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Incorporating positive deviance into comprehensive remediation projects: A case study from artisanal and small-scale gold mining in the municipality of Andes, Colombia

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ABSTRACT

Environmental remediation of polluted sites in developing communities often faces difficulties due to the misalignment of project objectives with the needs and interests of local communities, establishment of unrealistic expectations for the outcome of the project, and failure to account for the available resources in the community itself. Remediation decisions favor technical data and technical solutions as the main means of determining remediation options, requiring significant investment and local capacity that are often not found in developing communities. Often these systems fail to account for the social aspects in environmental management and remediation. In contrast, new approaches in local knowledge-based solutions focus on pre-existing environmental management initiatives to establish objectives that are meaningful to the community itself. "Positive deviance" – or the idea that there are solutions already in communities that are successful at addressing challenges despite the barriers that a community faces – are often overlooked during project design and implementation. Identifying examples of positive deviance and working with community members who are well versed in local challenges, available resources, and local capacity presents opportunities for community members to establish project objectives and provides the foundation for future environmental management projects in the area. We present a case study of artisanal and small-scale gold mining (ASGM) in the Andes municipality, Antioquia, Colombia and local initiatives to overcome community-identified environmental pollutants. Through a series of semi-structured interviews, surveys, and site visits, we identified community perception of environmental pollutants, management techniques for mining waste, and grassroots initiatives that were locally developed to address them. Through key communication and interaction between innovators with identified positive deviance projects, technical experts, and other miners facing similar challenges, innovative projects that account for the social, political, and economic realities of a developing community can become widespread, leading to improved environmental and social conditions.

1. Introduction

Attributed with releasing 1220 metric tons of mercury in 2015 alone, artisanal and small-scale gold mining (ASGM) has gained international attention as the largest anthropogenic source of mercury pollution in the world (UN Environment, 2019). ASGM is also responsible for the release of lead, arsenic, cadmium, copper, and a wide array of additional inorganic contaminants (Gottesfeld et al., 2019; Rajaee et al., 2015; Tirima et al., 2016) into water, soil, sediment, and air, making the practice a significant source of environmental contamination. The use of toxic chemicals, unsafe mining practices, and hazardous ore-processing methods also pose major health risks to both miners and surrounding communities. Despite the massive environmental footprint of ASGM and the local and global health risks posed by such activities, ASGM is prevalent in many developing communities worldwide as a predominant livelihood in rural regions. Without intervention, ASGM poses an urgent

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environmental and health risk to the global community (Esdaile and Chalker, 2018).

Despite the health and environmental concerns associated with mercury use in ASGM and the increased international awareness, environmental risks and therefore pollution cleanup are deprioritized by ASGM communities compared to security, drinking water quality, and formalization of the mining sector. Community members often prioritized these needs as they have a more visible effect or are believed to pose a more urgent risk to the community (Smith, 2019). Alternatively, some researchers cite unawareness of or indifference towards the environmental impact that ASGM activities have on the environment (Metcalf and Veiga, 2012; Ottenbros et al., 2019; Sana et al., 2017; Veiga and Marshall, 2017) as reasons for the deprioritization of the environmental and health impacts of ASGM. Examples of communities prioritizing and addressing environmental concerns associated with ASGM are limited to a couple of examples available in literature (Amedjoe and Gawu, 2013; Masuku, 2019). The absence of attention to community-led remediation projects in ASGM literature is a gap that needs to be addressed.

Instead, environmental management and remediation of ASGM is often motivated by formalization requirements (Veiga and Marshall, 2019) or by intervention from external agencies such as universities, intergovernmental organizations, non-governmental organizations (NGOs), and government entities. However, remediation of ASGM sites is challenging, as strategies for the remediation process need to be cost effective, socially acceptable, and effective. Environmental management and remediation projects in developing countries often perform poorly due to misunderstanding the social, political, technical, and economic contexts in which they are operating, which ultimately stems from poorly developed stakeholder engagement and community participation early on in project development (Fraser et al., 2006; O'Brien et al., 2020). Additionally, numerous environmental assessments exist that analyze the impact of ASGM on the surrounding environment, but these assessments rarely lead to remedial project implementation (e.g., Basu et al., 2015; Clifford, 2017; Rajaee et al., 2015; Wilson et al., 2015).

