobile element existing in three different chemical forms each with different mobilities and temporalities. The movement of mercury carried along with miners is yet another unintended consequence of the displacement of gold mining from Zones of Mining Exclusion. Thus, unevenly enforced strategies of containment unintentionally diffuse mercury through Madre de Dios as miners are rendered criminals and go on the run, taking mercury with them. But, the biogeochemical particularities of mercury are ignored in imposing these solutions, as mercury also travels independently of gold miners on currents of air, water, and in the bodies of wildlife.

3. A brief history of the politics of gold mining and environmental conservation in Madre de Dios

The histories of state engagement in the governance and development of the small-scale gold mining economy in Madre de Dios are relegated to the margins in critical debates around the contemporary expansion of illegal gold mining and concerns over associated mercury pollution in Madre de Dios. Dominant narratives attribute the recent expansion of gold mining in the buffer zone of Tambopata National Reserve to rising international gold prices following the global economic recession of 2008 and increased access to the region facilitated by the paving of the Inter-Oceanic Highway in 2012 (Ashe 2009; Fraser 2009; Swenson et al., 2011). But these current accounts ignore the long history of gold mining in Madre de Dios and occlude the importance of state actors and institutions that played critical roles in facilitating the development of a small-scale gold mining economy.

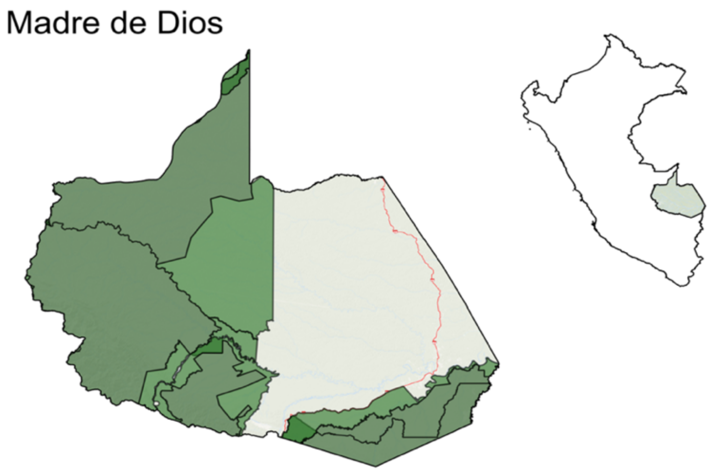

Figure 1. Map of study region showing the extent of protected areas and their buffer zones (green) and the Inter-Oceanic Highway (red) bisecting the region.

Contrary to narratives that paint Madre de Dios as a "new frontier" of gold extraction, the development of artisanal and small-scale gold mining began in the mid 20th century, with a few distinct peaks in production. One of these peaks stretched from the 1940s until the 1950s, when migrants from the Andean highlands travelled to Madre de Dios under informal agreements of debt-peonage to work on the shores of rivers exploiting surface alluvial gold deposits using non-mechanized technologies (Mosquera 2006; Pachas 2009; Valencia 2014, 2016). In addition, Migrants or colonos[1] established settlements in the floodplains of major rivers founding the towns of Huepetehue and Delta, which are still major centers of mining activity in the region (Mosquera 2006; Valencia 2014).

In the 1970s, the development of the small-scale gold mining economy accelerated in Madre de Dios. In-migration of colonos from Andean regions like Cusco, Arequipa, and Mocquegua drove population growth in Huepetehue and Delta, as new mining towns also emerged (Valencia 2014). The environmental impacts of gold mining were also beginning to grow as non-mechanized technologies were replaced by dredges and motor-powered pumps used to suction river sediments (Mosquera 2006; see Chapter Three). Historical accounts from this time period indicate that mercury was widely used to concentrate the fine gold flakes in sediments (Gray 1986). Despite the use of the same mercury amalgamation technique as is used now, during the 1970s concerns over mercury pollution from small-scale gold mining had not yet entered into popular or government discourse and instead state institutions and actors actively promoted alluvial gold mining as a means of rural economic development (Valencia 2014).

In 1978, in the middle of a global rise in gold prices, the military-led government of President Morales-Bermudez approved the Law of Gold Mining Promotion (Ley de Promocion de Mineria Aurifera), which formally declared gold mining an interest of the national state. The policies set under this law included financial incentives to extract gold, including an exemption from paying taxes on gold production for a set number of years (Law No. 22178, Article II, 1978).

1. Colonos is translated as colonists and is a word to describe any individual not indigenous to the Amazon

Formal justification in the text of the law claimed that it was the government's obligation to, "encourage mining at the national-level, thus contributing to the development and accelerated integration of different regions into the country's socio-economic process (Article I)." Incentivizing gold production was justified both as a way to generate revenue and to hasten the pace of rural economic development through resource extraction; this agenda has later been understood also as a civilizing project aimed at promoting colonization of rural regions of the country that were viewed as backwaters (Garcia 1982).

The state-run mining bank (*Banco Minero*), which operated from 1942 to 1991 under the jurisdiction of the Ministry of Energy and Mines – also played an important role in the development of the small-scale gold mining economy in Madre de Dios (INGEMMET 1993). Beginning in the 1970s, the Bank sold tools to miners, allegedly including mercury[2], and bought their gold at strategic outposts proximate to mining camps (INGEMMET 1993; Mosquera 2006; Valencia 2014; Junquera Rubio 2010; Pachas 2015). Not only did the Bank hold a monopoly on the legal purchase of gold from small-scale miners but they also employed geologists and mining engineers to survey gold deposits and demarcate parcels of land for gold mining (INGEMMET 1993; Mosquera 2006; Valencia 2014). The Bank's agents also registered miners and granted exploration and exploitation rights to these parcels (Mosquera 2006; Valencia 2014). By formalizing land and granting use rights to miners, the Bank asserted control over the management of land for gold mining, gold reserves, and acted as a governing authority in this remote region.

For gold miners who worked in Madre de Dios during the 1970s and early 1980s, the mining Bank was both a symbolic and material representation of state support for gold mining and mining livelihoods. As one miner recalled:

> When I arrived, there was the Mining Bank that encouraged us; they paid more than the informal buyers. There was no contraband or trafficking of gold in those days. The state supported us, they backed us (I-23, Puerto Maldonado, April 2019).

This quote demonstrates how for some miners, the everyday practices carried out by the Bank – particularly the purchase of gold at a competitive rate - not only provided material support for miners but was also symbolic of state actor's acceptance and approval of mining as a livelihood. Narratives such as these positioned miners as good development subjects, making best use of national patrimony (Mosquera 2006). Together with institutions like the Bank and the Law of Gold Mining Promotion, these narrative practices helped constitute a discourse of mining-based rural economic development. Today, this discourse remains an important legitimating ideology for state actor's promotion of large-scale industrial gold mining projects in economically underdeveloped Andean regions of Peru (Bebbington and Bury 2008; Bebbington et al., 2009).

State actors' support shifted away from small-scale gold mining and towards large-scale industrialized gold mining under the semi-authoritarian regime of President Alberto Fujimori, lasting from 1990 to 2000, (Bury 2005; Mosquera 2006; Valencia 2014). In line with Fujimori's adoption of orthodox neoliberal economic policies, the mining Bank was dissolved in 1991, opening up the commercialization of gold to private firms.

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2. I have yet to find official government documentation to corroborate miners' claim.

In 1992, Fujimori's government also heralded in a series of laws under a new constitution, that restructured the mining sector through reforms affecting land tenure and property rights (Bury 2005). To hasten the pace of foreign investment into the mining sector, Congress approved a new General Mining Law (Ley General de Mineria), that replaced the Mineral Code of 1950 and the Law of Gold Mining Promotion. The law introduced a new mapping system for demarcating the boundaries of mining concessions and eliminated procedures for resolving multiple land claims on concessions (Bury 2005). Further, the General Mining Law privatized national mining companies and introduced generous tax incentives to promote foreign direct investment in the large-scale mining sector. Effectively, this set of reforms granted foreign mining companies exclusive control over mining concessions by reducing government oversight of disputes over competing land claims, leading to a "bonanza" of foreign investment during the mid to late 1990s (Bridge 2004). Consequently, gold production increased dramatically during the 1990s, as Peru became Latin America's largest gold producer and the 6th largest gold producer globally (Bridge 2004).

The restructuring of Peru's mining sector during the 1990s not only affected large-scale, industrial gold mining but also affected small miners who experienced the loss of technical support and financial incentives provided by the Bank (Mosquera 2006; Valencia 2014). Despite the elimination of the Bank, the 1990s were a decade of gold mining expansion in Madre de Dios, coinciding with rising international gold prices and increased in-migration (Valencia 2014). Land claims for new mining concessions grew following adoption of the new mining law and began to engender conflicts between gold miners and Indigenous communities over legal surface lands (Mosquera 2006; Valencia 2014; 2016). Conflicts mostly centered around mining concessions that overlapped the boundaries of Indigenous territorial reserves - often granted without the knowledge or consent of Indigenous communities (Mosquera 2006; Pachas 2012; Valencia 2014). These conflicts were an outcome of the decades of development policy driven by an imperative to accelerate the pace of extraction of mineral resources by facilitating the acquisition of land rights for mining and eliminating mechanisms for resolving competing claims. But challenges to this dominant extraction-based development policy were quickly emerging under a competing discourse of sustainable development.

The politics of environmental conservation began to crystallize in Peru with the formation of national parks and reserves under a new set of laws ushered in during the late 1990s. Most important was the passage of the National Protected Areas Law in 1997 (Ley de Areas Naturales Protegidas, nº 26834), which constructed a legal framework for the creation and governance of protected areas with differing tiers of restrictions on land use (Solano 2010). While protected areas existed in Peru as early as 1961, the passage of the National Protected Areas Law institutionalized the use of protected areas as a tool designed, "for the conservation of biological diversity and associated cultural, scientific, or landscapes values of interest; as well as for their contribution to the sustainable development of the country (Article I, Ley nº 26834, 1997)." Under this law, now in 2019, more than 17% of the territorial extent of Peru is held under some form of protected status and in Madre de Dios, more than 67% of the land area is protected (Valencia 2014; Weisse and Naughton 2016, Figure 1).

During the 1990s, coalitions of foreign and domestic environmentalists, conservation scientists, and representatives from Indigenous groups joined together to champion the creation of protected areas in Madre de Dios, as a way to protect forested lands from the threat of expanding 'extractive frontiers' (Pacheco Medrano 2017). The coalitions deployed narratives that positioned Madre de Dios as a region with the potential for sustainable economic development based on ecotourism and extraction of non-timber forest products such as brazil nuts (Pachecho Medrano 2017, p. 23). Actors within this coalition viewed the expansion of small-scale gold mining, timber harvesting, and agricultural plantations as a threat to the 'unparalleled' biodiversity of the region. In the early 1990s, a series of stakeholder forums and planning committees were organized with the financial support of Conservation International to create a new protected area out of the famous Tambopata Candamo Reserve Zone (Pacheco Medrano 2017).

The history of the formation of Tambopata National Reserve spans more than two decades of sustained efforts by environmentalists to protect this forested land (Erwin 1985; Pachecho Medrano 2017). In 1977, Max Gunther, an American conservation scientist, constructed an ecolodge and birding retreat on the banks of the Tambopata River. Gunther successfully petitioned the Ministry of Agriculture to designate 5,500 hectares of land surrounding his lodge as an ecological reserve zone (Erwin 1985). The reserve zone and lodge attracted foreign and domestic conservation scientists and tourists, who set out to document the richness of biological diversity in the area. Over time, as scientists mapped the diversity of species, Gunther along with other foreign and domestic environmentalists, joined together to petition for an expansion of the reserve to incorporate neighboring areas of high conservation value. In 1990, these petitions were successful and nearly 1.5 million hectares of forested land were incorporated into the Tambopata Candamo Reserve Zone (RM 032-90-AG). Annexed out of this reserve zone were two protected areas - Bahuaja Sonene National Park created in 1996 and Tambopata National Reserve created in 2000. But as Madre de Dios was parceled off into territories for conservation and extraction, governed by different state agencies and actors with competing interests – the problems engendered by a fractured state land management system were coming to the fore.

In 2001, a moratorium was declared on granting mining concessions in Madre de Dios amidst increasing conflicts over surface land claims (Valencia 2014). In 2002, the total number of mining concessions added up to 560 but by 2013, this number jumped to over 2000, as claims were made overlapping Indigenous territorial reserves, reforestation, timber extraction, and brazil nut concessions, as well as protected areas (Valencia 2014). To organize the development of the small-scale gold mining economy in Madre de Dios and nationally, the first National Law of Formalization of Small-Scale Gold Mining was passed in 2002 (Ley de Formalizacion y Promocion de la Pequeña Mineria y Mineria Artesanal, no. 27651). This law instituted a legal framework and bureaucratic procedures for the formalization of the nation's artisanal and small-scale gold miners (Valencia 2014). Administratively, the law required miners to obtain a tax number, mining concession or contract with a concession owner, and to complete a series of environmental impact assessments before commencing their mining operations (Valencia 2014; Damonte 2016).

In Madre de Dios, the underfunded and understaffed regional office of the Ministry of Energy and Mines was charged with formalizing the region's small-scale miners. However, with no mechanisms to resolve competing legal surface land claims and with multiple state agencies and institutions responsible for overseeing compliance with different requirements of the formalization procedures, formalization failed to produce an ordered, controlled, and taxable small-scale gold mining economy (Pachas 2012; Valencia 2014). Amidst the confusion engendered by the stalled formalization process, moratorium, and the increasing scarcity of legally available lands, informal gold mining rapidly expanded in Madre de Dios throughout the 2000s. Historical centers of mining activity were superseded by new hubs of informal gold mining like La Pampa, located inside the buffer zone of Tambopata National Reserve.

The conflict today over the mercury problem is borne out of these histories; the clash between contradictory development discourses each supported by different constellations of state and non-state actors with different interests that crystallized in particular historical moments. Moreover, what this brief history demonstrates is that since at least 1978, the national state of Peru has bolstered the development of the small-scale gold mining economy in Madre de Dios by founding and supporting institutions like the Bank and laws promoting gold mining by providing incentives to gold miners. State actors within the Ministry of Energy and Mines facilitated the development of a small-scale gold mining economy and effectively endorsed gold production using mercury. This history also shows how present-day narratives that claim mercury pollution and illegal gold mining arose on their own accord, obscure the ways in which state policies and institutions promoted gold mining through both material and representational practices under a discourse of rural economic development through resource extraction. These presentist narratives in effect erase the legacy of decades of mercury releases from mining that was entirely legal and even promoted by state agencies.

4. Material and discursive strategies of territorial control

The Growth of La Pampa

La Pampa is the name given by miners to a gold field that begins on the southern margin of the Inter-Oceanic Highway and extends up until the boundary of Tambopata National Reserve Reserve (Map 2). Thousands of open-pit gold mines, impermanent mining camps, and a small town filled with bars, restaurants, gold buyers, repair shops, and gas stations constitute this hub of mining activity. Before it was widely known as *La Pampa* - from the Spanish word for plains or grasslands – this area was a mix of forested land, land used for smallholder agricultural production, brazil nut harvesting, and timber harvesting (Valencia 2016). But in the early 2000s, a gold strike was discovered beneath the surface of the forest, following the channel of a small tributary known as *Guacamayo* (Valencia 2014; Garcia Delgado 2019). The gold mines of *Guacamayo* closely followed the course of the channel all the way up to the northern margin of the Inter-Oceanic Highway. Recognizing that the gold deposit extended to the other side of the highway, miners began to work on the southern side of the highway in 2006 (Valencia 2016). Palm swamps which fed the stream channel gave way to open pit mines and mining camps as informal gold mines sprang up inside the now formally demarcated buffer zone of Tambopata National Reserve. The location of *La Pampa* within the buffer zone of Tambopata National Reserve proved a critical point of contention in responses to the growth of informal gold mining by state agencies, particularly the newly formed (ci. 2008) Ministry of Environment.

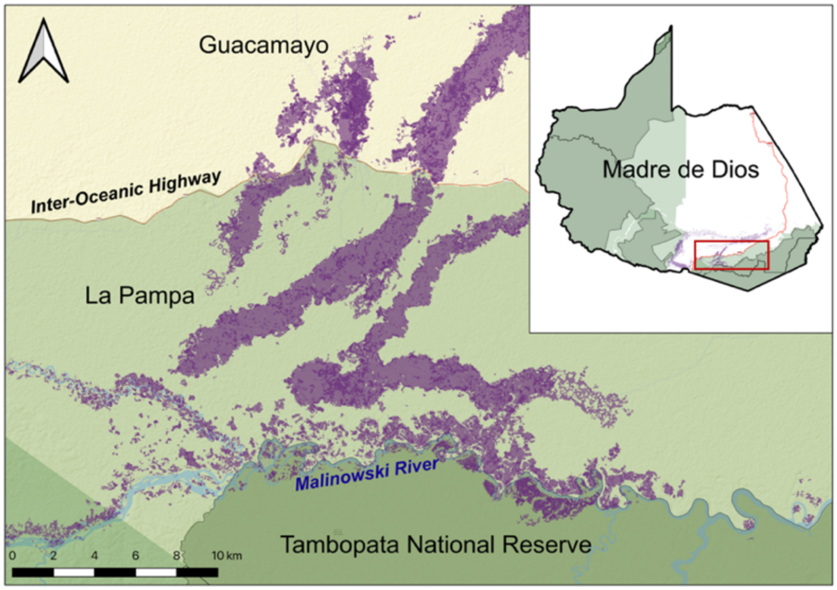

Figure 2. Map of study area showing the borders of Tambopata National Reserve (dark green) and the Reserve buffer zone (light green) as well as the land extent covered by small-scale gold mines in *La Pampa* (purple) up until 2017.

Before the growth of *La Pampa*, small-scale gold mining concessions were permitted within the buffer zone of Tambopata National Reserve (Mosquera et al., 2009; Valencia 2014). Zoned for multiple land uses, buffer zones as defined within the National Protected Areas Law, were ultimately meant to “reduce harmful extractive activities near protected areas” (Law No. 28634, Article 25, 1997). But, at the time of the establishment of the buffer zone in 2005 – five years after the designation of the Reserve – small-scale gold mining was not yet seen or represented as inherently harmful or threatening to the protection of the Reserve. In fact, a number of small-scale gold mining concessions were granted by the regional office of the Ministry of Energy and Mines inside the buffer zone and remain active today (Weisse and Naughton 2016; Damonte 2016, 2018). Local environmental NGOs even provided technical support to two associations of artisanal gold miners so that they could obtain titles to concessions within the buffer zone and formalize their mining operations (Valencia 2014; Damonte 2016). But the understanding that small-scale gold mining could co-exist within the buffer zone and posed no threat to the protection of the Reserve, quickly shifted as informal gold mining rapidly grew inside the buffer zone.

Figure 3. Aerial image of the open pit gold mines of *La Pampa* taken in a flyover following declaration of a state of emergency in 2019. Source: Ministry of Environment.

The magnitude and visibility of deforestation caused by the growth of gold mining inside the buffer zone, raised alarm amongst environmentalists active in the zoning of the Reserve, conservation scientists, and state actors within the Ministry of the Environment (Brack et al., 2011). The striking visuals emerging from *La Pampa* at the tail end of the 2000s, helped to reproduce crisis narratives that portrayed this space as a "ground zero" of environmental degradation (Ipenza 2012). Photos taken by the first Minister of the Environment from a helicopter flyover of *La Pampa* and data on the rates of deforestation collected using novel LiDAR and remote sensing technologies substantiated claims of the "chaotic" and "explosive" growth of gold mining within the buffer zone (Brack et al., 2011; Asner et al. 2013). Moreover, reports commissioned by environmental NGOs like Conservation International and the Peruvian Society for Environmental Justice, linked the growth of gold mining in *La Pampa* to increases in illicit activities like narcotrafficking, sex trafficking, and child trafficking (Mosquera et al., 2009). In media representations like the documentary, "River of Gold" - produced by the Amazon Aid Foundation – "illicit small scale gold mining" in *La Pampa* was accused of causing "the savage unravelling of pristine jungle." Along with narratives of environmental degradation from deforestation, claims of mercury pollution were also increasingly used to substantiate the crisis narratives surrounding gold mining expansion in the buffer zone of the Reserve.

In particular, a prominent publication by the Ministry of the Environment titled "Gold Mining in Madre de Dios and Mercury Contamination - a Time Bomb," argued that the use of mercury in illegal gold mining jeopardized the health of people and nature (Brack et al., 2011). The report stated, "We calculate that in the past 20 years more than 3,000 tons of mercury have been dumped into Amazonian rivers, contaminating the water, aquatic organisms, and people that consume water and fish (Brack et al., 2011, p. 15)." This report also reproduced narratives of criminality, describing the proliferation of 'mafias' controlling zones of illegal mining (p.5). The report's central message was that mercury contamination from illegal gold mining constituted an environmental emergency that threatened the ecological integrity of Madre de Dios' protected areas, people, and wildlife. The narratives of criminality, pollution, and environmental degradation from increasing deforestation in the buffer zone helped to constitute a discourse of dystopic development and substantiated the need for more forceful intervention to limit mining expansion.

4.2 Territorial and legalistic strategies of control

In 2010, following recommendations laid out by a multi-sector working group led by the Ministry of Environment, created to address concerns over the social and environmental impacts of informal mining expansion in Madre de Dios - President Alan Garcia signed a series of executive decrees that broke with previous government's policy of promotion of small-scale gold mining (Valencia 2014: 112). Decree of Urgency No. 012-2010 stated that ordering the development of gold mining in Madre de Dios was both in the national interest of the State and necessary to guarantee the conservation of national patrimony and the development of sustainable economic activities, amongst other objectives (Article 1, 2010). The first Minister of the Environment, Antonio Brack - a key architect of the decree - heralded the new policies as an important step in controlling the negative social and environmental impacts brought on by the growth of informal and illegal gold mining in places like *La Pampa* (Andina 2010).

Central to this decree was a territorial strategy of land control that designated "Zones of Exclusion" of artisanal and small-scale gold mining in Madre de Dios and granted authority to the Ministry of Interior to deploy marines and national police to enforce these demarcations using interdictions (DU 012-2010, Article 1). Minister Brack announced that gold mining concessions would only be permitted within an area designated as the 'mining corridor' – covering approximately 9 percent of the territorial extent of Madre de Dios (Andina 2010). The zones of exclusion, where new mining concessions were explicitly prohibited, included the buffer zone of Tambopata National Reserve, as well as other protected areas and indigenous territorial reserves in the region (DU-012, 2010, Article 4). Already titled mining concessions were unaffected by this policy – even if the concessions overlapped the buffer zone or an Indigenous territorial reserve - so long as concession holders complied with requirements to formalize their mining operations. For those miners who had yet to begin formalization procedures, the decree modified the requirements necessary to obtain an environmental certification - a prerequisite for authorization of exploitation rights (Valencia 2014). While this decree was the first government policy to use the term illegal gold mining in reference to the practice of gold mining in a zone of exclusion, no formal definition was included in the text of the decree. The prohibition on granting new mining concessions within the buffer zone of Tambopata National Reserve, represented the first step in a series of legalistic and territorial strategies of control aimed at constraining the behaviors and practices of miners operating within certain state spaces.