Although frequently not identified in literature, there are often existing projects led by community members that are able to address, in part, some aspect of an environmental and health concern despite environmental, social, and economic constraints (Amadei, 2014; Herington and van de Fliert, 2017; Mercy Corps, 2012). The process by which these existing successful projects are identified and shared with the rest of the community is known as the "positive deviance" approach ("Positive Deviance Collaborative," 2017). Some authors suggest the positive deviance approach for complex problems that involve social and behavioral change (Herington and van de Fliert, 2017; Pascale et al., 2010). The approach focuses on replicating the successes, rather than focusing on limitations and deficits (Doskey et al., 2013). Because of its ability to overcome local challenges and conditions, it has been widely applied to public health and medical practice (Mackintosh et al., 2002; Marra et al., 2013; Marsh et al., 2002; Pascale et al., 2010). However, to the authors' knowledge, the concept of positive deviance has not been previously applied to environmental remediation.

While some organizations acknowledge the possibility of positive deviance in a community, the general tendency is for organizations to focus on deficits in the community that prevent community members from achieving their goals (Mathie and Cunningham, 2005; Nel, 2018). By ignoring the existence of positive deviance, remediation initiatives are excluding projects that have already accounted for the environmental, social, and economic considerations that are often unknown to the external agency. The purpose of this study is to establish a benchmark understanding of the concept of positive deviance to existing environmental initiatives within an ASGM community. We applied a novel positive deviance approach utilizing analytical frameworks applied to positive deviance projects in the medical community and tailoring it to fit environmental management and remediation projects. We tested this approach in an ASGM community located in the municipality of Andes, Antioquia, Colombia. Through a series of semi-structured interviews, surveys, and site visits, we identify stakeholder perceptions of local environmental risks and grassroots initiatives that have been developed to achieve environmental objectives. We then further assessed how to potentially amplify the positive deviance projects throughout the community. This study demonstrates the importance of identifying positive deviance in complex environmental remediation projects and proposes ways forward to continue collaboration with project innovators and amplify the identified positive deviance projects.

2. Theory

The necessity for integrating social, economic, political, and environmental considerations into ASGM project design has long been understood by academics and NGOs (e.g., Hentschel et al., 2002; ILO, 1999). Numerous studies take commonly used socio-economic, environmental, political, and geographical concepts to better understand the ASGM sector and tailor their responses to the individual challenges the community is facing. Examples of such concepts include the Global Production Network framework, used by McQuilken and Hilson (2018), and mobility and trans-local relations, used by Mkodzongi and Spiegel (2020). More recently, researchers have applied frameworks utilizing the Sustainable Development Goals to understand the barriers and opportunities that ASGM poses for achieving established targets (e.g., Laing and Moonsammy, 2021; Hirons, 2020; Niesenbaum, 2020). This study seeks to do something similar by applying a commonly used social concept to better understand and assist members of ASGM communities with environmental remediation and management projects.

Initially used as a theory to explain social behaviors that deviated from established norms, positive deviance has been used to describe individuals who succeed despite barriers or constraints and amplify these successes throughout the community (Herington and van de Fliert, 2017). The theory of positive deviance is dependent on three key assumptions: (1) solutions to identified problems already exist, (2) some community members have already identified and implemented these solutions, and (3) these community members are succeeding in the implementation of these solutions despite facing the same barriers as the rest of the community (Pascale et al., 2010). Identifying these positive deviance examples often requires an understanding of the behaviors and norms within a community and a set of common themes or hypotheses as to how and why these positive deviance examples came into being (Bradley et al., 2009). Identifying these common themes requires fully understanding the contextual setting in which a positive deviance project was developed and the tools and resources used for developing and implementing the project. Klaiman et al. (2016) suggests using the "Context + Mechanism = Outcome" framework, in which the outcome is the identified positive deviance project, to identify common themes across positive deviance projects. Only by understanding the context and mechanisms of in positive deviances can a project be fully understood and widely implemented.