Table 1. Criminalization of gold mining was institutionalized in a set of legislative decrees passed under Law No. 29815 (2012). The following decrees were most pertinent to the case of illegal gold mining in Madre de Dios.

Date	Legislative Decree No.	Objectives
February 18, 2012	DL 1100	Authorizes the use of interdictions as a tool to combat illegal mining throughout Peru
February 28, 2012	DL 1101	Implements new legal frameworks for the prosecution of illegal mining as an environmental crime
February 28, 2012	DL 1102	Incorporates illegal mining into the penal code
March 3, 2012	DL 1103	Implements measures for control of the distribution, transportation, and commercialization of chemical products that could be used in illegal mining

In 2012, during the first months of the presidency of Ollanta Humala, the criminalization of mining and miners operating in zones of exclusion was formally codified in a series of legislative decrees (DL 1099 – DL 1108, 2012). Under Law No. 29815, congress delegated legislative powers to the President for 120 days to implement new policies to control illegal mining (Article 1, 2012). In subsequent months, President Humala signed nine legislative decrees that together constructed a framework for the criminalization of illegal mining throughout Peru by institutionalizing the use of interdictions as a tool to sanction illegal mining; granting authority to the National Police and marines to carry out these interdictions; and incorporated illegal mining into the penal code. A few of these decrees modified existing legislation pertaining to Madre de Dios, expanding the prohibition on mining not only within zones of exclusion but also within waterways (DL 1102, Table 1). Also included, was a definition of informal and illegal small-scale gold mining that differentiated the former from the latter based solely on whether mining activity occurred within a zone of exclusion (DL 1105, Article 3, 2012). Together, this set of legislative decrees, constituted a momentous shift in development policy away from the promotion of small-scale gold mining as a means for rural economic development and towards the criminalization of small-scale gold mining and miners based on territorial zones of mining prohibition. Not only was gold mining in certain state territories criminalized, but the practices of using mercury in mining – once supported by state institutions – were also being criminalized.

In 2013, Peru signed the Minamata Convention on Mercury – a binding international treaty that explicitly aims to "protect human health and the environment from anthropogenic mercury emissions (Minamata Convention, Article I, 2013)." As allegedly the largest global source of anthropogenic mercury emissions, mercury used in artisanal and small-scale gold mining is a target of international environmental governance (Rubiano Galvez 2020). Eliminating the use of mercury in illegal gold mining was a central objective of Peru's National Action Plan for reducing anthropogenic mercury emissions. The Ministry of Environment published a report outlining arguments in support of ratification of the Minamata Convention in Congress (MINAM 2014). Central to the Ministry's claim was that addressing mercury pollution required a national strategy to crack down on illegal gold mining, which was best executed under a national action plan as required by the Minamata Convention (MINAM 2014).

To eliminate the use of mercury in illegal gold mining, the central state granted authority to the customs and taxation agency, SUNAT, to regulate the commercialization, trade, and importation of mercury. Under a ministerial resolution passed by SUNAT in 2014 (no. 207-2014-SUNAT), a permit was required for the legal purchase of mercury destined to be used in gold mining operations not only in Madre de Dios but throughout Peru. Individuals or corporations may only apply for a permit if they hold the legal title to a gold mining concession. Moreover, as part of the sanctions on illegal mining introduced during Humala's government, selling or buying mercury destined to be used in illegal mining is now considered a crime that can be prosecuted under a special section of the penal code called Crimes Against the Environment (Ipenza 2012). Individuals caught buying or selling mercury without a permit, can now face up to 8 years in prison. Notably, this resolution does not prohibit the use of mercury in all small-scale gold mining operations - by permitting the sale of mercury to individuals with a title to a mining concession, it opens space for the continued use of mercury on certain lands where mining concessions are permissible. In effect, this series of legalistic actions borne out of the international pressure to regulate mercury use in small-scale gold mining has created even more avenues to sanction illegal gold mining and strengthen associations between mining and illicit operations like mercury trafficking.

In short, informal gold mining in the area known as *La Pampa* began to grow at a critical historical juncture where new actors and agencies in the Ministry of Environment played an outsized role in shaping the approach to the governance of small-scale gold mining in Madre de Dios. As a territory demarcated for conservation, the buffer zone of Tambopata National Reserve became a central focus of state and private-led efforts to contain and control the growth of informal gold mining. Narratives of environmental harm caused by mercury pollution and deforestation generated a crisis out of the growth of gold mining in the buffer zone. Drawing on evocative images of denuded Amazonian rainforests polluted by mercury, emboldened actors within the Ministry of the Environment used legalistic tools to exercise territorial control over the buffer zone by delimiting this space as a zone of mining exclusion. The creation of a juridical distinction between illegal gold mining and informal gold mining based on the former's presence within zones of exclusion like the buffer zone and the granting of authority to the National Police and marines to enforce these territorial demarcations are both processes of internal territorialization that continue today. Importantly, these territorializations are not new – instead, when considered in relation to the history of the development of the small-scale gold mining economy in Madre de Dios, these strategies are simply a continuation of extant territorial governing logics.

What is novel is the emergence of an entirely new discourse of criminality rather than national pride. Narratives associate illegal gold mining in zones of exclusion with widespread environmental degradation caused by mercury pollution and deforestation. These environmental crisis narratives, both justify the criminalization of gold mining and render gold miners operating within the buffer zone as environmental criminals, deepening the marginalization of small producers (Childs 2014; Tschakert and Singha 2017). Coinciding with the construction of criminality of gold mining in the buffer zone were international efforts aimed at reducing mercury emissions from artisanal and small-scale gold mining. The narratives of environmental degradation and pollution emerging at this historical juncture, helped constitute a discourse of dystopic development which provided a moral and political obligation for state actors to justify legalistic and territorial strategies of control of gold mining in certain places. Increasingly, these governance strategies are not only substantiated by narratives of environmental degradation but also by misrepresentations of the science of mercury.

4.3 Environmental Emergencies

There is a great degree of uncertainty in the sources of mercury pollution in not only Madre de Dios, but Amazonia more broadly, as the science of mercury cycling in the tropics is still not well understood (De Oliveira et al., 2001; Figuereido et al., 2018; Crespo-Lopez et al., 2020). There is however one technique that allows scientists to trace the source of mercury measured in wildlife or sediments to an anthropogenic source such as the mercury used in small-scale gold mining or to a natural source such as mercury stored in trees and soils. This technique relies on an unusual property of mercury isotopes (atoms with different numbers of neutrons) called mass independent fractionation (Bergquist and Blum, 2009). By comparing the isotopic signature of various potential sources of mercury such as the inorganic mercury added in mining operations or mercury in sediments or tree leaves, mercury stable isotopes can be used as a tracer of mercury's origin in a matrix of interest. Most recently, mercury stable isotopes have been used in studies of informal gold mining in the Amazon basin (Adler Miserendino et al., 2018; Schudel et al., 2018) and recently in Madre de Dios to measure the sources and concentrations of mercury in air samples collected near mining towns and in distant forests (Szponar et al., 2021, *forthcoming)*.

In one study in the Amazon basin, it was found that sediments downstream of mining activity had isotopic signatures more closely resembling natural mercury sources rather than that of mercury used in small-scale gold mining (Adler Miserendino et al., 2018). This finding highlights the fact that 'rereleases' of natural sources of mercury through deforestation and sediment runoff can add to mercury released in tailing from small-scale gold mining. Thus, any land use that results in deforestation, such as ranching, agriculture, or mining, can also drive releases of mercury trapped in trees and soils. Difficulty in characterizing the source of mercury pollution, demonstrates how the association between illegal gold mining and mercury releases is ultimately more politically motivated rather than scientifically supported. Despite this uncertainty, scientific findings on mercury pollution in Madre de Dios are often used as further justification for coercive interventions aimed at eliminating illegal gold mining.

In 2016, after four years of sporadic military interventions within the buffer zone, deforestation in *La Pampa* continued to grow at ever faster rates (Caballero Espejo et al., 2018). Small-scale gold mines also began to appear within the actual territory of Tambopata National Reserve, prompting alarm from state and extra state environmentalists who decried the "invasion" of the Reserve and the "toxic trail" left by gold miners (Pighi Bel 2016; Daley 2016). Narratives of widespread mercury pollution from illegal gold mining were reproduced by new studies that documented the bodily burden of mercury in humans and wildlife (Diringer et al., 2015). One study found that more than 60% of the fish sold in local markets exceeded international guidelines for mercury consumption, prompting a ban instituted by the Ministry of Health on the sale and distribution of certain fish species (Fernandez and Gonzalez 2009; SANIPES 2016). Yet another study documented high bodily burdens of neurotoxic methylmercury in Indigenous members of tribes located within Manu National Park – hundreds of kilometers upstream of mining activity (Diringer et al., 2015). As mercury's extra-local impacts were made legible by these studies, the actual scientific findings were also being used as justification for additional top-down interventions aimed at controlling illegal gold mining in the buffer zone.

By May of 2016, the crisis of mercury pollution allegedly driven by the expansion of illegal and informal gold mining led to the declaration of a sanitary state of emergency in Madre de Dios (No. 24-2016-PCM). The official text of the declaration of a state of emergency included the following:

> the contamination of air, water, sediment, and fish with mercury is a consequence of the inadequate practices used by illegal and informal mining during the extraction and processing of alluvial gold; and there exist populations located outside of mining extraction zones, who are at a high risk of being affected by mercury contamination because of the high concentrations of this mineral detected in the environment and distinct fish species… (El Peruano 2016: 2)

What this declaration makes clear is that at some point in the digestion of these scientific findings, informal and illegal gold mining was signaled out as the culprit for environmental mercury contamination despite a lack of scientific evidence to support these claims of causality. Moreover, this contamination was viewed not only as a threat to the health of humans living outside mining areas, but as an environmental emergency warranting state intervention. In a press conference following the declaration of the state of emergency, Minister of the Environment, Manuel Pulgar Vidal, compared the scale of mercury contamination in Madre de Dios to the 1956 disaster in Minamata Bay, Japan – decrying the irresponsible practices of mercury use in illegal gold mining (RPP Noticias 2016). Moreover, what followed were a series of military-led interdictions in *La Pampa* and deployment of marines to displace gold miners working within Tambopata Reserve (Pighi Bel 2016; Damonte 2018;).

The declaration of a state of emergency substantiated by associations between mercury concentrations in fish, sediments, people, and water and releases from a particular source – illegal gold mining – reveals one of the ways that mercury science is used as a justification for coercive governance interventions. However, this justification is based on a misrepresentation of scientific findings and the proposed solution of control and containment of illegal gold mining – enforced only in zones of mining exclusion – does not actually address the problem of mercury pollution. Further, as these interventions are unevenly applied, they ignore the reality that mercury is used in small-scale gold mining throughout Madre de Dios and is also released from natural reservoirs by land use activities aside from gold mining.

4.4 Operation Mercury 2019

> *La Pampa* represents all the evils of Peru - narcotrafficking, sex trafficking, illegal logging - for too long people have been dependent on illegal mining; we must sever that tie
>
> - Ex-Minister of the Environment, Fabiola Muñoz (El Comercio 2019).

Two months after the beginning of Operation Mercury 2019, I found myself on the other side of the Malinowski River, which forms the border between Tambopata National Reserve and the buffer zone (Figure 2). A group of 20 marines and National Police officers were housed at the ranger station where I stayed. The marines and police worked with park rangers patrolling this outer edge of the Reserve to prevent miners from (re)entering the protected area. During patrols, marines and rangers travel on foot or in boats, searching for miners. More often than not, they find abandoned mining equipment - motors, dredges, diesel, and recently constructed sluices. Under DL 1100, they are legally obligated to destroy whatever equipment they find, strapping dynamite to motors and sinking dredges to prevent miners from returning to their camps (DL1100, Article II, 2012).

These military interdictions are always well-documented; photos of commandos in full tactical gear equipped with automatic weapons standing proudly in front of a blown-up motor or the flaming ruins of a mining camp are reproduced in news reports and other media (Figure 4). Military personnel make note of how many dredges, motors, meters of PVC pipe, gallons of diesel, reams of carpet, and sluices they detonate. These numbers are added to a running total, often repeated by commanding officers, as evidence of their progress towards “eradicating” illegal gold mining and illustrative of the ‘successes’ of Operation Mercury (TelePuerto Noticias, 2019; Marina 2020). While these coercive governance interventions are now being lauded as a decisive step to eradicate illegal gold mining and its attendant social and environmental ills, with respect to mercury pollution, these uneven strategies of control negate the very ways in which mercury moves through and within the environment, both as a naturally occurring element and in releases associated with gold mining activity.

Figure 4. Media representations of military interventions in *La Pampa* at the beginning of Operation Mercury 2019, often depict the destruction of mining equipment and the occupation of mines.

5. Mobilities

As I have demonstrated, the criminalization of gold mining in Madre de Dios is a recent phenomenon underpinned by territorial governing logics that permit mining in certain places and prohibit it in others. But the criminalization of mining and mining practices using mercury only in zones of exclusion, in effect condones the practices of small-scale gold mining outside of these zones of exclusion regardless of the social or environmental impacts. Moreover, these top-down containment strategies obscure the mobilities of miners and mercury alike, as miners move about the region searching for productive gold deposits and evading interventions.

5.1 Mobile Miners

A few kilometers from one of the three bases that form the nucleus of Operation Mercury 2019, I stood in front of an open mining pit with my friend Vero, a restaurant owner turned mine boss, and soon to be licensed forestry engineer. Floating on a raft in the middle of this pit, was Vero's *traca*[3], a 220-horsepower motor attached to a suction pump with a long lance-like PVC pipe on one end. The maneuverable arm of the *traca* extended into the murky waters of the pit and dredged up bottom sediments containing fine flakes of gold that are pumped to a large sluice lined with carpet - used to trap the heavier gold particles while allowing the sediment to run-off. Vero used to have two *tracas* working in one of the hundreds of illegal mining camps found within *La Pampa*. But when the military arrived in mid-February, she like many of the estimated 40,000 miners working in *La Pampa*, ordered her crews to stop mining and buried both of her motors to prevent them from being destroyed by the military and police forces. Five months into Operation Mercury, with her cash flow run dry, Vero decided to unearth one of her motors so she could put her crew back to work.

3. Essentially a *traca* is a dredge set powered by a car motor and mounted on a raft.

She coordinated a move in the early hours of the morning, retrieved the motor, and transported it to a new site across the highway from *La Pampa*. This new site, located on a titled mining concession, required a weekly payment of rent in kind to the concession holder, and a one-time fee to the pit boss, but provided Vero with a way to continue mining while avoiding the military's interdictions.

As the mechanical chopping sound of the motors continued to drone on against the backdrop of a searing afternoon sun, Rodrigo - Vero's boyfriend and crew boss - removed a small bottle of silvery liquid from his pocket, the label read *Mercurio el Español*. I watched as he added the contents of the bottle to an empty oil drum containing a deep charcoal-colored sand that shimmered in the sunlight. He pulled up his red basketball shorts, lifted one leg into the barrel and began to mix the slurry of metals until the mercury enveloped the gold dust. In the distance another dynamite explosion marked the loss of a motor or a drum of diesel, the collateral damage of a war being waged against an invisible enemy.

Later as we finished lunch, Rodrigo placed a silvery amalgam of mercury and gold - about the size of a gumball - on an empty, rusted tin of evaporated milk. With nothing more than a simple blow torch and a metal spoon he began to roast the amalgam, working slowly and using the spoon to spread the hot metal against the surface of the can. The silvery amalgam turned from orange, to fiery red, and finally after about 15 minutes, gold. While the amalgam was roasting, I noticed the heaviness of the opaque-white mercury vapors sinewing off the metal, struggling to dissipate as the wind finally blew them away.

In this formal mining concession, mercury is mobilized on currents of air and water – absorbed through the pores of leaves into the tissue of trees or settling into soils and sediments (Hsu Kim et al., 2018). These vapors also enter the atmosphere, travelling on wind currents for days, weeks, or even years at a time; redeposited back to the forest and waterbodies through rain or attached to fine particles (Selin 2009; Driscoll et al., 2013). These mobilities of mercury coupled to those of miners subvert spatialized strategies of control, diffusing the impact of mercury pollution to ever-more remote corners of the forest.

Vero's story is not only illustrative of the ways that miners evade the top-down imposition of territorial control in response to coercive containment efforts, but it also shows how mercury's mobilities can articulate with those of miners. As new mines emerge in distant watersheds (MAAP 2020; TelePuerto Noticias 2021) following the occupation and displacement of miners in La Pampa, mercury is transported and released into these ever-more remote areas.

5.2 Mobile Mercury

Mosaics of manmade ponds filled with water in shades of cerulean blue, terra cotta red, and pea green form new networks of aquatic habitat out of the abandoned open pit mines in *La Pampa* (Figure 5). A diversity of wildlife colonize these manmade ponds, from insects to amphibians and even mammals like the giant river otter. During the rainy season when rivers rise and flood surrounding areas, these ponds become hydrologically connected to mainstem rivers. The landlocked organisms inhabiting these ponds can then move freely through the region transported by these hydrologic connections. These creatures make up part of the new ecologies forming in places like *La Pampa*; the created landscapes left behind by the displacement of mining from these zones of exclusion.

Fauna and flora aren't the only things present in these ponds - mercury from mine tailings is also found in bottom sediments; although the amount varies from pond to pond and even across ponds worked with different extraction technologies (Diaz Leiva et al., 2021). Importantly, these ponds are also sites where mercury can be converted from its inorganic form - used in mining - to its most biologically-available and toxic form, methylmercury (Gerson et al., 2020). The still waters provide ideal conditions for microbes to transform mercury into methylmercury in the low-oxygen environment found in the bottom sediments. Once methylated, this mercury is taken up and concentrated in the bodies of wildlife, primarily through dietary exposure (Eagles Smith et al., 2018).

But mercury doesn't just remain inside a mining pit, it moves from body to body as predator consumes prey. Mining pits export mercury in the bodies of insects. Spiders that colonize the vegetation on the riparian edge of mining pits consume adult insects emerging from the ponds, thus transferring mercury from aquatic to terrestrial ecosystems (Diaz Leiva et al., 2021). Mercury carried in the bodies of these emergent insects can then accumulate and concentrate up the food web into larger predators like birds and bats whose movement across larger areas further extends the footprint of mercury pollution. These food web interactions are one way that mercury is mobilized, carried and magnified in concentration in wildlife as they move through Amazonian ecosystems, irrespective of the territorial boundaries of protected areas or titled mining concessions.

In the flowing waters of Amazonian rivers, the movement of mercury in the bodies of wildlife is facilitated by a diversity of migratory fish species. The rivers of the Amazon basin are some of the world's most biologically diverse and are home to wildlife like freshwater sting rays, electric eels, and mega-fishes; fish species that can reach body sizes greater than 30 kg (He et al., 2019). Some of these mega-fish are migratory; travelling greater than 5000 km in their lifetimes to spawn in the major tributaries of the Amazon River like in Madre de Dios (Barthem et al., 2017). The risk of methylmercury exposure for humans who consume fish is compounded by the ecological context wherein these large and long-lived fish species both accumulate a lot of mercury over their lifetime and travel long distances - extending the potential for human mercury exposure over a larger area. Exposure albeit is uneven, as Indigenous communities who rely heavily on the consumption of fish protein have been found to have the highest bodily burdens of methylmercury of any population in Madre de Dios (Fernandez et al., 2019).

Figure 5. Abandoned gold mines inside Tambopata National Reserve form new aquatic habitat for wildlife and harbor mercury in bottom sediments. Source: Author.

By considering both the mobilities of miners and mercury alike, it is clear that the problem of mercury pollution cannot be addressed through an approach that centers containment of illegal gold mining. Mercury travels and moves with miners, beyond mines, and in the bodies of organisms that move unrestricted through the diverse ecologies of Amazonian rivers and rainforests. Moreover, mercury's movement – in water and air – is facilitated by both the biogeochemical properties of this substance *and* the mobilities of miners as they move about the region. These socio-ecological mobilities demonstrate why spatialized strategies of containment of illegal gold mining will ultimately fail to control mercury pollution. Moreover, the mercury problem, framed as a problem of illegal gold mining in certain places, directly undermines the very real problem of mercury exposure that is now diffuse throughout the region of Madre de Dios and beyond. The persistence of mercury in the environment for long periods of time further complicates this problem, as reductions in emissions and releases today will not result in reductions in the bodily burdens of organisms for many years to come, meaning that the risks of mercury exposure for humans will persist over time (Driscoll et al., 2013). As long as the mercury problem is framed as a problem associated with illegal gold mining - best solved through coercive containment strategies – the risks of mercury concentrating and accumulating in bodies outside of these foci of containment remains unaddressed.

Conclusion

State-led territorializations to control land, resources, and resource users - predate the existence of *La Pampa*, the buffer zone, and territory of Tambopata National Reserve. The long history of territorializations in Madre de Dios, produced a system of fragmented land management – a terrain rife with competing interests and claims of different state agencies manifested within a concessionary property regime. As different state agencies granted concessions - many overlapping one another - conflicts proliferated around competing land use designations in these legal territories. In the middle of this conflict, small-scale gold mining began to expand in the buffer zone of Tambopata National Reserve. As state and extra state actors mobilized both narratives of environmental degradation caused by mercury pollution and misrepresentations of mercury science, a discourse of criminality emerged, linking mercury pollution to illegal gold mining. Importantly, the criminalization of mining in territorialized zones of exclusion was meant to protect sensitive environments. But, the environmental impacts of gold mining - deforestation and mercury pollution - remain the same whether located within a zone of exclusion or not. The singular focus today on the illegality of gold mining in certain protected areas, contributes to the crisis narratives that legitimate coercive interventions but actually does little to mitigate or address the risks of mercury exposure for vulnerable populations in Madre de Dios.

Deploying mercury science to justify coercive governance interventions has only served to politicize and undermine the results of these scientific studies to the detriment of those populations who bear the uneven burden of mercury exposure. As long as mercury is used as a tool to justify coercive approaches to environmental governance, the risks of mercury exposure will never be truly addressed. In ignoring the ways in which mercury exists apart from gold mining and moves freely through the environment on currents of air, water, and through the 'natural' interactions between the plethora of species that make up these diverse Amazonian ecologies, the act of policing miners to reduce mercury pollution ends up exacerbating the risk to humans and wildlife by diffusing mercury to ever more remote corners of the forest. To begin to work towards socially and environmentally just solutions to the complex problem of mercury pollution, the politics of land use and land control underlying these coercive strategies need to be brought to light and the use of coercion as a mechanism to sanction and criminalize the practices of miners operating in certain places must be reexamined.