The variety of fields using the positive deviance approach illustrates its potential to be applied to any project that is dependent upon behavior change and community engagement. In developed countries, positive deviance has been applied to improving performance of hospitals and medical clinics (Bradley et al., 2009; Klaiman et al., 2016; Pascale et al., 2010). Positive deviance has also been applied successfully to medical studies in developing communities, such as child malnourishment in Vietnam (Mackintosh et al., 2002; Pascale et al., 2010), maternal and newborn healthcare in Pakistan (Marsh et al., 2002), and hand hygiene at hospitals in Brazil (Marra et al., 2013). Several studies have also theorized that this framework can be applied across other fields of study, such as business (Appelbaum et al., 2007; Delias, 2017; Pascale et al., 2010), agriculture (Birhanu et al., 2017), economics (Ochieng, 2007), and systems engineering (Doskey et al., 2013).

The concept of social capital is frequently used when describing complex social behavior and behavior change. Social capital describes the connections and networks between individuals in a community (Leonard, 2004). Social capital not only describes the existence of connections and networks, but it also highlights cultural norms associated with these links, such as reciprocity, trustworthiness, and participation in voluntary activities (Lee, 2020; Leonard, 2004). The concept of social capital has been applied across many topics, ranging from agriculture (Cofré-Bravo et al., 2019; de Krom, 2017d; Gao et al., 2019), to climate change (Hao et al., 2020; de Jalón et al., 2018d) and natural disaster preparedness (Lee, 2020).

Social capital is divided into two categories: bonding social capital and bridging social capital (Leonard, 2004). Bonding social capital is characterized by its strong ties, high levels of trust, and sociodemographic similarity between individuals within the network (Cofré-Bravo et al., 2019). Bonding social capital is an exclusive network of individuals who are from the same sociodemographic background. Benefits from bonding social capital only exists to individuals who are already members of the network (Leonard, 2004). In contrast, bridging social capital is more heterogeneous and open, allowing larger networks to be formed between individuals with different sociodemographic backgrounds. Bridging social capital is more formalized than bonding social capital and is characterized as having lower levels of trust, but participation within this network typically offers opportunities and ideas that would not typically be available to all members of a community (Cofré-Bravo et al., 2019). A balance between bonding and bridging social capital is recommended, as each type of social capital has different benefits and serves different purposes (Cofré-Bravo et al., 2019).

Social capital has rarely been identified as a mechanism for the development of positive deviance. Doucet et al. (2020) found that social capital was crucial for supporting families who refused to engage in the cultural norm of female genital mutilation in Guinea. Individuals who had found networks of support were often more outspoken and less concerned with the stigma associated by noncompliance with female genital mutilation. In contrast, individuals who did not have sufficient social capital were more reserved, hiding their noncompliance with the cultural norm. Often, these individuals had to supplement social capital with economic capital to allow them to continue with their positive deviance. A different study examined the link between positive deviance and social capital in livestock feeding practices in Ethiopia. Birhanu et al. (2017) identified that social capital had positive and statistically significant effect on the adoption of livestock feed practices, while individuals who were more isolated due to distance had lower adoption rates. To the authors knowledge, no other studies have been conducted identifying social capital as a mechanism that contributes to the development and amplification of positive deviance.

3. Site background and methods

The mining community and surrounding coffee farmers residing in the Andes municipality in Antioquia, Colombia were studied to evaluate the applicability of the concept of positive deviance to ASGM environmental remediation. This section begins with a brief overview of the site characteristics. It then turns to our methodology. Based on key site considerations and identified community norms, we developed techniques to establish the presence of positive deviance within the community. The methodologies deployed in the field consisted of semi-structured interviews, structured surveys, and site visits.

3.1. Site background

Andes is a municipality located in the southwest region of the department of Antioquia, Colombia with a population of approximately 42,000 ("Información del Municipio," 2018) Although it is currently well-known for its production of coffee and agricultural products (e.g., plantains and sugar cane), Andes has a long history of mining. Since its establishment in 1852, Andes has been the site of mining and mineral exploration, although the 20th century saw a decline in gold production in the region and a rise in agricultural products. Today, there has been a resurgence in ASGM occurring with migrants from other mining regions of Colombia coming to the region (Zapata Restrepo and Mejia Aramburo, 2019).

The quality of the ore and the mining processes used in Andes have all contributed to the release and transport of contaminants from ASGM. The mined and processed ore in Andes contains arsenic, sulfur, and iron, which all contribute to the formation of acid-mine drainage. These contaminants are found in tailings piles that are exposed to wind, rainfall, and humidity, allowing for the leaching and transport of metals to the environment. Additionally, mercury amalgamation was a historical practice in mining in Andes, and this practice produced tailings with mercury concentrations as high as 816 μg/kg of mercury (Servicio Geológico Colombiano, 2017). Ore processing in Andes also contributes to air pollution during the refining stage, in which impurities are vaporized by heating the gold. If mercury amalgamation were used for the processing of the ore, the final refining stage can produce hazardous mercury vapor that can be transported throughout the community.

Although the ASGM sector is associated with deleterious environmental impacts, there are external and internal motivators that drive miners and ore processers in Andes towards environmentally safer methods and technologies. The Minamata Convention, which was ratified by Colombia in 2013, has secured the commitment of over 100 countries to reduce and eliminate their release of mercury into the environment. Because of the Minamata Convention, Colombia began to eliminate the use of mercury in industrial and mining processes nationwide through criminalizing the sale of mercury and establishing mineral processing zones for artisanal mining (Veiga and Marshall, 2019). Andes in particular is well known for its "*cero mercurio*," or zero mercury, initiative for gold processing (Ortiz, 2018; Ramirez C., 2019), which encourages miners to switch from mercury amalgamation to a combination of gravimetric and cyanidation methods to extract ore in a more environmentally friendly manner. Miners and ore processors are pressured to obtain the legal protection of being formalized or risk losing their ability to mine a site should the mining rights be obtained by another mining company. These miners are working towards formalization[1], the process of becoming integrated into the formal economy that typically involves obtaining mining titles and permits, to achieve legal protection. In Colombia, formalization requires that miners comply with natural environmental regulations and obtain the proper environmental permits needed to operate, though few miners have accomplished this (Veiga and Marshall, 2019).

Miners and ore-processing center managers in Andes are also internally motivated to use environmentally safe mining and ore-processing methods. Miners and ore-processing center managers often move between mining and agricultural sectors, a phenomenon observed in several other countries with a presence of ASGM (Ofosu et al., 2020). Some miners and ore-processing center managers own a small plot of land for agriculture and divide their time evenly between farming and mining. Others rotate between sectors given the potential income they will receive, giving more focus on agriculture during peak harvest seasons and more focus on mining during the off season. Given that many miners and ore-processing center managers are closely connected to agriculture, they are motivated to preserve the environment. Miners who are not involved agriculture still maintain a respect for neighboring coffee farmers, whose prominent presence in the community directly relates to the political and economic wellbeing of the community.

[1] The topic of formalization is widely discussed in literature, and readers are referred to Ankenbrand et al. (2021); Hilson et al. (2017); Hilson and Maconachie (2020), and Maconachie and Conteh (2021) for more information about the complexities of formalization on social, political, and economic ramifications that formalization can have in an ASGM community.

3.2. Methods

During our field investigation from June-August 2019, we conducted site visits to seven out of the eleven ore-processing centers to establish a baseline of ore-processing techniques, which validated some information obtained through secondary literature. However, we also observed some locations practicing ore-processing and waste-disposal methods that were outside of the baseline activities we had previously established from either site visits or literature review. We later returned to the identified sites to for a follow-up unstructured interview regarding the motivation for using different, more environmentally conscious methods, of ore-processing and waste disposal. These perspectives of the individuals working at sites with modified operating methods were compared with those expressed by individuals using baseline methods of ore processing to identify what motivated and facilitated the adoption of environmentally conscious methods.

To better understand the context and mechanisms with which these positive deviance examples were developed, we used semi-structured interviews and structured surveys. Participants of semi-structured interviews were identified using snowball sampling from previously identified key informants (Bernard, 2006). Our semi-structured interview participants were selected based on their participation in the predominant livelihoods in Andes (i.e., coffee farming and artisanal mining). During semi-structured interviews, we asked participants about their livelihoods and their relationship with the surrounding livelihoods in the region. Participants were asked about their relationship to the mining sector and to elaborate on their experiences with interacting with other sectors. Finally, we asked the participants to reflect upon changes that they had observed in the environment during their time living in Andes and to suggest potential sources of this environmental change. In total, 18 people participated in the semi-structured interviews, representing miners, ore-processing center owners, coffee farmers, trout farmers, and government officials in the region.