Chapter Two

Social and ecological factors coproduce mercury pollution in abandoned gold mines

Abstract

Artisanal and small-scale mining is a significant and growing livelihood across the global South, which all too often leaves a legacy of contaminated landscapes. Given the increasing reliance of economies on metals and minerals, it is critical to understand what controls contamination outcomes in this rapidly expanding extraction-based livelihood. Here, I demonstrate that the emerging concept of co-production offers a novel way to elucidate the joint contributions of natural and societal factors in shaping contaminant exposure from artisanal and small-scale mining. Specifically, understanding the co-production of contaminated landscapes requires attention to both the political economy of mining, including how labor arrangements and extraction technologies differ across mines, as well as the sources and pathways of mercury exposure. In Madre de Dios, Peru, I measured mercury levels in wildlife inhabiting abandoned gold mining sites worked with different extraction technologies. I found that the type of technology used, whether heavy machinery or suction-pump based, influenced mercury loading into mines, and together with differences in food-web structure, mediated mercury bioaccumulation in wildlife. Mercury concentration increased 4.4 to 5.2-fold per trophic level, and bioaccumulation was high in both mined and unmined sites—indicating high background levels in the region. I also found evidence of lateral transfer of mercury from abandoned mining pits to terrestrial food webs. This observation indicates that the footprint of mercury contamination extends well beyond individual mines, affecting the larger landscape. My findings underscore the necessity of understanding the entangled ways in which social and natural factors contribute to the production of polluted landscapes.

Keywords

Artisanal and small-scale gold mining, bioaccumulation, biomagnification, food webs, coproduction

Introduction

Artisanal and small-scale mining (ASM) is a complex, entangled social-natural system. ASM currently underpins the well-being of over 200 million people (IGF 2017; Hilson et al., 2019), many of whom work under dangerous conditions to extract precious metals, gems, and minerals (Lahiri-Dutt 2018). However, like most mining, ASM often leaves a legacy of contaminated landscapes and sick people (Diaz Leiva 2021). Mining often causes the degradation of land, rendering it unsuitable for subsistence activities; all the while toxic elements used in processing can cause serious problems for individuals that consume contaminated food (Hsu-Kim et al., 2013; Alvarez-Berrios et al., 2015; Eagles Smith et al., 2018). I contend that understanding and addressing the environmental and social problems caused by ASM requires acknowledging that contamination is coproduced by social and natural processes. As an analytic approach, coproduction integrates not only environmental sources and pathways of contaminant exposure, but also an understanding of the heterogeneity in mining practices in a particular mining locality.

The case of artisanal and small-scale gold mining (ASGM) is particularly noteworthy because of the pronounced social and natural changes brought on by the growth of ASGM throughout the global South. ASGM is a low-tech, labor intensive form of gold production that largely occurs outside of formal economies and is the principal livelihood for over 40 million individuals and 150 million indirect beneficiaries—supplying more than 20% of global annual gold production (Hilson et al., 2019; IGF 2017). The livelihood benefits of ASGM are extensive, especially in rural communities but the environmental impacts are also substantial (Lahiri-Dutt 2018; Hilson 2002). There is a pressing need to nuance mainstream understandings of ASGM which commonly obscure heterogeneity in gold production practices within mining localities. We argue that these place-specific differences in mining practices mediate the intensity of environmental impacts from ASGM.

Miners often use mercury to extract gold (UNEP 2020). Processing gold releases inorganic mercury into the environment through two pathways: in emissions, released into the atmosphere and redeposited in nearby waterbodies, and through direct releases of mercury-laden tailings into waterways. In the bottom sediments of waterbodies, under certain abiotic conditions, inorganic mercury can undergo a microbially-mediated transformation into methylmercury, the most toxic and biologically available form of mercury (Eagles Smith et al. 2016; Barkay and Dobler 2005; Wiener 2003). Many studies have documented bioaccumulation of mercury in the vicinity of active mines (Mason et al., 2019; Martinez et al., 2018; Moreno-Brush et al., 2018; Palheta and Taylor 1995), in sediments and tailings downstream of mining (Nurfitriani et al., 2020; Dethier et al., 2019; Diringer et al., 2015), and even legacy contamination from mines that have long been abandoned (Krisnayati et al., 2012; Veiga and Hinton 2002). Bioaccumulation of mercury can cause a wide range of detrimental impacts to wildlife such as a reduction in growth, juvenile survivorship, and reproductive success (Whitney and Cristol 2018; Scheuhammer et al., 2017; Varian-Ramos et al., 2014; Burgess and Meyer 2008; Houck and Cech 2004). Humans are also exposed to mercury through the consumption of fish (Wiener 2003). Because ASGM is concentrated in culturally and biologically diverse areas of the globe, understanding risk of contaminant exposure in these unique ecosystems is critical (IGF 2017; Alvarez-Berrios et al., 2015).

The analytic of coproduction represents a novel conceptualization of the joint contributions of natural and societal factors in determining the risk from exposure to contaminants from ASGM. Coproduction has been defined in many ways across different fields (Palomo et al., 2016; Diaz et al., 2015). One recent definition used by Rademacher et al., (2019) emphasizes that coproduction is "an analytical tool for understanding how mutually generated social-ecological change takes place (p. 67)." I adopt this definition, focusing on how contamination can be understood as a process of social and natural change stemming from the extraction of subsoil resources. Specifically, gold mining is an example of how humans transform the natural wealth of geological deposits by using extractive technologies to remove, process, and refine auriferous rock. Contamination from the use of mercury in gold processing is the result of both production practices and the abiotic conditions present within that landscape that may or may not support bacterial production of toxic methylmercury. Both the social relations of gold production and the biogeochemical particularities of mercury cycling are then mutually constitutive of mercury contamination. A coproduction approach allows for a more complete understanding of how contamination is mediated by differences in both the practices of gold production *and* local environmental context.

The case of the bioaccumulation and biomagnification of mercury in wildlife inhabiting abandoned gold mines in Madre de Dios, Peru illustrates the potential of using the analytic of coproduction. In Madre de Dios, a diversity of gold production methods co-exist in geographically segregated areas. Miners extract gold from alluvial sediments within rivers or in inland areas where sediments have accumulated over time in near-surface placer deposits located beneath the forest floor. Gold-bearing sediments and soils are extracted through one of two methods: excavation or dredging. Depending on the method of extraction, different technologies are used that range from non-mechanized to highly mechanized operations using heavy machinery. The decision as to which method of extraction and which extraction technologies to use, emerges out of miners' cultural knowledge of mining practices, access to capital and land, site-specific geological characteristics, and socioeconomic class and identity (Diaz Leiva 2021). While extraction technology is only one factor in the broader organization of labor in gold mining, I posit that technology plays a central role in structuring the environmental impacts of mining. In particular, the choice of extraction technology drives variation in the intensity and nature of physical disturbance to the environment (Caballero-Espejo et al., 2018), as increasing mechanization generally increases the volume of gold-bearing material that can be processed per day. Depending on the quality of a deposit, the ability to process greater volumes of gold-bearing material yields greater quantities of gold and as a result necessitates more mercury to process and concentrate this gold. Assuming that mercury releases are proportional to the quantity of mercury used, we hypothesized that increased mechanization would lead to greater mercury loading into the environment.

Apart from the intensity of physical disturbance, another legacy of the increasing mechanization of ASGM in Madre de Dios, is the creation of networks of abandoned mining pits that have increased by more than 670% in land extent since 1980 (Araujo-Flores et al., 2021; Gerson et al., 2020; Caballero-Espejo et al., 2018). Open pit mines are formed in inland areas by excavation or dredging of subsurface soils following removal of aboveground vegetation. Later filled in by rainwater or water pumped in from a nearby source, these pits become ponds, some greater than a hectare in area. Over time, these ponds are colonized by wildlife forming new networks of aquatic habitat. However, these ponds also act as reservoirs where inorganic mercury can be transformed into methylmercury. Importantly, a recent study found that the rate of methylation in ponds was higher than in rivers and comparable to those in oxbow lakes (Gerson et al., 2020). Thus, the expansion of these ponds on the landscape exacerbates the risk of mercury exposure because of the increased methylation potential of the created aquatic habitat and because wildlife in these landlocked ponds readily accumulate methylmercury through diet. Moreover, these ponds can become hydrologically connected to nearby rivers during the rainy season, facilitating the bi-directional movement of wildlife, organic matter, and mercury (Araujo-Flores et al., 2021). As such, it is imperative to understand how the creation of these ponds may increase the risk of mercury exposure in wildlife.

My study focused on examining how mercury contamination is coproduced by social and ecological factors and mediates exposure risk to wildlife. First, I evaluated whether mercury concentrations in wildlife inhabiting abandoned gold mines differed when compared to wildlife found in unmined sites. I found that bioaccumulation was high in all sites, even unmined sites, but that bioaccumulation in wildlife was highest in sites where mining used suction-pump based extraction technologies occurred.

Second, I evaluated whether extraction technologies influenced mercury biomagnification rates by comparing natural lakes in an unmined watershed to areas worked with heavy machinery (HM) and those worked with suction-pump based techniques (SP). Heavy machinery or suction pump-based technologies are broad categories that do not fully encompass the constellation of differences in gold production practices between individual mines in Madre de Dios. However, these two broad categories do stand-in for notable socioeconomic and cultural differences in the organization of gold production. Importantly, labor arrangements and the degree of labor specialization vary depending on the choice of extraction technology, as some technologies necessitate more laborers to operate multiple motors and certain technology like heavy machinery requires trained operators and high capital investment. Technology is thus a structuring element in the organization of labor within a gold mine, but it is also only one difference among many in the ways that gold is produced across different mines. For my investigation, the choice to examine these types of sites, was driven by our interest in the bioaccumulation and biomagnification of mercury in wildlife inhabiting abandoned open pit mines created by these different technologies. Both heavy machinery and suction-pump based technologies create spatially discrete mining pits, bounding the sampling area and providing replicable units of study. In inland areas, these two types of extraction technologies are also geographically segregated allowing for comparison across distinct sites worked with the same type of technology. To compare biomagnification rates across these sites, I estimated a trophic magnification slope (TMS) by regressing total mercury concentrations (THg) against stable nitrogen isotopes ($\delta 15N$) of multiple consumers common to all mines. Our estimated TMS of 0.20 ± 0.01 was on the high end of reported values for tropical freshwater, lentic environments (Lavoie et al., 2013). I also found that the type of technology used in gold production influenced the degree of mercury loading, and together with differences in food-web structure across mines, these factors controlled the bioaccumulation of mercury at each site.

Materials and Methods

Study Site & Field Sampling

I conducted my study in the Department of Madre de Dios, Peru, a region located at the western edge of the Amazon basin (Fig. 1). I sampled across four sites, with each site characterized bythe use of either suction-pump (SP) or heavy machinery (HM) extraction technologies as well as one unmined site. On the surface, the mining pits created by these two different mining technologies appear similar, however they differ in key aspects. Suction pump-based technologies create mining pits that are more heterogeneous in their bathymetric profile and on average much deeper than their counterparts created with heavy machinery. Moreover, different extraction technologies affect both the intensity and extent of physical disturbance to the environment.

Abandoned mines are created aquatic habitats that may vary in their propensity to support or inhibit methylation and bioaccumulation of mercury (see *SI Appendix,* Fig. S3, for photos of sites). For example, in a pit created by excavation using heavy machinery, the banks are stabilized by vegetation that quickly colonizes the margins of the pit where topsoil is still left intact. Instead of the concave bathymetric profile of a pit created by dredging using suction-pump based technologies, the cross-section of heavy machinery pits is angular and box-like because of the curvature of the digging shovel of the excavator. Moreover, there is a pronounced absence of emergent vegetation along the margins of these heavy machinery pits, species like *Paspalum repens* that are normally quick to colonize the riparian edge of dredged pits fail to colonize the vegetated margins of these excavated pits.

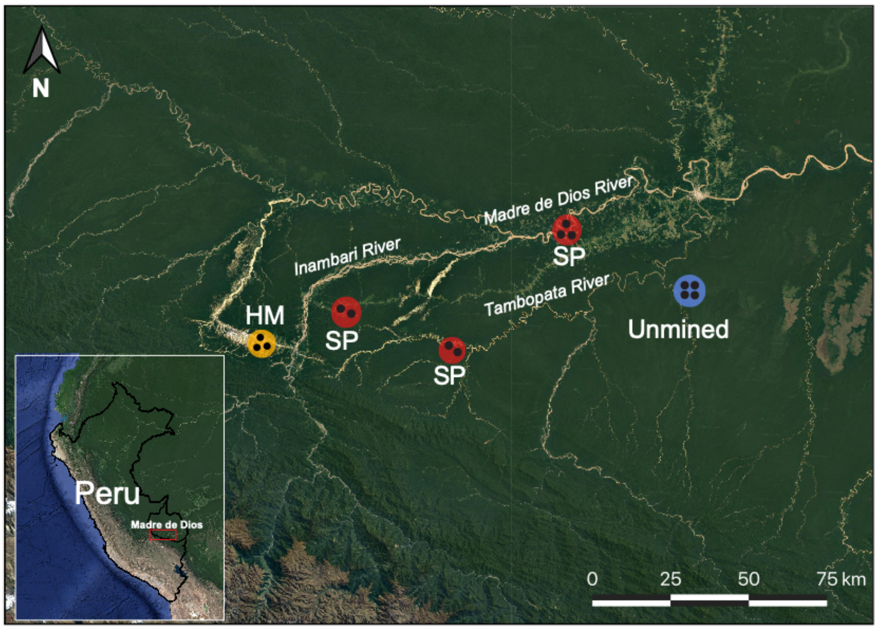

Figure 1. Map of study region showing approximate sampling locations and number of mines sampled (black dots) by type of extraction technology used in gold production: suction-pump based (SP) or heavy machinery (HM), and one unmined site.

In addition to vegetation structure, aquatic habitat structure varies greatly between pits worked with heavy machinery and those worked with suction-pump based technologies. In pits created with suction pump technologies there are often deep layers of silt, clay and sand at the bottom of pits from liquefaction of subsoil with high-power hoses. Water quality in some of these pits is often quite poor because of the heavy siltation and high amount of suspended sediments that come from stripping the topsoil and releasing fine particulates. Consequently, only the most tolerant taxa of benthic macroinvertebrates were found in these ponds. Some of the most important abiotic factors that are known to affect mercury bioaccumulation and biomagnification are pH, temperature, and dissolved organic carbon (Hsu-Kim et al., 2013; Ullrich et al., 2001). The type of technology used to create a pit again may influence these abiotic variables as depth can promote thermal stratification and promote anoxic conditions in bottom sediments (Eagles Smith et al., 2018; Hsu-Kim et al., 2013; Ullrich et al., 2001). Suction-pump based pits sometimes reach depths below 15 meters as multiple dredge sets work the same pit. Therefore, the variability in the physical disturbance to the environment caused by these different extraction methods influences more than just surficial habitat characteristics but may also indirectly affect the methylation potential and bioavailability of methylmercury in these pits.

While I did not directly measure methylmercury concentrations - I did measure total mercury which is a composite measure of both methylmercury and inorganic mercury. As many studies have found, at higher tropic levels such as those occupied by large-bodied predatory fish species similar to those we sampled, more than 95% of mercury in fish muscle tissue is methylmercury (Bloom 1992). Moreover, it is common in studies of biomagnification and bioaccumulation in wildlife to only analyze total mercury, especially when large-bodied predators are the top consumers (Ullrich et al., 2001; Watras et al., 1998; Palheta et al., 1995). Given that my study was principally focused on comparing rates of biomagnification using trophic magnification slopes, calculated with total mercury concentrations (Lavoie et al., 2013), I believe my decision to not directly measure methylmercury was justified.

To test whether production practices mediate mercury biomagnification, I sampled multiple abandoned gold mining pits (≥2) at each site. A total of 10 mining pits were sampled including seven mining pits where SP technologies were used and three mining pits where HM was used. I was unable to access more sites worked with HM due to the rapidly changing security threats posed by a state of emergency declared in the region. At the unmined site, we assessed background biomagnification rates in four natural oxbow lakes located along a river in a protected watershed unimpacted by gold mining. Mining pits resembled artificial ponds and many contained floating and emergent macrophytes including *Paspalum repens, Hymenache spp*., as well as a diversity of fauna. Pits ranged in size from 0.3 ha to ~ 4 ha and varied in bathymetric profile based on the type of technology used in gold production. The average depth of pits worked with SP was 2.48 ± 0.71 m and 1.76 ± 0.55 m for pits worked with HM.

To estimate the rate of biomagnification across sites, I sampled for the same taxa across all pits and oxbow lakes including benthic macroinvertebrates and algivorous and piscivorous fish. Benthic macroinvertebrates common across all pits and oxbow lakes included predatory dragonflies (Families: Gomphidae, Libellulidae), giant water bugs (Family: Belostomatidae), and water scorpions (Family: Nepidae). Primary consumer invertebrates (herbivorous/detritivorous strategies) included gastropods (Family: Caenogastropoda) and burrowing mayflies (Family: Polymitarcyidae). Benthic macroinvertebrates were live sorted to family level and then kept in water for 12-24 hours to clear gut contents. In the lab, the invertebrates were counted, measured and pooled by family to produce a composite sample for each pit. The invertebrates were kept frozen until they were freeze-dried at -56°C for 72 hours. Gastropods were used for estimation of baseline $\delta^{15}N$ following Post (2002). In addition, a maximum of three individuals of the following fish species were collected at each mining pit or oxbow lake; piranha (*Serrasalmus spp*.), wolf fish (*Hoplias malabaricus*), and armored catfish (*Hypostomus spp*.). Fish were collected using a gill net deployed on the same day as invertebrate collection; length and weight were measured, and dorsal muscle tissues were removed, placed on ice until they could be frozen, and later freeze-dried.

To determine whether riparian consumers of emergent aquatic insects bioaccumulate mercury from aquatic resource subsidies, I collected long jawed orb-weaving spiders (Family: Tetragnathidae) from the vegetation at the margins of each pit and lake. Many studies have shown that in temperate zones, long-jawed orb-weaving spiders (Family: Tetragnathidae) and other riparian consumers feed on emergent insects that accumulate mercury and other contaminants during their aquatic larval phase (Speir et al., 2014; Otter et al., 2013; Walters et al., 2010; Walters and Otter 2008). Hand collection of spiders occurred on the same day as collection of fish and benthic macroinvertebrates. Spiders were counted, frozen on ice and later freeze-dried at -56°C for 72 hours.

To estimate mercury loading in each pit or lake, surface sediment samples were collected in triplicate using an Ekman dredge and analyzed for total mercury content. Samples for water chemistry were also collected *in situ* at each point where a sediment sample was taken using a multiparameter Hanna HI91894. All sampling was conducted during the dry season from April-August 2019. Research protocol and methodologies for handling fish specimens were approved by UC Berkeley's Animal Care and Use Committee (#AUP-2018-06-11147).

Laboratory Analyses

Laboratory processing and analysis followed similar procedures to Wyn et al. (2014). Individual fish muscle samples and invertebrate samples (pooled with greater than 5 individuals per taxon) were freeze-dried, homogenized, and sampled once for each analysis. Approximately 20 mg (±10 mg) of homogenized fish muscle or whole macroinvertebrate composite was analyzed on a Milestone DMA-80 direct mercury analyzer (Milestone Inc., Shelton, CT, USA) at the Carnegie Institute for Global Ecology at Stanford University (Stanford, California, USA). Samples of certified reference material (DORM4 or TILL3) were within acceptable recovery limits. All Hg data are expressed on a dry weight basis. Duplicate analytic measurements were analyzed for each fish, invertebrate, and sediment sample analyzed for THg, and the two results were averaged for the reported result. The average relative percent difference in THg measurements of duplicate samples was 1.1%. Quality control measures included testing of standard reference materials, and internal laboratory standards. Continuing calibration verification and continuing calibration blank measurements were determined on every tenth sample analyzed in accordance with US EPA Method 7473 (EPA 1998). The Method Detection Limit for total Hg analysis is 2 ng/g. Additional information on QA/QC of samples can be found in supplemental materials (*SI Appendix)*.

Samples were analyzed for $\delta^{15}N$ and $\delta^{13}C$ at the Center for Stable Isotope Biogeochemistry at the University of California, Berkeley (Berkeley, California, USA). Stable isotope composition is expressed in parts per thousand as a deviation from a standard reference material. Nitrogen isotopic values were standardized against N_2 gas in air as follows:

$$\delta 15N = \left(\left(R_{sample} \div R_{standard}\right) - 1\right) * 1000 \qquad (1)$$

Stable nitrogen isotopes were used to approximate the relative trophic position of an organism because the relative abundance of ^{15}N in proportion to ^{14}N in a consumer is enriched by an estimated 3-4‰ per trophic level (Clayden et al., 2015; Chasar et al., 2009; Jardine et al., 2006; Post 2002; Kidd et al., 1995). The trophic level of an organism can then be adjusted by measuring $\delta^{15}N$ in a primary consumer such as algivorous freshwater snails and correcting $\delta^{15}N$ of higher-level consumers as in the following equation:

$$TL_{consumer} = \frac{\delta 15N_{consumer} - \delta 15_{primary\ consumer}}{\Delta 15N} + \lambda \qquad (2)$$

Where $\Delta^{15}N$ is one of the most common enrichment factors used in studies of aquatic food webs, 3.4‰ (this however is not the only enrichment factor used in studies) and λ is the trophic level of the baseline primary consumer (TL = 2). Additional information on QA/QC of samples can be found in supplemental materials (*SI Appendix)*.

Data Analyses

To test for differences in the biomagnification rate across sites worked with different extraction technologies, I used tests of analysis of covariance (ANCOVA; R Version 3.6.1). Trophic position (continuous independent variable) and technology (categorical independent variable) on total mercury concentration in biota (THg; continuous dependent variable). I $\log_{10}$ transformed total mercury concentrations to meet the assumptions of the ANOVA test. Residuals were normally distributed and homoscedastic. I tested for an interaction effect between technology and trophic position, which would indicate that the slope estimate for the relationship between trophic position and mercury concentration was dependent on the type of technology used. If the interaction effect was not significant, I removed the term and assessed the main effects of trophic position and technology independently. I also tested for differences in mercury loading across pits worked with the same technology using ANOVA and a post-hoc Tukey HSD test to evaluate whether there was a difference in sediment mercury loading across sites. Finally, I used a generalized linear mixed effects model, lme4 (lmer package, Bates et al., 2015) to evaluate the proportion of variance in total mercury concentration of biota that was explained by a model that accounted for the random effect of pits nested within sites worked with different extraction technologies, as well as the fixed effects of mercury loading as estimated by the average pit or lake sediment total mercury concentration (THgSed), trophic position, and the interaction between trophic position and extraction technology.