After completing semi-structured interviews, we developed and deployed structured surveys to understand how widely held the environmental concerns were within members of the identified stakeholder groups from the interviews. We identified structured survey participants using street-intercept sampling (Bernard, 2006), and respondents were selected purposively to evaluate whether the ideas stated during semi-structured interviews among the previously identified stakeholders were shared more broadly. Environmental risks discussed during the semi-structured interviews were compiled into a list and used for further analysis in the structured survey. We asked participants to identify whether an identified activity or product was harmful to the environment in the community at the time of taking the survey on a scale from 1 (not dangerous) to 5 (extremely dangerous). The word "*peligro*" ("danger") was not defined for the participants in an effort to have them respond based on their own understanding of what constituted an environmental harm[2] . One-hundred face-to-face surveys were given over the course of two months to adults in the community. Of the 100 surveys, 44 participants' primary sector of work was mining, 35 participants' primary sector of work was agriculture, 18 participants' primary sector of work was categorized as "other", and three participants' primary sector of work was both mining and agriculture. Data obtained from the semi-structured interviews and structured surveys were compiled and analyzed using non-parametric statistical analysis. Because the data obtained from the survey were Likert-type, ordinal-scale data, we analyzed the median and mode responses (Boone and Boone, 2012).

[2] All questions asked during interviews and surveys were pre-approved under Colorado IRB protocol #18-0233.

4. Results and discussion

Our results and discussion are organized following Kaiman's et al. (2016) framework of "Context + Mechanism = Outcome." First, we present the identified positive deviance projects found within the municipality of Andes, or the outcomes. Next, we discuss the context in which these positive deviances were created, highlighting the environmental perceptions and dynamics between stakeholder groups that shape the social and environmental setting in which these projects were developed. We then discuss the mechanisms used in these positive deviance projects, connecting the development and amplification of the projects to the innovators' social capital. Finally, we analyze the limitations with the identified positive deviance projects, tying the limitations back to the concept of context and mechanisms, and propose methods to address these limitations.

4.1. Observed positive deviances

During our site visits, we encountered deviations from the baseline mining operations evident in available literature and other ore-processing centers. These deviances include sedimentation basins for water reuse, fume hoods for refining ore, and mine tailing bricks for recycling mine tailings. Only three positive deviance projects were discovered and analyzed, which likely can be attributed to the small population of miners within the Andes municipality. The following sections discuss the three community-initiated environmental projects observed in the municipality of Andes.

4.1.1. Sedimentation basin systems for suspended sediment

Suspended sediment from mining and ore-processing methods are known to be a significant source of contamination, and discharges of materials from formalized mines are regulated (CORANTIOQUIA, 2016). The sedimentation basin systems (Fig. 1) at the ore-processing centers are part of a grassroots movement of miners and ore-processing center managers to become formalized. The systems consisted of at least three basins of water, placed after the gravimetric ore-processing systems, designed to reduce water velocity and promote settling of suspended sediment. After traveling through a series of basins, the water would end up in a clarifying basin to further promote the settling of finer material before the water was recirculated through the ore-processing center. These systems were designed to minimize water consumption of ore-processing centers, decrease sediment and contaminant loading into surface water systems, and collect finer gold particles that were not separated during the gravimetric processing.

Sedimentation basin systems were installed in seven out of the eleven ore-processing centers in Andes at the time of the site visit, and the performance of these systems varied considerably due to differences in design and flow rate. Ore-processing centers with the largest number of sedimentation basins tended to have the best results in removing suspended sediment compared with centers that have fewer basins, as the total surface area of the sedimentation basins increased with increasing number of basins. Likewise, basins with the lowest velocity and surface overflow rates had more success in depositing smaller sediments while basins with higher and more variable velocity and surface overflow rates often caused small particles to re-suspend in the water. These behaviors are well known in the water and wastewater treatment fields (Reynolds and Richards, 1996). Maintenance of the sedimentation basin system also caused variability in the performance of the system. Ore-processing centers that removed settled sediments more frequently maintained higher residence times and increased the settling in the system, while those that failed to maintain the system promoted resuspension of particles, decreasing the efficiency of the system.