I evaluated the following models: 1) restricted model including fixed effects accounting for taxonomic groups (Taxa), extraction technology (Tech), trophic position (Trophic Position), and a random effect of pit identity (1|Pit.ID), 2) model 1 plus a fixed effect of mercury loading (THgSed) in pits, 3) model 1 plus interaction between trophic position and extraction technology (1|Trophic Position:Tech), 4) model 3 plus the addition of mercury loading fixed effect. I compared our models using Bayesian information criterion (BIC) scores and chi-square log-likelihood ratio tests.

Results

I found high levels of mercury bioaccumulation in taxa sampled across all mined and unmined sites (Fig. 2A, and *SI Appendix*, Table S1, Fig. S1, Fig. S2). However, the highest mercury concentrations were found in wildlife collected in abandoned gold mines worked with suction pump-based technologies (Fig. 2A). While taxonomic groups showed relatively consistent trophic positions across sites (as measured by δ15N), spanning >2 trophic levels from snails (caenogastropoda), lowest in the food chain, to piranha (*Serrasalmus spp*.) and wolf fish (*Hoplias malabaricus*), apical predators (Fig. 2a, *SI Appendix,* Fig. S1) – in sites worked with heavy machinery, wolf fish had consistently higher trophic position than in unmined sites.

Accordingly, predatory fishes in mined sites and unmined sites contained the highest average concentrations of THg (*SI Appendix,* Table S1). At lower trophic levels, THg concentrations in wildlife in mined sites worked with heavy machinery and unmined sites were comparable (*SI Appendix,* Fig. S1, Fig. S2), but at higher trophic levels THg concentrations in wildlife were consistently higher than in unmined sites.

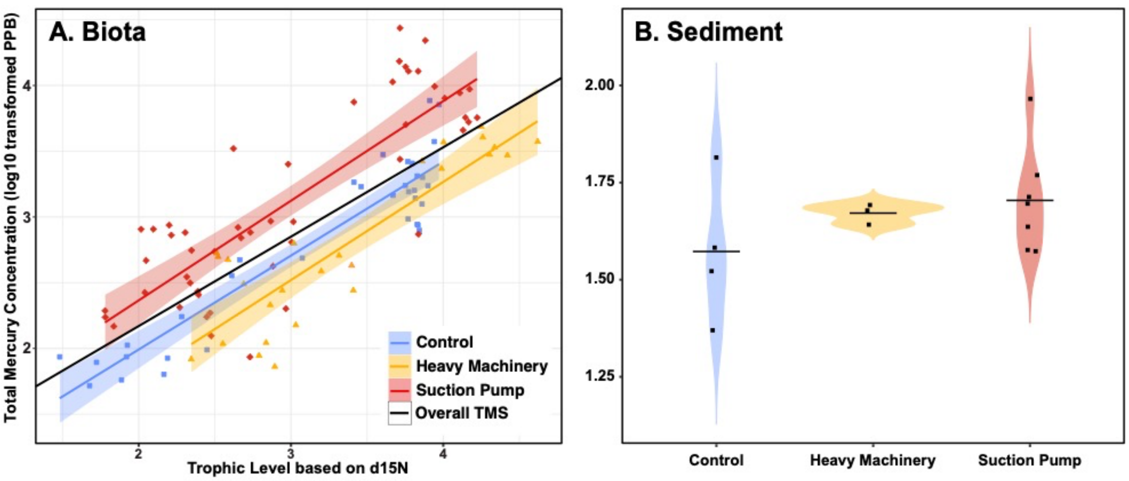

Figure 2. A. Evidence of mercury bioaccumulation and biomagnification in wildlife inhabiting abandoned gold mines worked with different extraction technologies and unmined, natural oxbow lakes. Bioaccumulation was highest in sites worked with suction-pump based technologies. The trophic magnification slope, an estimate of the relative increase in mercury concentration per trophic level was calculated from the linear regression of $\log_{10}$-transformed total mercury concentrations against trophic level (based on δ15N ‰). Given that the slopes were > 0, these data show that THg is being biomagnified through aquatic food chains in mining pits and unmined, natural oxbow lakes. Overall trophic magnification slope (TMS) estimate (black line), and by type of extraction technology used (colored lines). Lines represent least squares estimate of the linear regression of total mercury concentration of biota against trophic level of taxa (calculated using δ15N estimates corrected using δ15N of a baseline consumer – see methods), with one standard error in slope estimate represented by shading. **B.** Violin plot of total mercury sediment (THgSed) concentrations - a proxy for mercury loading - in pits across sites worked with different extraction technologies and an unmined site. On average, mercury loading was highest in pits worked with suction pump-based technologies as supported by mean THgSed (black bar) concentrations.

I also found evidence of biomagnification. Total mercury concentrations (THg) were significantly and positively correlated with estimated trophic position (δ15N) across all sites ($R^2 = 0.63$, $p < 0.0001$). The rate of mercury biomagnification represented by the average trophic magnification slope (TMS) calculated from the linear regression of $\log_{10}$-transformed total mercury concentrations against trophic position (δ15N ‰) was 0.20 ± 0.01 ($p < 0.0001$, n = 110, Fig. 2A). Given that TMS > 0, these data indicate that THg is biomagnified through aquatic food chains in mining pits and unmined, natural oxbow lakes. Moreover, the trophic magnification factor (TMF), an estimate of the relative increase in mercury concentration with each trophic transfer - calculated from the back-transformed TMS slope - was equivalent to a 4.4 to 5.2-fold increase in mercury concentration with each trophic transfer.

Beyond differences in THg concentrations between mined and unmined sites, I found evidence of coproduction of contamination: THg loading was influenced by both social and natural factors

(Fig. 2B, Fig. 3). In particular, I found that extraction technologies play a critical role in the ways that mercury is used in gold processing. Insights from more than eleven months of fieldwork and > 40 interviews with miners, revealed that in heavy machinery sites, pits are created as reservoirs to pump water to wash gold-bearing material excavated from elsewhere onsite (Fig. 3B). As a result, amalgamation of mercury does not occur proximate to the pit and direct mercury releases from tailings are unlikely to influence mercury loading into bottom sediments. In contrast, in pits worked with suction pump-based technologies, gold-bearing material is dredged up from the bottom of the pit and processed onsite with mercury, resulting in direct releases of mercury into the bottom sediments (Fig. 3B).

These qualitative findings were supported by our quantitative analysis of mercury concentration in sediments. I found that sediment total mercury concentration (THgSed), a proxy for mercury loading to each mining pit or reference lake, varied across sites worked with different technologies (Fig. 2B) with a significant difference in mean total mercury concentration ($\log_{10}$ transformed PPB) across site types ($F_{2,36} = 3.438$, $p = 0.043$). The highest levels of loading were recorded in pits worked by SP, followed by pits worked by HM, and then unmined oxbow lakes. A post-hoc Tukey HSD analysis indicates that sites worked with SP were significantly different in THgSed concentrations than those in unmined sites. There was no difference in THgSed between unmined sites and HM sites. However, we found that one of the oxbow lakes in our unmined sites was elevated in THgSed possibly due to the fact that the lake is a palm swamp with low concentrations of dissolved oxygen (*SI Appendix*, Table S3). If this lake were excluded from the analysis, then mean THgSed would be significantly different between all paired comparisons of sites.

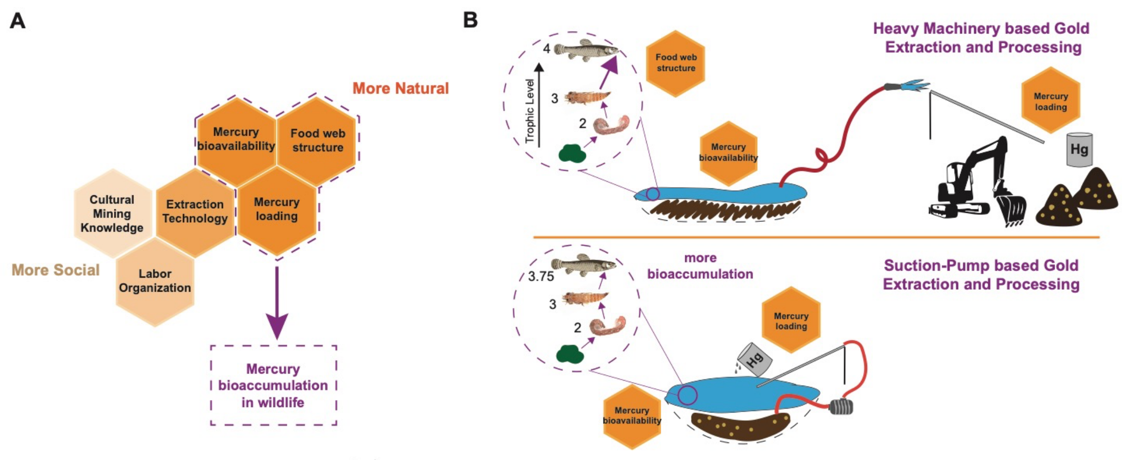

Figure 3. A. Conceptual diagram of the natural and social determinants of mercury bioaccumulation in wildlife. The union between factors (hexagons) represent direct linkages and interactions between factors. For example, the choice of extraction technology interacts with gold production practices and labor arrangements to influence mercury loading and bioavailability in gold mining pits through mercury releases from gold amalgamation. **B.** Conceptual figure demonstrating the differences in gold extraction and processing based on a miner's choice of extraction technology, whether heavy machinery or suction pump-based. Note, the major difference in the use of mining pits as either water sources in heavy machinery-based operations (top) or as the source of gold-bearing material in suction-pump based operations (bottom). This key difference in gold production practices results in direct mercury loading into sediments in mining pits in SP sites as mercury amalgamation occurs proximate to where gold is concentrated using sluice boxes. Simplified food webs represent differences in food chain length between sites worked with heavy machinery based or suction pump-based technologies. In sites worked with heavy machinery, food chain length in mining pit food webs was on average longer than in SP based sites. Food chain length affects the concentration of mercury in consumers at the top of the food chain (*Hoplias malabaricus*). Yet, mercury concentrations in wildlife were higher in sites worked with SP based technologies indicating that direct mercury loading into mining pits, driven by differences in production practices - structured by the choice of extraction technology – also interacts with food web structure to influence the relative contamination of wildlife in these two systems.

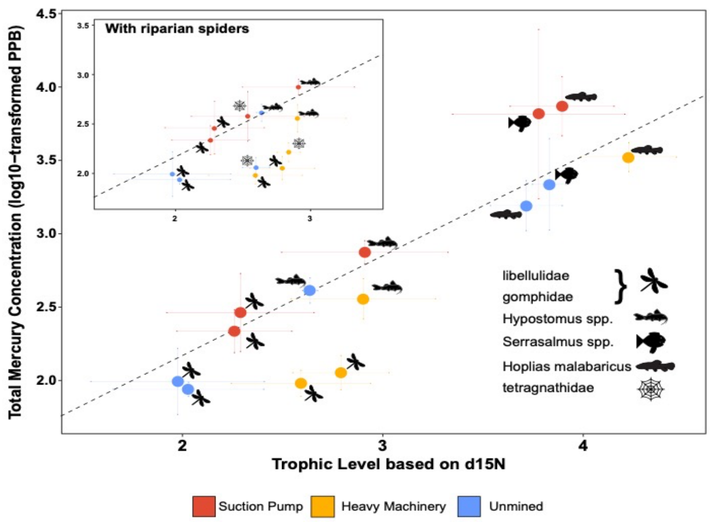

Figure 4. Differences in mean trophic level (calculated based on δ15N, see methods for more details) of taxa varied consistently across sites worked with different extraction technologies and unmined lakes. Similarly, bioaccumulation of mercury in individual taxa, represented by mean total mercury concentration also varied across sites worked with different extraction technologies and unmined lakes. Data points represent the mean trophic level and $\log_{10}$ transformed THg concentration ± 1 S.E. for selected taxonomic group sampled across all sites. **Inset:** Evidence of mercury export from abandoned mines and unmined lakes to a riparian predator present across all sites, the long-jawed orb weaving spider (Family: Tetragnathidae). The trophic position and mean total mercury concentration of spiders relative to the line representing the rate of biomagnification of mercury in aquatic taxa (dashed line) indicate that these spiders bioaccumulate mercury from aquatic taxa.

A one-way ANCOVA was conducted to determine a statistically significant difference between extraction technology (ie., whether a site was worked with HM, SP, or unmined) on THg concentration in biota controlling for differences in organism trophic position. I included an interaction effect between extraction technology and trophic position to test if the rate of biomagnification, differed between sites worked with different technologies and unmined sites. I found no significant interaction effect ($F_{2,104} = 0.115$, $p = 0.89$), but both the main effects of our covariate and independent variable were significant. To fully parse the relative importance of trophic position, THg loading in sediments, and extraction technology on bioaccumulation of mercury in biota, I compared fits of different explanatory model structures. Specifically, I compared support across four linear mixed-effect models using an information-theoretic approach via BIC (Table 1). I found that including an interaction effect between organism trophic position and extraction technology greatly improved model fit over a restricted model that included the effects of technology and trophic position separately. I also evaluated the two best fit models using log-likelihood tests (Table 1, models 3 & 4). I found that model 4, which included the interaction effect as well as the fixed effect of mercury loading (THgSed), was significantly different from model 3 (χ^2 (1) = 5.214, $p = 0.022$). This finding suggests that mercury loading, influenced by the type of extraction technology used, drives patterns in mercury bioaccumulation across a diversity of taxonomic groups.

Table 1. Evaluation and comparison of linear mixed effects models: 1) restricted model including fixed effects accounting for taxonomic groups (Taxa), extraction technology (Tech), trophic position (Trophic Position), and a random effect of pit identity (1|Pit.ID), 2) model 1 plus a fixed effect of mercury loading (THgSed) in pits, 3) model 1 plus interaction between trophic position and extraction technology (1|Trophic Position:Tech), 4) model 3 plus the addition of mercury loading fixed effect.

No.	Model	Residual Deviance	Residual df	BIC	Log Likelihood
1	Taxa + Tech + Trophic Position + (1|Pit.ID)	-75	15	11	38
2	Taxa + Tech + Trophic Position + THgSed + (1|Pit.ID)	-78	16	14	39
3	Taxa + Tech + Trophic Position + (1|Pit.ID) + (1|Trophic Position:Tech)	-708	16	-616	354
4	Taxa + Tech + Trophic Position + THgSed + (1|Pit.ID) + (1|Trophic Position:Tech)	-713	17	-616	357

Finally, I found evidence of lateral transfer of mercury from abandoned mining pits to terrestrial, riparian consumers (Inset Fig. 4). Stable isotopes of δ15N as well as field observations of feeding behavior, confirm that a riparian predator; long-jawed orb weaving spiders, consume emergent aquatic insects, acting as recipients of mercury exported from abandoned mines. These riparian consumers bioaccumulated mercury at concentrations that fell within those predicted by the relationship between THg and trophic position of aquatic taxa (Fig. 4).

Discussion

Mercury Contamination is Coproduced in ASGM Sites

I found strong novel evidence that mercury contamination in Madre de Dios, Peru, is coproduced by social and natural processes. Mercury bioaccumulation levels were driven by variation in mining practices and differences in food-web structure. Interviews with miners confirm that the use of different extraction technologies influenced the degree of mercury loading into mining sites. Where heavy machinery mining occurs, there is no direct mercury amalgamation in mining pits and thus limited inputs of mercury-laced tailings into sediments. Instead, these pits are constructed as water storage ponds filled-in by groundwater infiltration. Water is pumped out of the ponds to constructed sluice boxes sometimes more than 200 meters away to wash auriferous material that is brought from elsewhere on-site (Fig. 3B). Therefore, different gold production practices - using either HM or SP technologies - play an important role in mediating the quantity and location of mercury discharges on the landscape. This finding adds evidence to the argument that heterogeneity in gold production practices may affect mercury loading into aquatic ecosystems (Schudel et al., 2018).

Second, I found that the trophic position of taxa and average food chain length (FCL; estimated by subtracting trophic position of the top consumer from the primary consumers), which is known to affect bioaccumulation in top predators, varied by sites worked with different extraction technologies. In pits worked with heavy machinery, the average FCL was 2.70, for SP pits it was 2.30, and for reference lakes it was 2.05. While I do not know the mechanism driving differences in FCL across sites worked with different technologies, I postulate that differences in feeding behavior of the same organism across sites (i.e., omnivory in predatory fish) or food web complexity (i.e., addition or insertion of top consumers lengthening the food chain) may be responsible for this variation (Post and Takimoto 2007). Understanding the exact mechanism is particularly important given that wildlife in these landlocked ponds will readily bioaccumulate contaminants from dietary exposure and differences in FCL will mediate the accumulation of contaminants at the top of the food chain. However, trophic position alone did not explain variation in bioaccumulation of THg in wildlife across sites, as taxa with the same trophic position (e.g., *Hypostomus spp*., *Serrasalmus spp*.) were consistently higher in THg concentration in SP pits relative to HM pits. Only when I took the full suite of coproduction factors - trophic position, extraction technology, and mercury loading - into account did our model (Table 1) best explain the patterns in bioaccumulation I observed across sites.

Diffuse Mercury Contamination in Madre de Dios

I found high mercury biomagnification rates in our study sites. Our estimated TMS (0.20 ± 0.01) is almost double that of the mean global value for freshwater tropical sites, 0.12 ± 0.12 (Lavoie et al., 2013), but at the low end of the range for studies restricted to Amazonia -from 0.21 – 0.43 (Molina et al., 2010; Lechler et al., 2000; Kwon et al., 2012; Pouilly et al., 2013; Acevedo-Silva et al., 2016). These magnification rates have led to levels of top-predator mercury bioaccumulation that represent a significant public and environmental health risk. Predatory fish species (*Hoplias malabaricus* and *Serrasalmus spp*.) caught in both unmined natural lakes and abandoned mines contained concentrations of mercury that exceeded international consumption limits by two to five times on average. Our findings are consistent with previous measurements of bioaccumulation in *H. malabaricus* in oxbow lakes in the Bolivian Amazon (Pouilly et al., 2013). The concentration of THg in two piranha (*Serrasalmus spp*.) was 26.7 and 26.1 mg/kg respectively, more than 13 times the European Union's recommended consumption limit of 2 mg/kg based on dry weight. These values are comparable to those reported in highly contaminated spill sites (Bravo et al., 2013).

Perhaps most importantly, I found consistently high concentrations of THg in higher trophic-level organisms—irrespective of presumed differences in mercury loading across abandoned mining pits and unmined oxbow lakes. This result corroborates recent findings (Gerson et al., 2020) that show that the rate of methylation in abandoned mines is higher than that of riverine environments but lower than or comparable to oxbow lakes, suggesting that bioavailable methylmercury is bioaccumulating in organisms inhabiting lentic environments in this region. Importantly, our reference sites were located in a densely forested, protected watershed far from direct mercury inputs. Future research should focus on understanding the sources of this mercury to parse apart what drives high background levels in Madre de Dios. Researchers should leverage environmental tracers such as mercury stable isotopes to determine whether these high background levels bear the signature of mercury used in ASGM or whether these high levels are due to the release of mercury from natural sources such as soil erosion or biomass burning. This question remains unresolved in the literature as some studies have found that the signature of mercury in sediments collected downstream of ASGM does not belong to mercury used in these operations but is instead from mercury released from soils and trees due to deforestation from mining and other land uses (Lechler et al., 2000; Adler-Miserendino et al., 2018).

Cross-Ecosystem Transfer of Mercury Extends the Footprint of Contamination

Beyond high background levels, my findings indicate that networks of abandoned gold mining pits may act as hotspots of bioaccumulation in landscapes impacted by informal gold mining. Given that long jawed orb weaving spiders are consumed by mobile predators such as bats and are not the only terrestrial consumers of emergent aquatic insects, I expect this contaminant subsidy to propagate through food webs far beyond the riparian zone of abandoned mining pits. Moreover, this study is the first to demonstrate that the footprint of mercury contamination extends beyond the boundaries of a mine as abandoned mining pits are an important source of mercury to the terrestrial biota inhabiting these highly impacted systems. More work is needed to fully understand the risk of contaminant exposure to higher trophic levels organisms. Previous work suggests that the degree to which these mining pits export mercury via emergent aquatic insects depends on the life histories of these insects, as metamorphosis of aquatic larvae into adults reduces heavy metal burden in aquatic predators such as dragonflies and consequent accumulation in cross-system predators (Kraus et al., 2017). In addition, body size of emergent aquatic insects, mediated by top-down interactions, can also alter contaminant flux into terrestrial ecosystems (Walters et al., 2018). These mosaics of abandoned mining pits also form new habitat for migratory birds and other higher trophic levels organisms whose mobility allows them to further extend the footprint of mercury contamination from ASGM.

While abandoned mines can act as sources of methylmercury to wildlife, it should be noted that our findings also indicate that there is high heterogeneity in mercury bioaccumulation within mining impacted landscapes driven largely by the heterogeneity in gold production practices within individual mining localities. Namely, mining practices using different extraction technologies drive variation in the quantity and location of mercury discharges such that not everywhere in a mined landscape will there be evidence of high levels of mercury in biota. In turn, areas far removed from gold mining could have high levels of mercury in wildlife due to cross-ecosystem mercury transfer and mobility of consumers. Thus, sampling only one compartment such as the sediment of mining pits or the soils around abandoned mines can lead to inconclusive results, as differences in mercury bioaccumulation higher up in the food chain are not apparent from the relatively small differences in mercury loading in sediment (on the order of 10 ng). Further, proposals to remediate these contaminated landscapes for aquaculture or farming should take into account the type of extraction technology used. Surprisingly, despite the fact that sites worked with heavy machinery tend to have a greater physical impact on the environment due to high levels of mechanization in these more ‘industrialized’ operations, they may be safer candidates for remediation than sites worked with suction-pumps. This unexpected finding should be carefully considered in relation to policies governing ASGM in Peru which currently prohibit the use of dredges and other suction-pump based machinery in waterways but make no such prohibitions in inland areas. Moreover, it should be noted that heavy machinery is largely inaccessible to all but the most capitalized of miners and thus, any policy changes should consider the potential of exacerbating inequality amongst the large number of individuals employed within the small-scale mining economy.

Conclusion

Environmental contamination is not an isolated or unique phenomenon, but instead it is part of a ubiquitous pattern that implicates human's continued consumption of resources in the alteration of natural processes (IPBES 2018). Our globalized economy's reliance on non-renewable resources is unlikely to diminish in the near future, especially with the use of precious metals in climate-change mitigating technologies like solar panels and electric car batteries (Watari et al., 2018; Banza et al., 2018). To have any hope of mitigating the worst effects of contaminant exposure or remediating already contaminated landscapes, we must understand the entangled ways in which social and natural factors contribute to the production of contaminated landscapes. A coproduction approach, that explicitly incorporates the social and natural, can help guide the kind of studies that are urgently needed to ensure that our planet continues to provide life supporting services while also ensuring socially and environmentally just outcomes for those people who depend on extraction-based livelihoods.

Supplemental Figures and Tables

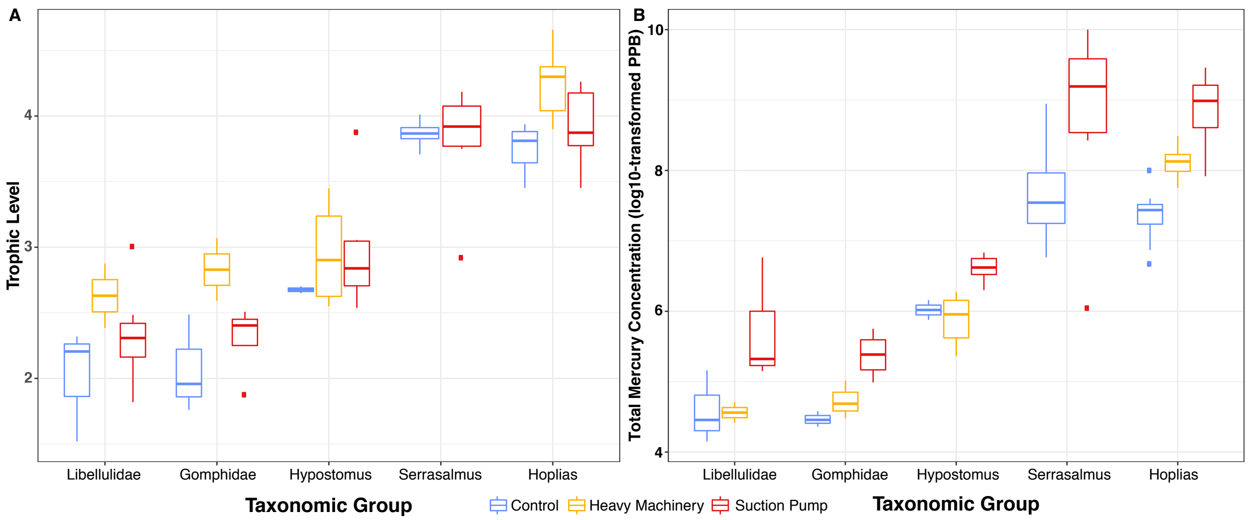

Figure S1. A. Differences in trophic level (calculated from δ15N, see methods for more details) of taxa varied consistently across sites worked with different extraction technologies and reference oxbow lakes. **B.** Bioaccumulation of total mercury across sites worked with different extraction technologies. Taxonomic groups organized by increasing trophic level.

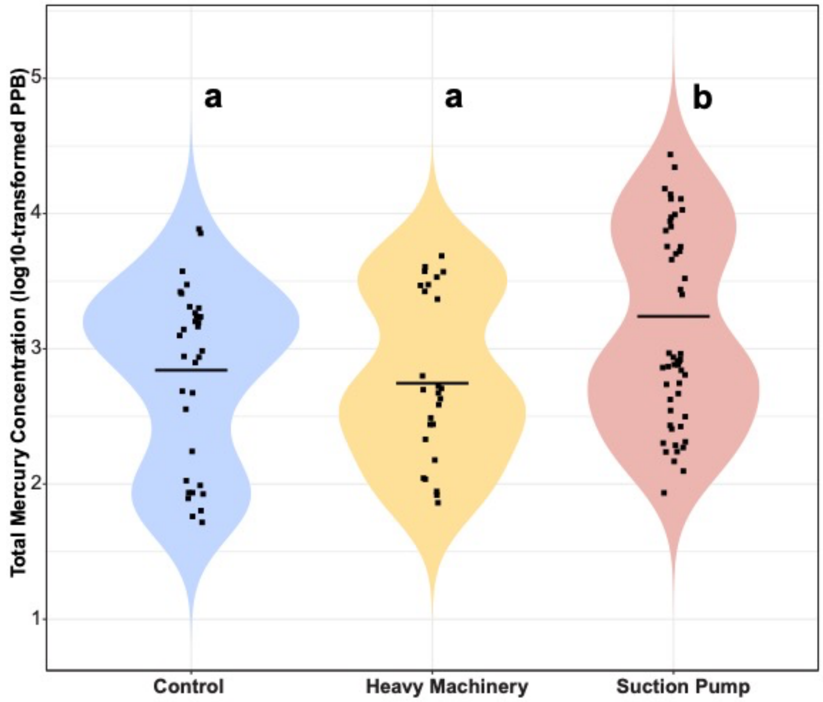

Figure S2. Total mercury (THg) concentration (log10 transformed PPB) of individual taxa across mining pits worked with different extraction technologies and unmined lakes. Black bars represent the mean THg concentration of biota across all mining pits worked by either heavy machinery or suction-pump based technologies or unmined lakes. Mean estimates were adjusted to account for the effect of differing trophic position (del15N values) of individual taxa across pits. Letters refer to statistically significant differences in adjusted mean values ($F_{2,106} = 31.83$, $p < 0.001$, n=110) derived from the results of a post-hoc Tukey HSD test. Mean THg Control = 2.79 +/- 0.06, THg HM = 2.61 +/- 0.07, THg SP = 3.21 +/- 0.05.

Figure S3. Photos of ponds worked by heavy machinery (HM) and suction-pump based (SP) technologies in Madre de Dios. Note the erosion of the banks in the suction-pump sites is due the fact that these pits are created through dredging and liquefaction of the subsoil using water powered hoses.

Table S1. Total mercury (THg) concentrations (mg/kg) in all taxa sampled across sites worked with different technologies and unmined, control site. Values reported as mean ± 1 standard deviation with sample size in parentheses. For cells with less than two samples, only the mean is reported. N/A indicates that these taxa were not found in pits or lakes at the indicated site.

Taxa	Mean THg Control	Trophic Level Control	Mean THg Heavy Machinery	Trophic Level Heavy Machinery	Mean THg Suction Pump	Trophic Level Suction Pump
Belostomatidae	0.285 (2)	2.6	0.073 (1)	2.9	0.98 ± 0.78 (6)	2.3
Caenogastropoda	0.07 ± 0.03 (3)	1.8	N/A	N/A	0.14 (1)	2.2
Gomphidae	0.09 ± 0.010(3)	2	0.12 ± 0.03 (3)	2.8	0.23 ± 0.07 (4)	2.3
Libellulidae	0.11 ± 0.06 (3)	1.9	0.10 (2)	2.6	0.35 ± 0.25 (7)	2.3
Polymitarcyidae	N/A	N/A	0.05 (2)	N/A	0.15 ± 0.11 (4)	2.4
Nepidae	N/A	N/A	0.57 (2)	3.1	1.94 (2)	2.5
Hypostomus spp.	0.42 (2)	2.6	0.38 ± 0.11 (9)	2.9	0.76 ± 0.13 (8)	2.9
H. malabaricus	1.66 ± 0.63 (9)	3.7	3.41 ± 0.78 (9)	4.2	8.07 ± 3.25 (11)	3.9
Serrasalmus spp.	2.80 ± 2.31 (12)	3.8	N/A	N/A	10.24 ± 7.37 (7)	3.7

Table S2. Water quality data of individual sampling points in either unmined sites or mined sites worked with heavy machinery (HM) or suction-pump based (SP) technologies. Data collected using a Hanna Multiparameter (Model No. HI98194). All samples taken at a depth of 60 cm.

Site ID	Site Type	pH	Oxidation Reduction Potential (mv)	Dissolved Oxygen (PPM)	Conductivity (µS/cm)	Total Dissolved Solids (PPM)	Temperature (°C)
RNT001	Unmined	6.78	316	7.63	31	16	26.2
RNT002	Unmined	6.38	203	3.9	21	11	24
RNT003	Unmined	6.15	273	2.11	25	38	26.7
RNT004	Unmined	6.72	294	8.27	20	10	25.6
PAO001	Suction Pump	7.39	278	7.45	75	38	27.7
PAO002	Suction Pump	7.32	270	6.13	71	36	25.8
PAO004	Suction Pump	6.98	246	0.295	103	52	26.6
AZU001	Suction Pump	6.68	217	2.85	68	34	29.8
AZU002	Suction Pump	6.64	292	4.71	21	6	29.6
SR002	Suction Pump	6.2	312	4.26	13	7	24.7
SR004	Suction Pump	6.18	319	4.28	21	11	24.6
HUE001	Heavy Machinery	6.93	277	9.39	22	11	23.7
HUE004	Heavy Machinery	6.83	292	9.14	24	12	23
HUE005	Heavy Machinery	6.45	293	7.05	21	10	22.5

Chapter Three

Appropriate technologies and the geosocial evolution of small-scale gold mining in Madre de Dios, Peru

1. Abstract

This article examines the evolution of gold extraction and processing technologies in the Amazonian region of Madre de Dios, Peru. Going beyond documentation of a historical process of technological adaptation, I discuss how differentiation in gold production practices has important implications for the governance of small-scale gold mining in a changing policy landscape. Proposals by policymakers and practitioners to reform small-scale gold mining into a more environmentally sustainable and economically productive sector often obscure the differences in gold production practices within particular mining localities or mining regions. These technological interventions aim to replace certain gold production practices like mercury amalgamation – commonly used in small-scale gold mining - with alternative technologies that increase the efficiency of gold extraction and purport to bring about clean gold production. However, as I argue in this article, diverse modalities of gold production have evolved over time in Madre de Dios as a response to site-specific geological conditions, differences in miner's access to capital, and a changing socio-political landscape. In a discussion of my findings, I propose alternative policy and governance approaches that take into account the heterogeneity in gold production practices and the attendant socio-economic differentiation within the small-scale gold mining economy in Madre de Dios, Peru.

Keywords: small-scale gold mining, technological intervention, appropriate technology, mercury

2. Intro

In the Amazonian region of Madre de Dios, Peru, gold carried down from the Andes mountains has been extracted from river sediments and placer deposits buried beneath the jungle floor for more than 70 years. As the small-scale gold mining economy has grown over time, non-mechanized technologies like shovels and wheelbarrows have given way to the use of heavy machinery and large motor-powered dredgers (Pachas 2009; Valencia 2014). The result on-the-ground is a diversity of gold mining practices with a spectrum of associated environmental impacts that differ depending on the types of extraction technologies used, the micro-environment in which they're deployed, and the methods of gold processing that are implemented. Despite this diversity, a homogenizing representation of small-scale gold mining still prevails amongst policymakers and development practitioners, who aim to reform the gold mining economy through formalization of the region's miners and top-down technological interventions designed to replace miners' 'rudimentary' technologies (UNEP 2020; Esdaile and Chalker 2018).

Homogenous portrayals of small-scale gold mining in Madre de Dios are reproduced by environmentalists, researchers, politicians, and in media reports (Ipenza et al., 2011). But not only are gold production practices different from one area to the next in Madre de Dios, these practices had developed over time as technologies were adapted to meet socio-political circumstances and to maximize gold production under varying geological conditions. The result a diversity of gold production practices characterized by different arrangements of extraction technologies and labor relations - which together form what I call modalities of gold production. These modalities are not fixed categories but instead represent dynamic and porous arrangements that change over time. Not only do these modalities affect gold extraction and processing, but they also affect the ways that mining impacts the physical and natural environment. In this article, I argue that these diverse modalities of gold production have evolved over time, such that today's gold extraction and processing technologies are locally 'appropriate' and can be adapted to fit site-specific geological conditions as well as a changing socio-political landscape. Further, I posit that analyzing the development of gold production modalities is critical in devising effective interventions and policies to alleviate the social and environmental impacts associated with small-scale gold mining.

2.1 *Contrasting production modalities*

In Madre de Dios, this diversity of gold production modalities is readily apparent in a visit to an open pit mine – much like the one where my friend Lucia[1] worked. Lucia is a 29-year-old mine boss and single mother of a 10-year-old boy. Ownership of a motor-powered dredge set constitutes whether someone is considered a 'miner' or not in Madre de Dios; Lucia owns two motors. The first is a 220 horsepower Deus and the other is a 180 horsepower Nissan motor, both are car motors about the size of a refrigerator. Each motor powers a suction pump mounted on a raft that floats on empty oil drums in an open pit mine; this set-up is locally known as working *traca* (Figure 1). The *traca* is a relatively recent technology in Madre de Dios, adapted from the floating dredges that first worked on the vast network of Amazonian rivers in the region during the 1980s (Valencia 2014). The *traca* is now used in inland areas, where open pit mines are created to extract fine particles of gold buried beneath the forest floor.

The simplicity of the *traca* allows for a smaller work crew - only four laborers in this case - who work in shifts of two at a time. The *traca* itself can be operated by just one person seated on the raft controlling a steering apparatus that maneuvers a lance-like PVC pipe up and down, suctioning a slurry of gold-bearing soil from the bottom of pits and pumping this slurry to a nearby constructed sluice box. The sluice box is lined with heavy fiber carpets that capture the fine particles of gold in the weave (Figure 2).

The second laborer, called the *bravo*, is responsible for clearing vegetation at the edge of the pit using a chainsaw or machete, and shuttles diesel and motor oil to the *traquero*. At the end of a 32-hour shift comes the moment of truth; the concentration and processing of the day's gold production known as the *alce*. During the *alce*, the carpets are removed from the sluice and beaten out in a small plastic lined pond where the gold-bearing material is clarified with water and then transferred to an oil drum. Quicksilver or elemental mercury is added to the oil drum and one laborer then spends about half an hour using their leg to churn the mixture until the mercury envelops the fine particles of gold in an amalgam.

1. All names in this article are pseudonyms.

The amalgam is roasted on-site, in the open air using a blow torch. After about fifteen minutes the sheen of silvery mercury is burnt off to reveal doré; a spongelike gold disc flecked with remnant particles of mercury.

On the day that I visited Lucia's camp, the *alce* yielded 13 grams of gold, 25 percent of which was divided evenly between the laborers while the remaining production was kept by Lucia. In addition, 5 grams of gold were captured in the final three carpets of the sluice, called the *chivola*.[2] The *chivola* is a custom in Madre de Dios in mining operations that work a percentage-based production modality. These final three carpets on the sluice are reserved as a bonus for laborers. The final carpets often capture the least amount of gold and as such the *chivola* is both a tip and a gesture of good will; the extra earnings customarily spent on entertainment in nearby bars. Instead of splitting 25 percent of the production from the *chivola* with the boss, the four laborers evenly split the entirety of the 5 grams adding to their day's payment which comes out to just over 2 grams per laborer. At 40 USD per gram this amounts to more than S./240 (70 USD) for a 32-hr shift; well over the standard S./50 (15 USD) paid to day laborers in the region.

Contrast Lucia's *traca*-based production with that of David, a 58-year-old career miner, who holds the title to a 1000-hectare mining concession just outside the town of Huepetehue; one of the oldest mining settlements in Madre de Dios. David oversees a heavy machinery-based gold production modality on his concession, employing three salaried operators to drive a dump truck, front loader and excavator. In addition, two laborers called *huaychuleros*, a foreman, and a cook round out his crew. The *huaychuleros* sit inside wooden cabins shielded from the sun and use large hoses to carefully wash gold bearing material deposited at the top of a constructed sluice (Figure 1). In contrast to the 13, 1 x 1/2-meter segments of carpet used on a sluice in a *traca*-based production modality, in this heavy machinery-based operation 30 carpets line the double panel sluice box (Figure 2).

There is no *chivola* for the workers in David's operation as they are not paid in a percentage of daily gold production but are instead given a monthly salary based on their role. Excavator and front loader operators make the most at S./3000 (1000 USD) a month while the *huaychuleros* and the cook make the least at around S./800 (250 USD) a month. The hierarchy of labor roles is reflected in the social relations between laborers, as *huaychuleros* often eat meals apart from the operators. These differences in the arrangement of labor, payment structure, and responsibilities of laborers, all depend in part on the choice of extraction technology. As such, investigating the development of extraction technologies helps to understand the diversity of gold production practices in Madre de Dios today. Moreover, this differentiation in gold production practices is increasingly acknowledged as a defining feature of the artisanal and small-scale gold mining economy; estimated to produce more than 20% of global annual gold supply (IGF 2019).

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2. *Chivola* is a Spanish word, meaning young woman or young girl.

Figure 1. Diverse modalities of gold production in the small-scale gold mining economy in Madre de Dios, Peru. Left, the *traca*, a dredge set floating on a raft supported by empty oil drums that works by suctioning slurries of gold-bearing soils from the bottom of an open pit mine. Right, *huaychuleros*, sit atop wooden cabins in a heavy machinery-based production modality. The *huaychuleros* are responsible for washing gold-bearing soils deposited at the top of the sluice by a dump truck.

In 2013, more than 70 nations adopted and ratified the Minamata Convention on Mercury, a binding international treaty aimed at eliminating anthropogenic mercury releases and emissions. As allegedly the largest contributor to global annual anthropogenic mercury emissions, the practice of using mercury to concentrate gold in small-scale gold[3] mining has been increasingly scrutinized (Rubiano Galvis 2020). Transfer of 'clean' mercury-free technologies, innovation to improve existing extraction technologies, and the development of alternative technologies are all interventions proposed by development practitioners and scholars aiming to 'improve' the small-scale gold mining sector (Zolnikov and Ortiz 2018; Esdaile and Chalker 2018). Underlying these proposed interventions is an assumption that gold miners use of 'rudimentary' and 'crude' technologies results in inefficiencies in gold production and degradation and pollution of the environment (UNEP 2020; Buxton 2013). My research shows otherwise: a wide variety of sophisticated and simple technologies are used in gold extraction and processing. Moreover each technological arrangement comes with different costs, returns, and environmental impacts.

3. For the purpose of this article, I adopt the term small-scale gold mining instead of the more commonly used artisanal and small-scale gold mining (ASGM) in an effort to reflect the on-the-ground reality in Madre de Dios where a spectrum of mining operations of varying levels of mechanization, daily production capacity, and environmental impact exists under the catch-all phrase ASGM. Still the term SSGM is inadequate.

Figure 2. Sluices constructed on-site in a *traca* based operation (left) and a heavy machinery-based operation in Madre de Dios, Peru. Sluices are lined with carpets to capture fine gold particles present within alluvial sediments and soils. Note that the number of carpets differs between these operations as greater volumes of gold-bearing material are processed in heavy machinery-based operations.

Proponents of technological interventions in small-scale gold mining argue that with 'appropriate' technologies artisanal and small-scale miners would increase their gold production and reduce their environmental impact, resulting in an environmentally sustainable sector (Veiga and Fadina 2020; Zolnikov and Ortiz 2018; Veiga et al., 2014; Jønnson et al., 2013; Swain et al., 2007; Hinton and Veiga 2003). While increasingly scholars such as Teschner et al. (2017), rightfully acknowledge that no one technological intervention will act as a panacea to cure all of ASGM's associated social and environmental ills – these arguments still rest on the assumption that miners are lacking in appropriate technologies and technological understanding. Recently, scholars like Massaro and de Theije (2020) and Veiga and Fadina (2020), acknowledge the shortcomings of an approach rooted in providing technological alternatives by recognizing that miners themselves have adapted their technologies over time to meet place-specific local conditions. However, these analyses still reproduce dominant narratives that portray small-scale gold mining as a sector to be improved through technoscientific intervention.

This article seeks to examine changes in gold production practices from the perspective of small-scale miners. I contextualize my findings by demonstrating how a diversity of gold production modalities and socioeconomic differentiation among miners has important implications for the governance of ASGM in a changing policy landscape. In particular, nations that have signed onto the Minamata Convention are obliged to institute policies and outline specific actions that will be taken to reduce and where feasible eliminate mercury use in small-scale gold mining (UNEP 2020). Central to these national action plans are two strategies: formalization of miners and technological interventions to replace mercury with mercury-free technologies and introduce new technologies that increase the efficiency of gold production (UNEP 2020). Through formalization of gold mining concessions and extraction rights, nations like Peru hope to promote the adoption of cleaner gold production by requiring environmental impact analyses and mine closure plans to reduce the environmental impacts associated with deforestation and mercury use in SSGM. However, these top-down policies and interventions have largely been unsuccessful as the number of miners working informally continues to grow and the impacts from deforestation and mercury pollution are increasingly apparent (Diaz Leiva 2021).

To unpack the problems surrounding a top-down technoscientific approach to improving small-scale gold mining, this article begins from the understanding that in Madre de Dios, Peru, small-scale gold mining is highly differentiated within a particular mining locality. To substantiate my argument that miners have developed locally appropriate modalities of gold production in response to changing socio-political circumstances and different geological conditions, I first review the literature surrounding top-down technological interventions in artisanal and small-scale gold mining, demonstrating the need for an approach that considers place-specific heterogeneity in production practices from the perspective of miners and the need to better define what are considered 'appropriate' technologies. I then present empirical evidence derived from nearly a year of field work in Madre de Dios, Peru where I conducted semi-structured interviews with more than 40 miners working across every type of gold production modality and visited mines located in every district within the region. Drawing from this rich case study, I demonstrate the historical development of gold production modalities, the ways that miners have developed locally appropriate technologies to fit changing sociopolitical circumstances, differences in access to capital, and site-specific geological conditions. Finally, I extend my insights to consider the implications of these diverse production modalities for the success or failure of technological interventions that seek to foster sustainable production techniques and reduce environmental degradation and pollution caused by small-scale gold mining. I propose alternative policies and governance approaches that might better reflect the on-the-ground realities of a differentiated small-scale gold mining economy.

3. Technoscientific solutions in ASGM

Technology is central to how small-scale gold mining is defined, categorized, and understood. The most common definitions of what is frequently called artisanal and small-scale gold mining or ASGM, characterize this 'sector' as a low-technology and labor-intensive form of gold extraction and processing (UNEP 2020; Delve 2019; IISF 2017; Hilson et al., 2017; Buxton 2013). Often, the technologies used in mining - which vary from non-mechanized, manual methods to highly mechanized heavy machinery – are described as 'rudimentary,' 'inefficient,' 'improper,' 'primitive,' or 'simple' (Veiga and Fadina 2020; Buxton 2013; Hilson 2002; Hinton and Veiga 2003; Suding 2005).' In effect, these representations construct a narrative of small-scale miners as lacking knowledge of appropriate technologies and methods of gold production. As, development institutions, researchers, and policymakers assert that the technologies used in gold extraction and processing cause outsize environmental impacts and occupational health and safety issues, technology has also become a target of interventions aimed at 'improving' small-scale gold mining (Veiga and Fadina 2020; Esdaile and Chalker 2018; Zolnikov and Ortiz 2018; Zvarivadza 2018; Seccatore an de Theije 2017; Jønsson et al., 2013; Suding 2005). These interventions are premised around the idea that with the introduction of 'appropriate' (i.e., more capital intensive and technologically modern) technologies, ASGM could be reformed into a ‘clean’ production sector that contributes to sustainable development of rural landscapes (Hinton et al., 2003).