4.1.2. Fume hood for refining ore

To counteract the detrimental environmental and health effects associated with burning off impurities from the gold before final sale,

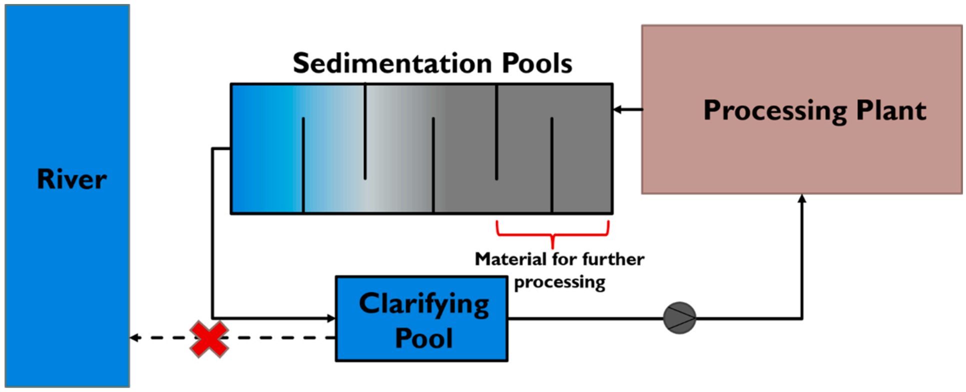

Fig. 1. Conceptual flow chart of water recirculation system being implemented in the municipality of Andes. Not to scale.

two ore-processing center managers, who have years of experience in mining in different regions of Antioquia, have constructed fume hoods. The functioning fume hood (Fig. 2) draws mercury and other vapors through the hood, which is made out of equipment used for processing coffee cherries. A fan then directs this vapor through a series of water barrels meant to serve as filtration systems. As the vapor cools, much of the hazardous materials, such as mercury, transition from a vapor to a solid or liquid state, which is retained by the water barrels. The remaining vapors are then released at an outlet that was positioned away from the ore-processing center and surrounding community.

Only two out of eleven ore-processing centers in Andes have installed fume hoods, but only one of the two fume hoods are in operation. In contrast, other ore-processing center managers tend to refine their ore in the open air or in metal barrels, allowing for vapors to be directly released into the environment. While the fume hood technology appears to be a marked improvement in managing hazardous vapors, its overall functionality in treating the gases prior to their release into the environment is unknown without further testing. The design of the system is similar to the one proposed by the United Nations Environment Program (UNEP), which can remove approximately 80 % of mercury vapor produced during burning if constructed properly (Telmer and Stapper, 2012), but there is no information regarding how this system handle other contaminants of concern.

Fig. 2. Example of a fume hood system attached to a series of water barrels meant to capture mercury vapor before releasing gases into the atmosphere. Materials are burned in clay bowls under the mouth of the fume hood. A fan draws the vapors through the mouth and down through a series of water barrels. The remaining vapors are released (not shown).

4.1.3. Recycling mine tailings for construction materials

To address the environmental risks posed by mine tailings, one ore-processing center owner has experimented with recycling mine tailings as the primary constituent in bricks. This initiative serves two primary purposes: to address the environmental risk from mercury-contaminated tailings and to earn a profit off the waste materials. If done properly, the owner believes that mine tailing recycling could provide the economic incentive for remediating tailings piles found throughout Andes, creating more interest among miners and ore processors to address the legacy of pollution in the region. Although the construction materials have yet to be incorporated into any local construction project, the ore-processing center owner stated that he was hopeful that this practice will both address the environmental threat posed by old mine tailings and provide another source of income to the processing center.

The mine tailing recycling initiative is widely known among other ore-processing center managers and miners in Andes, but only the ore-processing center manager has been actively working towards developing a protocol to decontaminate and recycle mine tailings. To date, the ore processor has used a variety of methods to remove mercury from old tailings, such as thermal treatment of tailings and gravimetric techniques. The ore processor has also developed a network of local and international universities to assist with the protocol to test the lability and mobility of mercury in the bricks. Unfortunately, the decontamination processes that were previously tried are untested, meaning that the safe use of mine tailing construction material is unverified. Other miners and ore-processing center managers in Andes state that they are waiting for an established process that is approved by the local environmental regulatory agency before they are willing to adopt similar practices.