Proponents of these technoscientific approaches to reforming small-scale gold mining assert that the introduction of more efficient extraction and processing technologies will lead to gains in economic productivity for small-scale miners and alleviate the environmental impacts associated with both the use of mercury in gold processing and technologies that cause deforestation and environmental degradation (Esdaile and Chalker 2018). Hinton et al. (2003) argue that small-scale gold mining can drive sustainable development of underdeveloped rural regions with improved technologies that minimize environmental damages and maximize profits for producers. Underlying this argument is a belief that producers lack appropriate technologies and a general understanding of 'proper' or 'efficient' methods of gold production (p. 103). Small-scale gold mining is depicted as an under-capitalized and therefore less efficient and economically sensible method of gold production:

> Technical alternatives derived from formal mining, or developed specifically for artisanal and small-scale mining, must be thoroughly examined, pre-tested, appropriately modified, and successfully transferred before artisanal and small-scale mining is likely to transform into an environmentally sound and socioeconomically sustainable activity (p. 102).

Seccatore and de Theije (2017) argue that small-scale and artisanal gold miners choose particular extraction technologies only for short-term economic gains while ignoring the environmental and occupational safety risks of these technologies. Their analysis exemplifies many of the common tropes that are used as justification for technoscientific interventions in small-scale gold mining. They state:

> In general, all the operations observed during the field trip were rudimentary. The technology level was always low, as was the technological, operational and geological awareness. As is typical of artisanal mining, technologies, techniques and strategies appeared to be used because they are customary or because people nearby are using them (p. 115)

These narratives emphasize a problem not only with the extraction technologies but with the operators themselves, depicting small-scale miners as lacking expertise and knowledge of the best methods for gold production given certain geological conditions. These perspectives discount the place-specific knowledge of miners who have often adapted their methods of production to fit particular socio-political, economic, and geological conditions (Libassi 2020a, 2020b; Massaro and de Theije 2020; Klein 2020; Peluso 2018; Ferring et al., 2016). Moreover, this perspective fails to take into account the structural factors that enable or constrain the choice of particular technologies, as well as the histories of technological development and adaptation in a particular mining locality. As Lahiri Dutt (2018) emphasizes, these types of narratives reinforce an understanding that artisanal and small-scale mining is no more than a ‘problematic’ subsector of the global extractive industries rather than a complex livelihood practice driven by multiply scaled social, economic, cultural, and environmental factors (p. 9).

Recent scholarship complicates the underlying assumptions of proponents of technoscientific interventions in small-scale gold mining, emphasizing the structural factors that come to enable or constrain miners’ choices of certain technologies for gold extraction and processing (Libassi

2020b, Spiegel et al., 2018; Jønnson et al., 2013). Spiegel et al. (2018), examine miners' decision to use mercury in gold processing in Indonesia following ratification of the Minamata Convention and consequent national-level commitments to eliminate the use of mercury in ASGM. The authors call for a "careful understanding of the inter-linked socio-economic relations and power dynamics that shape technology choices, material flows, and mercury use practices (p. 2)." The authors emphasize that the decision to use mercury in a particular mining locality is both enabled by the domestic production of mercury from cinnabar mining - which results in access to cheap mercury supplies - and also by socially embedded, differential power relations wherein powerful actors in gold processing centers and mercury suppliers have vested economic interests in keeping miners using mercury (p. 6). This case illustrates some of the reasons why after more than 15 years of development interventions focused on introduction of mercury-free technologies, these interventions have yet to bring about the purported benefits of clean and sustainable gold production in artisanal and small-scale mining (Veiga and Fadina 2020; Zolnikov and Ortiz 2018).

Socially embedded mining practices aren't the only factors that influence the decision to use particular mining technologies in the extraction and processing of gold; socioeconomic differentiation within small-scale gold mining economies also plays a significant role. In an insightful analysis of the diversity of labor arrangements within one particular informal gold mining locality in West Java, Indonesia, Libassi (2020a), argues that heterogeneity within individual mining localities in the organization and arrangement of labor, shapes both the informal gold mining economy and the experiences of the participants within it. The author leverages data from ethnographic fieldwork and a critical agrarian studies lens to delve deep into the political economy of informal gold mining, analyzing the diversity of labor roles and arrangements within underground mines and how these differences structure the subjectivities of miners. Moreover, Libassi analyzes how this heterogeneity in labor arrangements has both expanded livelihood opportunities for miners but also led to a widening socioeconomic differentiation of the labor force, exacerbating economic inequality between the most capitalized producers and the most marginal laborers. The author's case along with similar scholarship by Ferring et al. (2016) reinforces the importance of deeply examining the nuances in production practices within specific mining localities so as to better devise development interventions or policy prescriptions that fit the reality of a differentiated work force and avoid reinforcing existing inequities within the class structure of small-scale mining economies.

While most scholarship on technological interventions in small-scale gold mining focus on how mining engineers and development institutions can successfully introduce new 'clean' technologies and increase adoption through top-down interventions, Massaro and de Theije (2020) consider how innovations in technologies used to extract *and* process gold – developed by miners – may spur the evolution of 'sustainable gold extraction.' Focusing on a region of informal gold mining in Mato Grosso, Brazil, the authors use a technographic approach to ground their analysis in the regionally specific evolution of mining technologies. They argue that innovation in mining technologies is the product of social and economic processes of technological development and adoption (p. 619). Although the authors aim to show how miners can spur the development of 'clean' production in small-scale gold mining through bottom-up innovations in mining technologies; ultimately, they fail to problematize the idea that technologies alone will improve mining practices and lead to more environmentally and socially sustainable economic development. Their analysis for example, does not consider class differentiation amongst miners and structural factors like access to legally titled mineral concessions that may constrain or enable miners' ability to adopt more sustainable mining technologies. Moreover, this analysis does not problematize the very concept of what is considered an 'appropriate technology' for sustainable gold production. In this regard, my article seeks to contest the assumptions of miners purported lack of "appropriate" technologies for gold production by showing how what may be viewed as an inappropriate technology due to negative environmental impacts may be appropriate for site-specific geological conditions, flexible arrangements of labor and property regimes, and changing socio-political circumstances.

Following from this recent scholarly attention to the differentiation of production practices within small-scale gold mining, this article examines the heterogeneity in extraction technologies in Madre de Dios, Peru from the perspective of miners. I argue that extraction technologies act as a structuring element in the development of diverse modalities of gold production as small-scale miners have historically produced flexible arrangements of extraction technologies and methods of gold production. Rather than passive adoption of existing mining technologies, the adaptation of existing technologies has occurred in response to socio-political circumstances, different site-specific geological conditions, and differences in access to capital, leading to the development of locally 'appropriate' technologies. These technologies are not rudimentary or simple but rather historically produced and socially *and* geologically embedded.

3. Heterogeneity in modalities of gold production in Madre de Dios

3.1 Study Area

The Amazonian region of Madre de Dios, Peru is a densely forested region that spans the eastern slopes of the Andes-Amazon transition zone and forms the most western limit of the Amazon basin. Since at least the early 20th century, small-scale alluvial gold mining has been practiced along the major rivers of the region (Valencia 2014). In the latter half of the 20th century, the small-scale gold mining economy grew rapidly as the Peruvian central state promoted and facilitated gold mining as a means to accelerate rural economic development and regional integration (Diaz Leiva 2021, *in prep*). Despite over 15 years of attempts by state actors to order and formalize small-scale gold mining, most gold production in Madre de Dios remains informal (Damonte 2018). Moreover, there now exist areas where gold mining is illegal due to recent changes in zoning that prohibit mining within territorially demarcated 'zones of exclusion' (DL 012-2010). Nevertheless, small-scale gold mining remains an engine of economic growth in Madre de Dios, providing direct employment to an estimated 50,000 miners and indirect employment through associated service sectors that provision goods and services to miners (Salo et al., 2016).

Small-scale gold mining isn't concentrated in any one particular locality in Madre de Dios but is rather diffuse throughout a number of historical and more recent mining settlements as well as increasingly dispersed in small mines located proximate to the region's extensive river network (Caballero Espejo et al., 2018). Situated at the triple-border between Bolivia, Brazil, and Peru – Madre de Dios has long been a porous frontier of extractive exchange where rubber and now gold are carried across national borders (Valencia 2014). The transfer of extraction technologies from Brazil to Madre de Dios and the adaptation of these technologies, is an as-of-yet untold story that plays a central role in the history of small-scale gold mining in Madre de Dios.

3.2 Evolution of gold production modalities over time

The first extraction technologies used in Madre de Dios were gold pans (*bateas* or *cuyas*) that relied on miners' skilled knowledge of gravity separation and prospecting. In later years – beginning around 1950 - Andean migrants began to settle in Madre de Dios and the use of wheelbarrows and shovels became more prominent (Valencia 2014). These non-mechanized technologies relied on a large work force that was organized into crews serving under a mine boss. Workers describe the labor relations structured around non-mechanized extraction technologies like the wheelbarrow (*carretillas,* Table 1) as hierarchical and exploitative. Central to this gold production modality was a system of debt peonage that relied on migrant labor, brought to work for a boss under 90-day contracts (locally called *noventas*). Wages were calculated on a daily rate but were not paid to laborers until the end of their 90-day contract. Workers reported that deductions - in payments for missed days of work or consumption of goods such as cigarettes bought on credit from bosses - were common. Wages amounted to approximately S./2 per day (< $1) and with deductions, some laborers were left in debt to the boss and forced to complete another 90-day contract. While food and housing were provided in camps located proximate to the beaches where laborers worked, the earnings accrued to laborers during their contracts were often insufficient to allow for upward economic mobility.

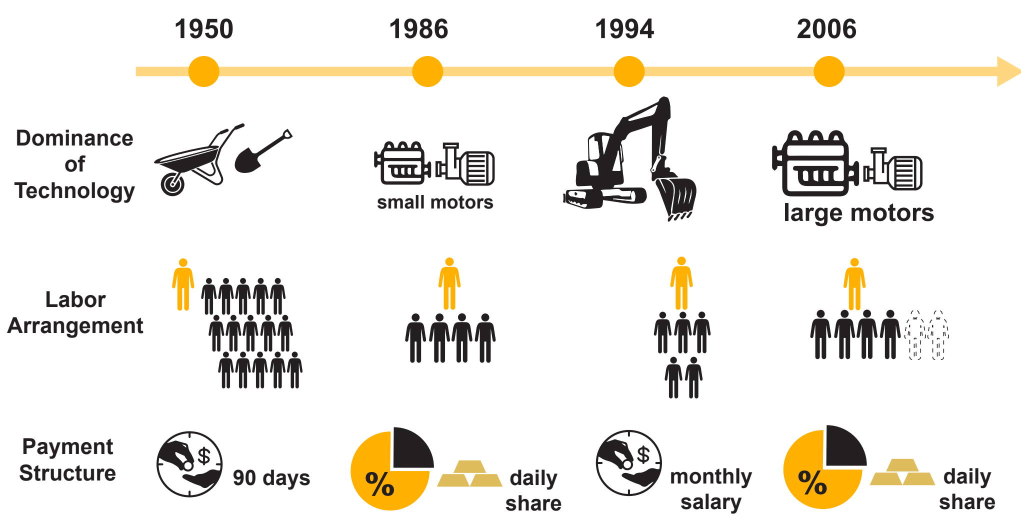

Figure 3. Changes in the predominance of different gold extraction technologies and associated labor arrangements and payment structures in Madre de Dios, Peru. Dates are an approximation of when certain extraction technologies were introduced or adapted based on the convergence of interview respondent answers. Dominance of technology represents the most common technologies used in gold mining at the time but does not signify that prior technologies are no longer used at present. Labor arrangements differ in the number of workers (black) employed under a mine boss (gold). Differences in payment structure are based on salary versus share-based compensation.

Don Richard, a 61-year-old career miner described his experience migrating to Madre de Dios in the 1980s, at a time when working *carretilla* was still common:

> I was born in Arequipa and came here 30 years ago searching for work. I was 28 years old at the time. I used to work in agriculture and for short periods of time in factories. There were no jobs in Arequipa. When I arrived, there were a lot of people working [in mining]. Each miner had 50 laborers in those times working *carretilla*. Everyone worked *carretilla*. You worked for an owner [boss] and produced 20, 25, sometimes 50 grams a day.

While the *carretilla* allowed bosses to maximize gold production by using a large, low-paid work force, this modality of production was limited by environmental factors. In the rainy season (October – March) in Madre de Dios, river levels rise and occlude the beaches where miners work point bar deposits, or gold deposits formed on the inside of river meanders. The *carretilla* as a gold production modality was then limited to the dry season months when point bar deposits were exposed by receding water levels. The seasonal restriction on the *carretilla* and the reliance on large work crews, left an opening for more flexible technologies that could increase production capacity and extend the gold mining season. These requirements would be met with the introduction of mechanized extraction technologies reliant on smaller number of laborers and able to be used both in waterways and in inland areas.

Table 1. A limited selection of gold production modalities currently practiced in Madre de Dios, Peru. The translation of common names of modalities (italics) are my own. Technology requirements are non-exhaustive and instead meant to illustrate key differences in the level of mechanization across different modalities. Modalities should be understood not as fixed typologies but instead as flexible arrangements of technology and labor, changing over time.

Modality of Gold Production	Technology Requirements	Number of Laborers	Payment Structure	Environmental Restrictions
Carretilla (wheelbarrow)	wheelbarrow, shovel, wooden sluice	crews of variable size	wages paid every 90 days	on beaches and only during the dry season
Carranchera	small motor, suction pump, wooden sluice	two laborers	percentage	on beaches and only during the dry season
Traca	large motor, raft, suction pump, PVC pipe lance, wooden sluice	two to four laborers; one crew boss	percentage	floating on waterways or inland in open pits
Chupadera (suctioner)	two large motors, two suction pumps, spraying hose, PVC pipe for suctioning, wooden sluice	three to six laborers; one crew boss	percentage	inland only
Maquinaria (machinery)	dump truck, front loader, excavator	varies by the number of operators, but at least two operators and two laborers; one crew boss	wages paid monthly	inland only

The most central moment in the technological history of small-scale mining in Madre de Dios was the introduction of the *motobomba* - a suction pump (*bomba*) powered by a car motor (Figure 4), allegedly brought to Madre de Dios by Brazilian *garimpeiros* during the mid-1980s. Brazilian *garimpeiros* in the Tapajos River Basin, located across the border from Madre de Dios in the state of Acre, largely extracted gold bearing material by dredging river sediments using *motobombas* (Cleary 1990). The porous border between Brazil and Peru likely facilitated the movement of *garimpeiros,* bringing the *motobomba* and large dredgers to Madre de Dios. The *motobomba* has become a keystone technology in Madre de Dios, as the adoption of this technology led to the development of diverse production modalities centered around the method of dredging fine gold particles from river sediments and slurries of soil. Manuel, a 43-year-old career miner, who has worked in almost every different type of production modality except heavy machinery, speaks to the importance of the introduction of the *motobomba*:

> The arrival of the motors changed a lot. They managed to use the motor to suction material via the pump. That's how it [mining] has been technified. First the *carretilla*, then the *carranchera,* after they brought the *motobomba* (I-8, Puerto Maldonado, May 2019).

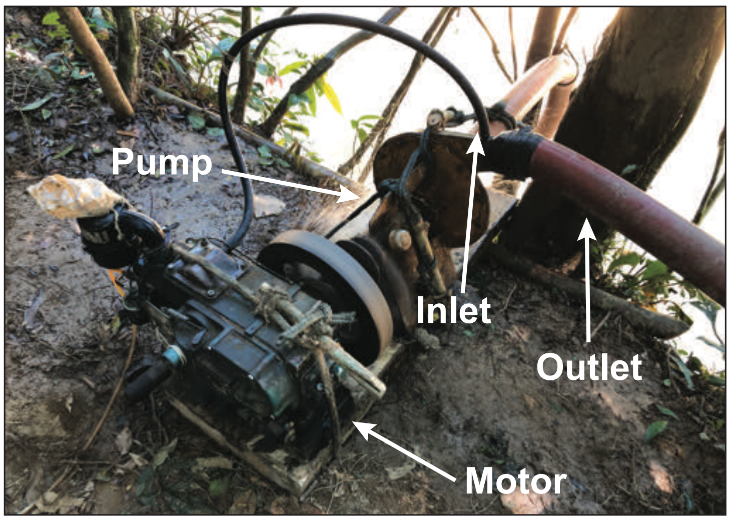

Figure 4. The introduction of the *motobomba* facilitated the expansion of gold mining into inland areas. In the picture above, a small motor, locally called a *chinito* is used to power a suction pump that pumps water from a small stream to an open pit mine more than 400 meters away where laborers work a *traca* based production modality.

The first use of the *motobomba* in Madre de Dios appeared to be as a dredge mounted on a boat known as a *buzo*. The *buzo* was a gold production modality that required one laborer to dive to the bottom of a river, holding a flexible hose to dredge up sediments, all the while breathing compressed air through a small tube. The *buzo* operated under a production-sharing arrangement wherein crews of four to five laborers would take turns diving for two-hours at a time and share in a percentage of daily gold production, usually 25 percent. The boss owned the equipment, hired the crew, and provided food and housing to laborers. As described by Cleary (1990), the emergence of a production sharing arrangement in small-scale gold mining in the Amazon, likely reflected the adoption of more dangerous methods of gold extraction like diving in rivers. Ricardo, a 46-year-old career miner, notes that accidents were common when working *buzo:* "Every miner had his dead; they died inside the overburden, buried alive, crushed (I-18, Puerto Maldonado, May 2019)." The dangers of diving in murky Amazonian rivers with little or no visibility and where entire trees are often pulled downriver in floods during the rainy season, failed to outweigh the possibilities of greater gold production and the temporal expansion of the mining season allowed by the *buzo*.

Starting around the late 1980s, the *motobomba* moved inland as miners began to dredge up gold from placer deposits buried beneath the forest floor. The use of *motobomba* based production modalities in inland areas required both the removal of vegetation and proximity to water as a source for the high-pressured hoses that were used to liquefy the soil - forming an open pit mine. The movement of the *motobomba* inland brought a new suite of environmental impacts that included deforestation and the creation of manmade ponds colonized by wildlife and often containing mercury-laced tailings. However, the move inland led to increases in gold production as near surface placer deposits were exploited at larger scales.

The adaptation of the *motobomba* led to a differentiation in labor arrangements and payment structures amongst different production modalities, wherein production-sharing arrangements became the customary payment structure for all *motobomba* based production modalities. These production sharing arrangements which offered ~ 25 percent[3] of daily production split evenly between laborers, provided more opportunities for upward mobility than wage-based payment structures that were associated with the *carretilla* production modality. Especially in areas with rich gold deposits, 25 percent shares could amount to a substantial payday for laborers, enabling capital accumulation and acquisition of assets like land for subsistence farming. Many interview respondents described purchasing their own motors after having saved up their earnings from working as laborers under *motobomba* based production modalities, allowing them to become miners in their own right.

One of the dominant themes emerging out of semi-structured interviews with miners and laborers was the fact that many had worked with different types of extraction technologies and in many (> five) mining sites. Respondents describe having worked *traca* or worked *chupadera*, or they refer to their roles in a work crew, stating they have worked as *traqueros* (*traca* operators) or *marakeros (chupadera* operators). The way that laborers describe their roles in relation to the modality of gold production, demonstrates how the diversity of production methods also influences miner's identity. The bodily risk borne by a laborer working as a *bravo,* clearing forest around a pit with machetes, chainsaws, and burning vegetation, is very different to that of a *traquero*, who spends his shift sitting on the raft and operating the mechanical arm of the dredge set (called the *mecanica*). These differentiated labor roles are reflected in the experiences of miners and can come to influence their subjectivities as well.

Nevertheless, labor specialization is uncommon in *motobomba*-based production modalities because of the constant evolution in extraction technologies and laborers proclivity to move between different production modalities in search of the richest gold deposits and thus largest payouts. For example, one of the most dominant gold production modalities in the early 2000s was the *chupadera*, a dual-motor dredge set requiring crews of six to eight laborers (Figure 5).

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4. Laborers split approximately 25 percent of gold production in every *motobomba* based production modality, though the exact percentage varies slightly between crews depending on the mine boss.

One laborer would operate a high-pressure hose, spraying away soil to form an open pit mine. Another operator worked simultaneously to suction the slurry of gold-bearing material produced by liquefaction. As laborers stood inside an open pit spraying away the soil, accidents could occur when overburden collapsed, burying laborers inside a pit. While popular because of the increased volume of gold-bearing material that could be processed on a daily basis, this production modality was also more expensive because of the operation costs borne by the use of two large motors, requiring more laborers and diesel to the fuel the motors.

The *chupadera* began to fall out of favor and was overtaken in popularity by the *traca* as a result of diminished access to unworked lands. Because of its similarity to other *motobomba* based production modalities, laborers transferred their knowledge of operating the *chupadera* to the *traca,* as both relied on the same method of dredging up slurries of gold-bearing material.

Figure 5. The *chupadera* is a production modality featuring two large motors that are used in tandem to power high-pressure hoses and suction gold-bearing slurries to a sluice box.

While the *motobomba* was adapted for mining on rivers and inland, opening up new land for gold production, highly mechanized technologies were introduced in historic centers of mining. In 1994, the first front loader arrived in Huepetehue, one of the oldest mining settlements established by *colonos* during the 1950s (Valencia 2014). Don Armando, a 60-year-old gold buyer, describes how he secured the first piece of heavy machinery for the most famous miner in Madre de Dios, Gregoria (Goya) Baca:

> I gave Goya and her family an advance to buy their first piece of heavy machinery; a Fiat front loader that we brought from Cusco. She herself came to ask for an advance and I gave her $50,000. Her kids came back a week later with 20 kilograms of gold. Her land was virgin land, but the woman didn't know how to invest. My friend worked at the machinery importer, they would import machines to Lima and from there transport them to Cusco and finally Mazuko [Madre de Dios]. The front loaders cost $160,000 – 200,000. That was in 1994. After that, everyone started buying heavy machinery. (I-24, May 2019, Puerto Maldonado).

The introduction of heavy machinery into already established mining localities once again caused a shift in the social relations of gold production. Heavy machinery increased gold production by increasing the volume of gold-bearing material that could be worked in a day, but it also increased fixed costs needed to purchase extraction technologies and to cover daily operating costs. The incredibly high capital costs required to acquire and operate a heavy machinery-based production modality restricted this method to only the wealthiest and most connected miners – often individuals who arrived in Madre de Dios during the first gold rushes of the 1950s-1970s and acquired many titled mining concessions along the way (Cortes McPherson 2019).

The adoption of heavy machinery also led to labor specialization and a professionalization of small-scale gold mining in these older mining localities. Some heavy machinery operators have completed coursework and received certificates from trade schools in urban centers like Cusco and Juliaca. As mining has become more capital intensive and professionalized in places like Huepetehue, relying exclusively on the use of heavy machinery, miners have come to search for operators with more specialized training, preferring those that received training rather than those that have learned on the job. Nonetheless, the ecological context of operating heavy machinery in the Andes in hard rock mines is quite different than in the rainforest, where vegetation must be cleared before any excavation can even occur. One miner described to me how he had to 'break in' new operators, training them to handle the complex landscape of the jungle (Figure 6).

Even in places like Huepetehue where the labor is more specialized and hierarchical, there are still opportunities for advancement. The *huaychuleros* (Figure 1) that wash gold bearing material, sitting for 8-10 hours a day in a small wooden cabin, adjacent to the sluices, are the least specialized laborers. The *huaychuleros,* like all laborers in heavy machinery-based production modalities are paid a monthly wage instead of a percentage of daily gold production. Still, even a *huaychulero* can find ways to advance to become an operator. Jose, a *huaychulero*, spoke of the importance of building trust with operators by showing interest in learning about the machinery, assisting with basic repairs, and even providing small gifts like soda or a cigarette to gain favor with an operator. As Jose explained, an operator will only be willing to teach you if they like and trust you. Learning is also largely self-directed and spending time with operators as they sit in the cab is often a good way to learn by seeing what operators are doing. The opportunity to become an operator means a significant advance in socio-economic standing for a *huaychulero* who can go from making around ~S./800 (250 USD) a month to more than S./3000 (900 USD) as an operator.

Specialization of labor in heavy machinery-based production modalities also coincides with more hierarchical labor relations than in the *motobomba*-based production modalities. Operators are treated with greater respect and responsibility than *huaychuleros* by the mine boss or foreman. Laborers also recognize these hierarchies of responsibilities and respect, as one respondent described how operators always ate separately from *huaychuleros* during meals in the camps he worked at. Even within the category of operators, there is a perceived hierarchy of importance and degree of skill required. Dump truck drivers are the least skilled, only responsible for transporting material to and from the excavation site. Front loader operators are next in the hierarchy, given the responsibility of clearing the piles of gravel and rock from around the sluice. Finally, the excavator operator is the most skilled, both central to the construction of the sluice box by setting the tree posts into the overburden pile and loading the dump truck during day-to-day operations. The specialization of labor roles demonstrates how extraction technologies have played a central role in the development of the social relations of work in gold mining in Madre de Dios. Operators who drive dump trucks, front loaders, or excavators cultivate an identity structured around operation of certain technologies. In this way, technology is not only a tool that facilitates gold production but is also a structuring element in the development of diverse modalities of gold production.

Figure 6. Excavator operator in Huepetehue. Photo credit: S. Antoni Delgado.

3.3 'Seeing' the subsoil

Proponents of technoscientific solutions to the environmental impacts associated with artisanal and small-scale gold mining argue that the lack of 'appropriate' technologies for gold extraction and processing results in the releases of contaminants like mercury and cyanide into the environment and deforestation and sedimentation caused by dredging and excavation. These individuals posit that with appropriate technologies and training, 'cleaner' and 'less environmentally impactful' gold production is possible (Massaro and de Theije 2020). Yet, these arguments belie the fact that many of the extraction technologies and production practices have evolved over time to fit particular site-specific geological and socio-political circumstances. In particular, in Madre de Dios miners respond to changes in the quantity of gold production at individual sites, continually evaluating the economic productivity of a gold deposit to decide if it is worthwhile to continue working at a site or better to move elsewhere. In this way, the geology of gold deposits while not the sole determinant of the choice in extraction technology and production modality, is a major factor in the consideration of whether to use a certain type of technology or not. While proponents of technoscientific interventions point to a lack of knowledge of appropriate technologies by miners (Buxton 2013), analyzing the development of mining technologies in Madre de Dios reveals a complex cultural knowledge and geosocial (Clark and Yusoff 2017) process of adaptation of mining technologies that has resulted in the development of locally 'appropriate' gold production modalities to fit miners' technical needs.

The gold deposits found in Madre de Dios are what are known as secondary deposits or placer deposits, formed by weathering and erosion of hard rock ores in the Andes that have produced fine grains of gold, carried down in rivers to the lowlands of Madre de Dios (Lanckneus 1991). These fine gold particles settle in deposits along the inside of river meanders -known as point bar deposits - and overtime with changes in river geomorphology and seasonal inundation, have also formed near-surface deposits in the floodplains of these rivers (*ibid*). Some deposits are more productive than others both in terms of the concentration of gold particles per volume of material and in terms of the size of these particles (Figure 7). In near-surface floodplain deposits, the vertical profile of the deposit differs markedly in depth and composition of the substrate of the soil and subsoil strata. The geology of these differing deposits makes it more or less profitable to extract gold in any particular site, as the depth of overburden increases production costs. Gold miners in Madre de Dios are deeply aware of this geological variability and commonly remark that 'there's gold everywhere in the forest,' but that it is not profitable to extract in all places.

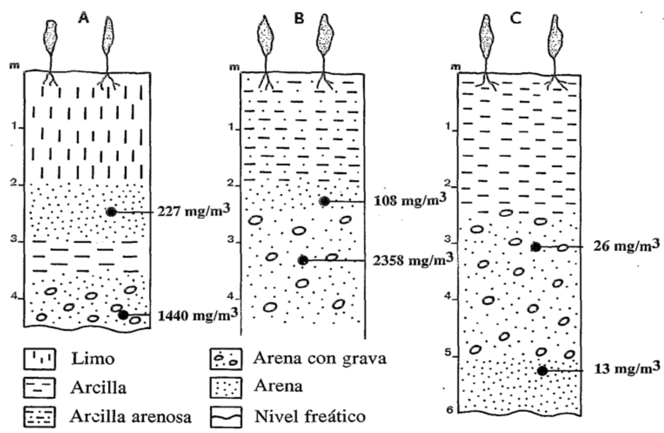

Figure 7. Diversity in the composition of geological substrata of placer deposits in Madre de Dios, Peru (from Lanckneus 1991). The different types of substrata are characterized by different productivity of deposits (mg/m^3 of gold), different compositions of substrate (gravel, sand, loam, clay), and different depths of overburden (topsoil).

One of the most important factors that miners must contend with in their choice of a particular modality of gold production, are the site-specific geological conditions of a gold deposit. Interview respondents consistently pointed to the importance of evaluating the land (*el terreno*) before selecting a modality of gold production. When miners refer to the land, they are referring to the composition of the subsoil and the vertical profile of a placer deposit with varying quality, composition, and depths of overburden. These factors influence operating costs as areas with deep topsoil strata require more capital investment to remove this material before accessing the gold-bearing substrata. Moreover, the composition of the subsoil whether characterized by a rocky-gravelly matrix, sandy-loamy or clay matrix will affect which extraction technologies can be used. As one miner summarized, "you have to select the modality [of production] in accordance with the land (I-13, Puerto Maldonado, May 2019)."

The diminishing availability of 'virgin land' (*terreno virgen*) or land that has not yet been worked is a factor that limits many miners to working previously opened pits. In one formalized mining concession, the owner only worked previously worked pits, justifying this decision because of the high operating costs of opening new pits in areas where production is lower. Don Miguel recounts acquiring his concession from a miner who had already worked the subsoil for many years. He describes his decision-making around what type of production modality he employs:

> Not all the forest is profitable, but it does contain gold. Before, the land lasted for months, now only 15 days maybe. You used to work virgin land for four to six years, now around this area [Laberinto], it's one year at most. If I had the land, I would work *chupadera*, it's more expensive but it also leaves you more [profit]. In virgin land, you can work it. There is no longer land to work *chupadera*. Here, I work in pits that have already been opened. You return [to these pits] with the *traca* because it is more profitable, the costs are lower. (I-15, Laberinto, May 2019).

Don Miguel's testimony highlights many of the important factors that miners must take into consideration when choosing a particular production modality. In particular, his account reinforces the fact that miners understanding of the productivity of a gold deposit as well as the potential operating costs of working a particular deposit all come to influence their decision of which type of production modality to use. Moreover, as Don Miguel's story attests, the history of land use also plays a critical role as land that has been previously worked will no longer yield as much as virgin land and thus the investment in higher powered motors under production modalities like the *chupadera* are not economically worthwhile in these types of areas. However, a particular production modality is not a fixed arrangement of technologies but is constantly shifting in relation to the changing productivity of deposits and miner's adaptation to these changes in gold production. Lucho, a 46-year-old miner from Cusco describes the evolution of these extraction technologies over time, highlighting the adaptations made to the now dominant *motobomba* based modality known as the *traca*:

> When I arrived, some people were still working *carretilla*. But people have invested and innovated. Depending on the area, you work either a *traca* or with a dredge. In the past months, people are using larger suction pumps with the *traca*. They are adapting [the pumps] here. Here they have done it all.

When I asked miners to describe how the popularity of different modalities of production has changed over time, many would often respond like Lucho that while it was the *garimpeiros* that introduced the *motobomba* to Peruvian miners, the Peruvians had not only adapted the *motobomba* to fit local geological conditions, but they had also 'made it better.' This adaptation is exemplified in the case of the *traca* that has now become the most popular *motobomba*-based production modality, displacing the *chupadera* due to its lower operating costs. Lucho describes how on his own titled mining concession, a third-party miner (*invitado*) has increased production using a larger diameter pipe fitted to the suction pump of the *traca:*

> I have invited someone coming from La Pampa who works *traca* with eight [8 in. diameter tubing] and he is getting three times the production. The land is ideal for *traca* with eight. There is *traca* with ten in Inambari and above [upriver] because there are large rocks. (I-21, May 2019)

Lucho's testimony highlights how the *traca* has become a flexible production modality that can fit a variety of different geological conditions. The suction pump on the *traca* now features a larger intake valve, adapted by local mechanics to fit a larger PVC pipe lance (Figure 4). The ability to use a larger diameter pipe not only increases the volume of gold bearing material that can be suctioned but also mitigates damage to the machinery caused by rocky substrates that crack the intake valve on the suction pump.

While the adaptation of the *traca* has made it possible to work or rework certain gold deposits, there are still important geological limitations that have yet to be overcome. For example, the *traca* is not the best production modality for rockier subsoil strata. Leandro reinforces this limitation of the *traca* by saying: "You have to see the land; is it gravelly, loamy, or silty? The *traca* can't enter into gravel (I-3, PEM, April 2019)." Moreover, there is the problem of working blind (*ciego*) when working *traca* because the suctioning lance is submerged in water and there is no way to see what the gold-bearing strata looks like. Working blindly is a risk for laborers who may unwittingly undercut a bank and cause the overburden to collapse. As Don Miguel describes:

> The *traca* isn't the best because you can't see the material. The [tree] roots get drowned because the *traca* suctions and you need to be pumping water constantly from somewhere else. You never work in dry conditions. The roots are dangerous because they will pull down all the soil [overburden] and then the worker needs to escape.

The adaptation of the *traca* based production modality, particularly the modification of the suction pump intake valve to accommodate larger diameter PVC pipes, has allowed miners to adapt to differences in site-specific geological conditions and diminishing gold production. However, geology and the search for greater profits are not the only factors that drive the choice of production modality. Changes in socio-political circumstances and the legality of certain mining practices have also influenced the development of particular modalities of gold production.

3.4 Changing sociopolitical and legal landscape

Small-scale gold mining in Madre de Dios like in many other mining localities across the globe is characterized by a high degree of informality, wherein miners often lack formal government authorization in the form of property and mineral rights to extract gold (Damonte 2016; Valencia 2014). While Peru passed legislation at the national level in 2002 to bring small-scale and artisanal miners into the formal economy, in Madre de Dios, formalization efforts have fallen short of their intended goals of creating an organized, taxable and controllable small-scale gold mining economy (Salo et al., 2018; Damonte 2018; Salman and de Theije 2018; Valencia 2014). One of the most difficult obstacles for miners to overcome in formalizing their operations is acquiring the legal title to a mining concession or a legal contract with a concession holder. The produced scarcity of legally available mining concessions has arisen out of a historical disjuncture between competing development discourses (Diaz Leiva 2021, *in prep*). The result of this disjuncture is diminished access to legally available land for gold mining and a legal landscape in which mining outside of formally titled concessions is now considered illegal and subject to military interventions and prosecution (Legislative Decree 1101-1107, 2012). The precarity in the legal landscape has affected how miners work and which extraction technologies they choose to use in a particular production modality. The portability of particular extraction technologies comes to play a central role in this decision as certain technologies are more flexible and mobile in the face of militarized interventions. The story of the now commonly used, Chinese motor (*motor chino* or *chinito*), a 20-22 HP car motor imported from China, illustrates how the move towards smaller, more portable motors is happening in response to a changing legal landscape.

> The *chinito* can be used in the *traca*, the *carranchera*, and even the *chupadera* if you use two motors. The *chinito* motor can work two to five meters in depth at the most. A 220-horsepower motor can get up to ten to fifteen meters in depth. Now they [miners working outside titled concessions] are going in with the *chinito* motors. There are *chinito* motors that play the interdictions (I-13, Puerto Maldonado, June 2019).

David's testimony demonstrates the ways that smaller, more portable motors are now being used in already established production modalities like the *chupadera* and *traca* because they are more easily hidden and can 'play the interdictions.' This phrase alludes to the fact that militarized interventions often result in the loss of motors and suction pumps that are legally required to be destroyed under Legislative Decree 1100 (2012). When referencing playing the interdictions, David was referring to the common practice of sinking or burying motors in mining pits when interventions are rumored to occur. Because the *chinito* is about the size of a toaster (Figure 5) in comparison to the 220 or 180 HP motors that typically power a *traca* or *chupadera* and are the size of a refrigerator, it is easier to transport, bury, occlude, or sink these smaller motors. Moreover, losing a *chinito* which is estimated to cost around S./3000 (1,000 USD) is substantially less economically damaging than losing a 220 HP motor which can run up to S./20,000 (6,000 USD). The increasing use of these smaller motors also lowers the barrier to entry for individuals with less capital, who cannot purchase larger motors. This example demonstrates how already flexible modalities of gold production are adapted to fit a changing legal landscape in which militarized interventions are increasingly used as a tool to displace miners from zones of mining exclusion. Extraction technologies using the *chinito* facilitate the transience of already mobile miners as they move in search of more productive deposits and avoid punishment.

4. Discussion and Policy Implications

4.1 Flexible Governance

A limited understanding of the diversity of gold production modalities within a particular mining locality like Madre de Dios, has real implications for the management and governance of small-scale gold mining on-the-ground. As argued by many other authors (Verbrugge and Geenan 2020; Verbrugge and Besmanos 2016; Hilson et al., 2017), one-size fits all approaches to formalization or technological interventions, negate socio-economic differentiation in the small-scale gold mining economy. These policies reinforce a homogenizing view of small-scale gold mining as only a limited subsection of individuals (i.e., the most highly capitalized gold miners) are able to navigate complex formalization procedures or can afford to invest in alternative, mercury-free processing technologies (Libassi 2020a; Verbrugge and Geenan 2020; Verbrugge and Besmanos 2016). Instead, a greater recognition of the diversity of production modalities and socioeconomic differentiation of miners must compel policymakers towards more flexible and targeted approaches to governance (Hilson et al., 2017).

Currently in Peru, the Law of Small-Scale Mining Formalization requires the acquisition of a mining concession or legal agreement with a concession holder before a miner can qualify to formalize their operations (Valencia 2014). However, there are now limited areas where mining concessions are legally allowable and access to titled concessions has diminished over time as moratoriums on the granting of concessions have effectively eliminated the transfer of expired concessions to new grantees (Valencia 2014). The diminishing availability of land for mining produces informality in small-scale gold mining as miners increasingly look to informal agreements with landholders that allow them to access land in exchange for weekly payments of rent in kind. As in other mining localities across the globe (Verbrugge and Geenan 2020), these informal arrangements are not reflected in policy and constitute a legal loophole through which miners are able to work in areas that are not zoned for mining, increasing conflicts with competing surface land claimants (Damonte 2018; Salman and de Theije 2018). Limited access to titled mining concessions also exposes laborers to militarized interventions that target 'illegal miners' or individuals working outside of titled concessions (DS 1105, 2012). Moreover, the reality on-the-ground is that these interventions unevenly affect the most marginalized laborers – the least-capitalized miners working on waterways with small motors and usually laboring alone or with a family member. These interventions only serve to reinforce existing inequities between producers, allowing the most capitalized and powerful mining actors to go unpunished even as their 'small-scale' operations exact high environmental and social costs.

A more socially just and environmentally sustainable approach to small-scale mining governance must recognize the socioeconomic differentiation of producers and the diverse production modalities that they work under. In this respect, there is room for improvement of existing legislation that sets technological restrictions and capacity limits on small-scale and artisanal miners. Under the Law of Small-Scale Mining Formalization, producers are divided into two categories, either small miners (*pequeños mineros*) or artisanal small miners (*pequeños mineros artesanales*). The categories are delineated based on three criteria: maximum daily processing volume of gold-bearing material, maximum allowable hectares held under mining concessions, and technologies used to extract gold. The restrictions on technology state that artisanal miners may only work with non-mechanized technologies and must mine to meet subsistence needs (Valencia 2016). There are no restrictions on the technologies used by small miners, effectively allowing the continued use of heavy machinery despite the fact that processing capacity likely exceeds the allowable limits in a typical heavy machinery-based production modality. These regulations – aimed at reforming production practices to achieve environmentally sustainability, again unevenly impose upon certain individuals while allowing others to continue mining with highly mechanized, capital intensive extraction technologies.

A better approach to the categorization and regulation of gold production practices could focus on installed capacity of machinery and taxation rates differentiated based on gold production rather than concession size. Limits on installed capacity could reduce the environmental impacts from deforestation caused by the use of heavy machinery as well as promote the use of less powerful motors, like *chinitos*, that are unable to create large open pit mines. Moreover, current prohibitions (DL 1101) on the use of dredges within waterways could be revised to permit the use of *carrancheras,* reliant on small motors and used by the least capitalized and most marginal small producers. Redefining these categories of small and artisanal miners would align policy with the diversity in production modalities that comes to define mining in Madre de Dios, while also dissuading the use of more environmentally damaging and ‘medium-scale’ mining technologies.

Recent international efforts to eliminate mercury emissions from small-scale gold mining under the Minamata Convention on Mercury posit that the introduction of mercury-free technologies to small miners will facilitate cleaner gold production (UNEP 2020). My findings indicate that more than just technological interventions and the transfer of ‘clean’ technologies will be required to eliminate the use of mercury by miners. Without sustained efforts to understand local socio-political and geological conditions that affect miner’s choice of particular extraction technologies and gold processing methods, these top-down interventions will continue to fail. A greater recognition and understanding of knowledge and expertise of miners, who have developed locally appropriate methods of gold production may better facilitate the introduction of alternative processing technologies not reliant on mercury. While recent scholarship (Veiga and Fadina 2020), acknowledges that transfer of mercury-free technologies has not delivered on promises of an environmentally sustainable small-scale gold mining economy – the authors fail to recognize how alternative techniques like cyanidation or shaker tables may again only be accessible to a certain subsection of individuals. These authors argue for the use of processing centers with more advanced technological methods for gold recovery, that may eliminate mercury use by miners in the processing phase. However, this solution is based on the assumption that miners will be willing to sell their unprocessed gold concentrates to processors and that informal gold buyers will cease to purchase gold amalgams concentrated with mercury.

As with any policy, possible interventions must ask who benefits from the introduction of new technologies and who is left out. Recent scholarship reinforces the idea that without a deep understanding of on-the-ground complexities in the organization of small-scale mining and knowledge of the differences in production practices within a mining locality, the introduction of alternative extraction and processing technologies is doomed to repeat the failures of the past (Veiga and Fadina 2020; Libassi 2020b; Zolnikov and Ortiz 2018; Siegel et al., 2018). While technology is no silver bullet for the myriad environmental impacts caused by small-scale mining, it can play a role in a multi-sector and multi-scalar suite of solutions if led by participatory and miner-driven needs.

5. Conclusions

I have demonstrated that bottom-up development in gold extraction and processing has occurred in Madre de Dios over time, resulting in a diversity of gold production modalities, these technologies are not necessarily more environmentally sustainable or cleaner. However, they are still ‘appropriate’ technologies in many different respects. First, they are appropriate for the site-specific geological conditions that miners face. They are also appropriate for the types of flexible arrangements of labor that are characteristic of mining labor relations. Third, they are appropriate for the property regimes and land use agreements that increasingly define the informal gold mining economy and require the movement of motors and dredge sets. Finally, they are appropriate for the shifting sociopolitical circumstances that miners face as a turn towards criminalization of small producers working within zones of exclusion requires the flexibility and mobility to hide and transport motors in response to interventions. The fact that miners have developed ‘appropriate’ technologies should be considered in governance.

The discrepancy between what is portrayed as a relatively palatable solution to the environmental and social impacts associated with small-scale gold mining may not fit the reality of miners that have produced locally appropriate production modalities centered around flexible technologies and labor arrangements that are best suited for their particular needs. While it is likely that miners may be willing to continue to adapt these production modalities in the face of potentially greater profits, introduced technologies must still allow for adaptations in response to ever changing sociopolitical circumstances while meeting a diversity of geological conditions.

CONCLUSION

Summary and Integration of Findings

This dissertation is organized around three chapters that make up the body of this text. In Chapter One, I demonstrated that during the latter half of the 20th century, the Peruvian central state played a key role in facilitating and supporting the development of a small-scale gold mining economy in Madre de Dios. Contrary to current narratives of a new "mercury problem" in Madre de Dios, I showed that mercury use in small-scale gold mining has a long history of state support. Recent shifts towards criminalization of small-scale gold mining and miners in particular zones where gold mining is prohibited, thus represents a historical disjuncture in the nation state's own dominant, extractive development discourses. Moreover, I demonstrated how an understanding of mercury as a mobile element, existing in nature in three different chemical forms - each with their own mobilities and toxicities – further complicates state and non-state actors' efforts to control and contain mercury pollution allegedly caused by illegal gold mining.

Central to my dissertation's contribution to furthering scholarly understanding of the social, political, and ecological impacts of mercury use in informal gold mining, is the explicit treatment of mercury as a mobile element. Mercury travels and moves with miners, beyond mines, and in the bodies of organisms that travel unrestricted through the diverse ecologies of Amazonian rivers and forests. While extensive scholarship has documented the social and environmental impacts of mercury use in informal gold mining in Madre de Dios and around the globe, too often these studies treat mercury as an inert object rather than a substance embedded in webs of environmental and social relations. By considering how mercury is embedded in social and environmental relations, I demonstrate that the problem of mercury pollution in Madre de Dios cannot be addressed without first understanding history, political economy, environmental politics, resource governance, and food web ecology. It is only by understanding mercury as a single node in a vast web of relations that make up the ecologies of gold production, that we begin to see the ways that the mercury problem in Madre de Dios is only one part of a much larger issue surrounding the paradoxical governance of informal gold mining in a country whose history has been profoundly shaped by the extraction of mineral resources.

My findings in Chapter One should be understood as both a critique of coercive governance approaches to informal gold mining and an indictment of apolitical understandings of mercury pollution. As I demonstrated, the socio-ecological mobilities of mercury and miners make it so that uneven strategies of containment of illegal gold mining will always ultimately fail to control mercury pollution. In particular, the demarcation of certain conservation areas as Zones of Mining Exclusion, and subsequent criminalization of mining in these areas has rendered certain people working in certain places, criminals. The mercury problem, framed as a problem of illegal gold mining, undermines the very real problem of mercury exposure that is now diffuse throughout the region of Madre de Dios and beyond. Moreover, this exposure is uneven and indigenous communities who do not participate in the extraction of gold are those that are most affected by mercury pollution through consumption of fish. As long as mercury use is framed as "an environmental and human health problem" associated *solely* with illegal gold mining, the risk of mercury concentrating and accumulating in human and non-human bodies outside of military-occupied zones, remains unaddressed. The mercury problem is a problem of environmental justice and should be framed as such so that mitigation of mercury exposure in indigenous communities and the criminalization of small-scale miners becomes a focal point of government and non-governmental interventions and policy reforms.

As I demonstrated in Chapter One, long histories of state territorialization in Madre de Dios produced a system of fragmented land management – a terrain rife with competing interests and claims of different state agencies to the same land for competing land uses. These land use and bureaucratic conflicts are still unresolved, and I would argue that as long as they remain unresolved, the negative social and ecological impacts of informal gold mining will continue. Conflicts are bound to arise from a fractured system of land management where the Ministry of Energy and Mines can grant mining concessions on indigenous territories and within protected areas or where protected areas can be declared in longstanding mining districts. At the same time because of the decentralization of mining governance in relation to the formalization of mineral claims and mining concessions - which rests under the purview of multiple ministries – competing interests and claims of state actors will always end up complicating solutions to these land use conflicts as different agencies try to exert control over resources, territories, and people.

In Chapter One, I demonstrated how a discourse of criminality emerged from narratives deployed by state and extra-state actors regarding mercury pollution, deforestation, and degradation, as well as misrepresentations of mercury science. These narratives helped created an inseparable association between mercury pollution and illegal gold mining and was meant to protect high conservation-value environments like Tambopata National Reserve from gold mining. But the environmental impacts of small-scale gold mining - deforestation and mercury pollution - remain the same whether mining occurs within a zone of exclusion or in a legally titled mining concession. These impacts also remain the same whether mercury is legally permitted or not given that enforcement of prohibitions on mercury use in small-scale gold mining are as unevenly sanctioned as small-scale gold mining itself. Therefore, it should not be surprising that mining is not declining in Madre de Dios, despite successively larger militarized intervention – instead miners simply move to other places, bringing mercury with them. Rather than providing a solution, declaring gold mining illegal in certain protected areas only contributes to crisis narratives that legitimate coercive governance interventions. These interventions are ineffective in directly mitigating or addressing the risks of mercury exposure for vulnerable populations in Madre de Dios.

Moreover, deploying mercury science to justify coercive governance interventions has only served to politicize and undermine the results of these scientific studies to the detriment of those populations who bear the uneven burden of mercury exposure. As long as mercury is used as a tool to justify coercive approaches to environmental governance, the risks of mercury exposure will never be truly addressed. And in ignoring the ways in which mercury exists apart from gold mining and moves freely through the environment on currents of air, water, and through the 'natural' interactions between the plethora of species that make up biologically diverse Amazonian food webs, the act of policing miners to reduce mercury pollution ends up exacerbating the risk to humans and wildlife by diffusing mercury to ever more remote corners of the forest. I believe that to begin to work towards socially and environmentally just solutions to the complex problem of mercury pollution, the politics of land use and land control underlying these coercive strategies need to be brought to light and the use of coercion as a mechanism to sanction and criminalize the practices of miners operating in certain places must be fundamentally reexamined.

My second chapter was grounded in ecological science and methods in ecotoxicology and food web ecology to assess whether or not mined landscapes are sites of mercury pollution and mercury bioaccumulation and biomagnification. In Chapter Two, I demonstrated how the relative level of mercury pollution, as measured in the bodies of wildlife inhabiting abandoned gold mines, is the result of the interaction between social and ecological factors that implicate heterogeneity in gold production practices within Madre de Dios as well as differences in ecological food web structure within abandoned mines. Using an analytic of coproduction, defined in Chapter Two as "an analytical tool for understanding how mutually generated social-ecological change takes place (Rademacher et al. 2019, p. 67);" I showed how mercury pollution can be understood as a coupled process of social and natural change, stemming from the extraction of subsoil resources. I argued that pollution arises from the use of mercury in gold production because of both differences in gold production practices and differences in the abiotic conditions present within a mined landscape that may or may not promote bacterially mediated transformation of mercury into methylmercury.

In Chapter Two, I found strong evidence that mercury bioaccumulation levels were driven by variation in mining practices and differences in food-web structure. Interviews with miners confirmed that the use of different extraction technologies influenced the degree of mercury loading into mining sites. Where heavy machinery mining occurred, there was never direct mercury amalgamation in mining pits and thus limited inputs of mercury-laced tailings into sediments. Instead, heavy machinery pits are constructed as water storage ponds filled-in by groundwater infiltration. The differences in gold production practices - using either heavy machinery or suction pump-based technologies - plays an important role in mediating the quantity and location of mercury discharges on the landscape. My finding yet again reinforces the notion that heterogeneity in gold production practices within a mining locality have far reaching implications for not only the governance of small-scale gold mining but also for ecological and ecotoxicological understandings of mercury fate and transport in the context of small-scale mining. These findings contribute to the field of mercury ecotoxicology where an increasing focus is on the interactions between different forms of land use change and mercury biogeochemical cycling (Hsu Kim et al., 2018).

In addition, in Chapter Two, I leveraged the use of a biological indicator species, long-jawed orb-weaving spiders to show how mercury moves beyond a gold mining pit and into the surrounding forest ecosystem. I found that these spiders - obligate predators of emerging aquatic insects that accumulate mercury from their larval life cycle in gold mining pits – accumulate mercury exported from mining pit through consumption of insect prey. This finding demonstrated how the mining pit itself acts as a source of mercury in the landscape; a hotspot where mercury is deposited in sediments and then transformed into its biologically available form. Even more concerning is the fact that this exported mercury subsidy is likely to propagate up the food web, accumulating in the bodies of wildlife, and transported across ecosystems into the forest food webs. Given that long jawed orb weaving spiders are consumed by mobile predators such as bats and birds and are not the only terrestrial consumers of emergent aquatic insects, I expect that these contaminant subsidies from emergent insects will affect wildlife found far beyond the riparian zone of abandoned mining pits.

My findings in Chapter Two are the first to demonstrate that the footprint of mercury contamination extends beyond the boundaries of a mine as abandoned mining pits are an important source of mercury to the terrestrial biota inhabiting mining impacted landscapes. I believe that more work is needed to fully understand the risk of contaminant exposure to higher trophic levels organisms that may feed from prey found within these abandoned mines. Previous work suggests that the degree to which these mining pits export mercury via emergent aquatic insects depends on the life history of these insects, as metamorphosis of aquatic larvae into adults reduces heavy metal burden in aquatic predators such as dragonflies and consequent accumulation in cross-system predators (Kraus et al., 2017). In addition, body size of emergent aquatic insects, mediated by top-down interactions, can also alter contaminant flux into terrestrial ecosystems (Walters et al., 2018). These mosaics of abandoned mining pits also form new habitat for migratory birds and other higher trophic levels organisms whose mobility allows them to further extend the footprint of mercury contamination from small-scale gold mining. Surprisingly, these abandoned mining pits are not part of government discourse surrounding the remediation and rehabilitation of mined landscapes. They must become a focal point of remediation as they are threat multipliers for mercury exposure in humans and wildlife. Not only are some of the ponds – particularly those worked with suction-pump based technologies – sites of methylmercury accumulation in wildlife, but recent findings also show that the rate of methylation in these ponds is also elevated (Gerson et al., 2020).

Some findings from Chapter Two, were very unexpected and should be carefully contextualized within the current regulatory framework in Peru governing small-scale gold mining. While abandoned mines can act as sources of methylmercury to wildlife, it should be noted that my findings also indicate that there is high heterogeneity in mercury bioaccumulation within mining impacted landscapes driven largely by the heterogeneity in gold production practices within individual mining localities. Namely, mining practices using different extraction technologies drive variation in the quantity and location of mercury discharges such that not everywhere in a mined landscape will there be evidence of high levels of mercury in biota. In turn, areas far removed from gold mining could have high levels of mercury in wildlife due to cross-ecosystem mercury transfer and mobility of consumers. Thus, sampling only one compartment such as the sediment of mining pits or the soils around abandoned mines can lead to inconclusive results, as differences in mercury bioaccumulation higher up in the food chain are not apparent from the relatively small differences in mercury loading in sediment (on the order of 10 ng). Further, proposals to remediate these contaminated landscapes for aquaculture or farming should take into account the type of extraction technology used. Surprisingly, despite the fact that sites worked with heavy machinery tend to have a greater physical impact on the environment due to high levels of mechanization in these more 'industrialized' operations, they may be safer candidates for remediation than sites worked with suction-pumps. This unexpected finding should be carefully considered in relation to policies governing small-scale gold mining in Peru which currently prohibit the use of dredges and other suction-pump based machinery in waterways but make no such prohibitions in inland areas. Moreover, it should be noted that heavy machinery is largely inaccessible to all but the most capitalized of miners and thus, any policy changes should consider the potential of exacerbating inequality amongst the large number of individuals employed within the small-scale mining economy.

Finally, in Chapter Three**,** I delved further into the differences in gold production practices within Madre de Dios from a socio-political and historical perspective that compliments and extends my analysis in Chapter Two. Going beyond documentation of a historical process of technological adaptation and improvement in gold production practices, I discussed how an understanding of heterogeneity in gold production within Madre de Dios has important implications for the governance of small-scale gold mining in a changing policy landscape. Top-down, technological interventions aimed at replacing mercury with mercury-free technologies and introducing mining technologies that increase the efficiency of gold production in small-scale gold mining are viewed as politically palatable approaches to spur the development of an environmentally sustainable and economically productive small-scale mining sector. In Chapter Three, I argued that diverse modalities of gold production have evolved over time as a result of technological transfer and innovation and adaptation of these introduced technologies – the outcome is a convergence on locally-appropriate technologies that can be adapted to fit site-specific geological conditions as well as a rapidly changing socio-political landscape. I extend my insights to consider the implications of these differentiated production modalities for the success or failure of technological interventions that seek to foster sustainable production techniques and reduce environmental degradation and pollution caused by artisanal and small-scale gold mining. I consider possible alternative policy and governance approaches that take into account the heterogeneity in gold production practices and the attendant socio-economic differentiation within the small-scale gold mining economy in Madre de Dios, Peru.

My analysis in Chapter Three underscored the dangers of a limited understanding of the diversity of gold production modalities within a particular mining locality like Madre de Dios. A homogenizing view of small-scale gold mining has real implications for the management and governance of small-scale gold mining on-the-ground. As argued by many other authors (Verbrugge and Geenan 2020; Verbrugge and Besmanos 2016; Hilson et al., 2017), one-size fits all approaches to formalization or technological interventions, negate socio-economic differentiation in the small-scale gold mining economy. These policies reinforce a homogenizing view of small-scale gold mining as only a limited subsection of individuals (i.e., the most highly capitalized gold miners) are able to navigate complex formalization procedures or can afford to invest in alternative, mercury-free processing technologies (Libassi 2020a; Verbrugge and Geenan 2020; Verbrugge and Besmanos 2016). Instead, a greater recognition of the diversity of production modalities and socioeconomic differentiation of miners must compel policymakers towards more flexible and targeted approaches to governance (Hilson et al., 2017).

The claims presented in these three chapters and the findings that support my assertions, push back against dominant narratives that depict the social and ecological impacts of mercury use in small-scale gold mining as a consequence of 'environmental criminals' engaged in profit-seeking activities at the expense of human and environmental health. My aim in countering these narratives is to put forward not only a more holistic analysis of the many layered and multi-scalar processes that surround the 'mercury problem' in Madre de Dios, but also to suggest more socially and environmentally just policy prescriptions that address the root causes of these problems.

For too long, informal, small-scale gold mining in Madre de Dios has been treated as a homogeneous 'industry' populated by greed-driven individuals, economically motivated by rising international gold prices (Swenson et al., 2011). After, nearly a year of field work in Madre de Dios, it is now clear to me that these narratives obscure the reality on-the-ground and belies the underlying causes of rapid expansion of informal mining in the region in the past 20 years. Each of my three claims in the preceding chapters has shown how dominant understandings not only of small-scale gold mining and miners but also of mercury use and mercury pollution from mining are abstractions from reality. Not only do these narratives belie the positive livelihood benefits provided by mining but they also reproduce violence against miners. In the future, I hope that with greater understanding of the tensions between the benefits and environmental costs of mining, that more balanced narratives will make their way into mainstream discourse.

Policy Recommendations

In Peru, economic productivity, especially GDP, is largely dependent on the extraction and exportation of natural resources, primarily minerals, hydrocarbons, and metals. But the growth of informal gold mining in Madre de Dios has brought about a paradox in the governance of resource extraction and resource development policy; state governance today in Madre de Dios, represents a historical disjuncture in national-level natural resource development policy. Actors within the Peruvian central state, particularly within the Ministry of Environment, are working to criminalize and effectively eliminate small-scale gold mining in Madre de Dios while continuing to permit large-scale mega-mining projects in the Andean regions of the country. Throughout this dissertation I have shown what the consequences of these coercive governance approaches are for people and the environment. I want to be exceedingly clear in the conclusion to this dissertation that I think that policies that rely on coercion and violence only reproduce violence in the region. A different path forward is possible, and I would argue necessary and actionable. The first step to reforming the governance of informal, small-scale gold mining in Peru should be revise the existing legislation surrounding formalization of small-scale and artisanal miners as written in the 2002 Law of Small-Scale Mining Formalization. This law codifies a definition of who is considered a small-scale or artisanal miner based on three criteria (see Chapter Three for more information). These criteria include limits on the maximum size of mining concessions allotted to miners, the volumetric processing capacity of their operations, and only in the case of artisanal miners (*pequeños mineros artesanales*), the types of extraction technologies that are permitted to be used. These categories are poorly defined and leave many openings for the use of environmentally damaging equipment like heavy machinery and for 'small miners' to acquire up to 1000 hectares of land under a mining concession. These 'small-scale' operations are not small in their environmental impact nor in their production capacity.

The law defining these categories need to be narrowed to exclude these more medium-scale semi-industrialized operators. Obviously, this would be an unpopular proposal and the Ministry of Energy and Mines is unlikely to take up this case. One potential way of building support for this proposal would be to add a third category of miner under this formalization law; they could be called medium scale miners and their gold production could be taxed at a progressive rate to account for their greater productivity. To address the environmental impacts of this medium-scale mining, the requirements for formalization of these types of miners should be more stringent and require the use of mercury-free alternative processing technologies (though cyanide processing should not be encouraged).

As these miners have greater access to capital and can in many cases hire consultants or advisors, with proper knowledge and technology transfer initiatives, these more stringent environmental regulations could actually be met by these actors. This is not to say that all miners will comply with these regulations; in this case, I do see an opportunity for monetary and progressive sanctions that fine miners for non-compliance. Though of course the effectiveness of these sanctions is only as strong as the capacity of government agents and agencies to enforce regulations. In Madre de Dios, this capacity is quite limited, and this is an area in which the central state could provide more funding and resources to decentralized offices of the Ministry of Energy and Mines, and the Ministry of the Environment to carry out monitoring and enforcement.

One last policy proposal that I will put forward is the reinstitution of the state-run Mining Bank (*Banco Minero,* see Chapter One for more information). During the decades that the Bank operated, miners in Madre de Dios felt a sense of state support for their lives and livelihoods. This understanding, I believe, helped to engender miner's respect for the regulatory frameworks and laws that governed mining. Today, that trust is understandably eroded because of the recent focus on criminalization of mining and miners in particular zones of mining exclusion. The creation of a multi-agency run mining bank could help to restore that trust. Moreover, the Bank could be jointly run by the Ministries of Energy and Mines, the Ministry of Environment and the Ministry of Health. By forcing these different state actors to cooperate and reach consensus around their political objectives, the Bank could act as a centralized agency that produces more equitable policies around the governance of small-scale mining and provides technical support and incentives to encourage more sustainable mining practices. A new and improved, centralized Mining Bank could be a palatable solution to both miners and state agents in the push towards a more equitable and just approach to reforming informal, small-scale gold mining not only in Peru but throughout Amazonia.

CLOSING

My last trip to a gold mine was with a friend, informant, and mine boss named Vero (see Chapters One and Three for more of Vero's story). I accompanied Vero on a visit to a newly opened mining pit where she had recently relocated her dredge set - it had been buried beneath the forest for more than five months during the military interventions started under Operation Mercury 2019. It was August, late in the dry season, and the sun was blistering in the mid-day heat – I was again inappropriately dressed but not for lack of understanding. Vero had called me the night before and told me not to dress 'like a *gringa.'* She said we would need to disguise my identity as an outsider to ensure that no one mistook me for a foreign journalist or government-affiliate. The best way to 'hide' my identity, according to Vero, was to dress like a local. Clad in my only pair of blue jeans and a blouse, I was dripping sweat in the intense heat of the afternoon sun as I stood before an active mine watching Vero's crew work.

The journey to this mine was an odyssey. After hopping on a *colectivo* in Puerto Maldonado, we rode for three hours to kilometer 110 of the Inter-Oceanic Highway. We got out of the *colectivo* at the juncture where the road to Mazuko and the road to Jacinto meet. There stood a blue tarp tent, beneath which moto-taxi drivers waited for passengers. The '*tigres*' are a group of moto-taxi drivers with tiger striped helmets who can safely enter the informal mining camps on this northern side of the highway. They are the only drivers who can safely transport passengers to these camps where outsiders are unwelcome and actively kept out. As Vero negotiated our fare to her work site, I looked around at the bustling town of *La Pampa,* where the evening's mine shifts had just ended and miners were returning to sleep, drink, eat, and sell their gold in town. As I rode on the back of a moto-taxi that took us to Vero's work site, the forested landscape quickly gave way to a familiar scene – the desert-like appearance of a mined landscape; sandy plains dotted with abandoned and active mining pits. I counted the number of dredge sets as we rode past; at least 20 and seemingly many more out of my view. At one point we had to cross over a mining pit – a wooden plank had been hastily strewn across to form a sort of make-shift bridge, just wide enough for a motorcycle tire. I closed my eyes.

After about fifteen minutes, we arrived at a boundary – an imaginary line separating the desert landscape from a stand of seemingly undisturbed forest. I couldn't see a path for the motorcycle to pass, but the driver knew better. Winding through the narrowest of trails, five minutes later, we arrived at a non-descript patch of trees where the path ended. The driver told me this was Pablo's camp. Vero and her driver still had not arrived. I got off the motorcycle, paid the driver, and he sped off. What felt like an eternity passed before Vero finally arrived. She laughed easily at my nerves and told me to put on the rain boots I had packed in my backpack.
We began to walk through the trees, across sandy soils until the standing vegetation gave way to muddy sections of trail. We scrambled over log bridges formed from the slash and wearily waded through boot deep water in submerged portions of the trail. In the distance, I heard a chainsaw and as we continued walking, the sounds became louder. Finally, we arrived at a large, downed tree that blocked the path before us. As I crawled over the tree, I caught my first glimpse of Vero's worksite: the sounds, smells, and scenery around this mine remain imprinted in my memory like a moving picture.

Before me was a mining pit – no more than 100 meters wide - with two dredge sets floating atop the water. The aroma of burning wood and the heat of flames overwhelmed me as we made our way around the edge of the pit. A few meters from us, a worker was clearing vegetation and burning the slash to make way for the expansion of the pit. The drone of the motors, the thrumming of the chainsaw, and the sound of men's voices filled the air. I felt like a trapeze artist carefully navigating the obstacle course formed by the downed trees; trying to avoid falling onto the jagged slash or in the mining pit itself. We made our way around the pit to the opposite end where Vero's crew was in the midst of a shift change. Vero greeted her boyfriend and crew boss, Rodrigo, and the three other men that rounded out the work force. She introduced me as her friend and as a student wanting to learn more about how mining actually 'worked.' We sat together chewing coca leaves as the men began to open up to me and tell me their stories. After about half an hour it was time to get back to work. I tried to stay out of the way while the men worked.

As the crew boss, Rodrigo was responsible for clarifying and concentrating the *arenilla* or gold-bearing sands collected from the last shift. I watched him and another worker beat out the carpets, which trapped the sand, in a small plastic lined pool until all the sand had been removed. Then, he collected the sand into a 50-gallon oil drum and added water from the pit. He removed a small plastic bottle from the pocket of his red basketball shorts. I watched as he poured quicksilver into the oil drum and threw the empty bottle aside. He then pulled up the waistband of his shorts, removed one of his rubber boots, and lifted his leg into the oil drum. As I watched him churn this slurry of metals with his leg, I heard a loud bang far off in the distance. It was a dynamite explosion from the military interventions across the highway; each blast was the sound of a detonated motor.

Uncomfortable from the exposure and worried for my friend Vero, I thought of the many ways that I now understood the scene in front of me. After spending almost one year in Madre de Dios, working to build relationships with miners, I held many new understandings about informal gold mining. Now, I thought of the ordinary life of miners like Vero and her boyfriend Rodrigo - similar in many ways to the stories I had heard from the dozens of miners that I had interviewed over the months. I thought of the forest, of the downed trees and streams choked by mine tailings and sediments. I thought of the military – the immense absurdity of an intervention named Operation Mercury which purported to eradicate illegal mining in *La Pampa* and thus 'solve' the mercury problem, while negating the reality that miners like Vero simply moved to new areas deeper in the forest to mine. I thought of the mercury itself, as I watched Rodrigo pour off the excess mercury-laced water in the oil drum into the pit, leaving only the amalgam of mercury and gold behind. As I stood there watching dragonflies zip through the air – I thought of the webs of ecological interactions that carry mercury across the boundaries of the pit and into the rest of the wildlife in the forest. I imagined the mercury travelling within and across bodies and environments once the pit was no longer a productive site and was left abandoned. And I thought of the species that would recolonize these areas and those which may never return.

Finally, I thought of my place within and across the social and ecological interactions that make up these ecologies of gold. I thought of how I had engaged with these interactions in different ways - as a researcher, as a student, as a person that values human and non-human life, as a friend, as a woman, as an outsider, as an American, as a Peruvian. I took a step back and realized that these mined landscapes were no longer spaces of mystery held up by narratives of environmental destruction. While I mourned the loss of non-human life before me, I could also finally hold hope for a better future. A future filled with possibilities for not only the environment but also for the lives and livelihoods of my friends Rodrigo and Vero and the thousands of others that share their experiences.

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