4.2. Context

Many factors may have contributed to the development of these three positive deviance projects in Andes. The political context of Andes, which allowed miners to work towards becoming formalized at the time of the field investigation, has contributed to a culture in which miners and local universities can experiment with alternative ore-processing methods without the threat of closure. The Andes municipality is relatively free of the violence that affects other mining regions in the country, as observed by four different miners across three separate interviews. Additionally, both miners and coffee farmers described the local environmental regulatory agency as being “vigilant” and “attentive,” describing how water quality, mining activities, and coffee farming are regulated and monitored. The perceived vigilance of the environmental regulatory agency may have contributed to the generation of the sedimentation basins, as this project directly addresses one of the primary environmental concerns discussed by the environmental regulatory agency.

The perceived dominance of agricultural interests also plays a critical role in the development of positive deviance projects that focus on the environment. As one miner stated during an interview, "The people [within Andes] prefer coffee growing [to mining]." An ore-processing manager expressed a similar sentiment and described the importance of preserving the environment so that the neighboring coffee farms could maintain their livelihood. The dominant presence of coffee farming, including the environmental perceptions held by members of the agricultural sector, influences relationship between Andes citizens and the environment. For example, one coffee farmer in the municipality cited the importance of preserving the environment for the future and his children as a driving force for developing or adopting environmentally friendly coffee processing methods and waste repurposing. Some miners also described their commitment to the environment, as they perceive their work as being dependent upon nature as well. To explain how both mining and coffee farming were dependent on nature, one miner explained that farmers rely on surface soil while miners rely on subsurface soil.

Environmental concerns figure centrally in how people in Andes view mining. While several miners described their relationship with coffee farmers as free of conflict, citing the environmental regulatory agency's influence and the recent "*cero mercurio*" initiative, some coffee farmers expressed that they would prefer mining to not occur within Andes due to its environmental impact. Of the surveyed members of the agricultural sector, 44 % believed that Andes had achieved "*cero mercurio*." In contrast, 61 % of miners believed that Andes had achieved "*cero mercurio*." One coffee farmer described his awareness of mercury contamination and how it affects fish population. This farmer believed that mercury was the cause of a significant decrease in the local fish population. Another farmer described his concern with mercury levels in fish in the river, even explaining how he has witnessed sick and dead fish in rivers impacted by mining activities. A third farmer described how he got sick from eating fish from the river, believing that the mercury within the fish was the cause of his illness.

Further analysis on the perceived environmental impacts of mining in Andes revealed that miners and coffee farmers perceive the environmental risk of certain products and activities differently. Fig. 3 illustrates this difference by showing the results of the structured survey given to miners, coffee farmers, and others (e.g., government officials, business owners, and transportation employees). Individuals whose primary source of income came from the mining sector perceived old tailings and ore refining to be less harmful to the environment than individuals working primarily in other sectors. This difference in perception may have contributed to the creation of two of the identified positive deviance projects: mine tailing recycling and the fume hood.

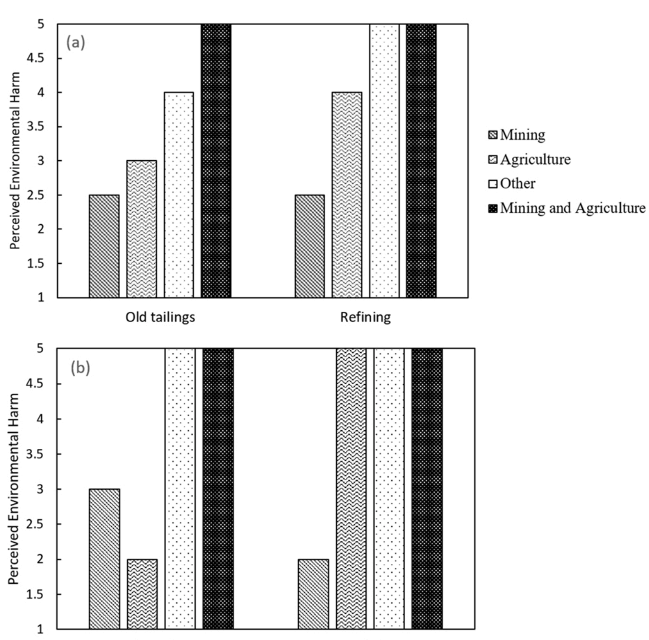

Fig. 3. (a) Median and (b) Mode perceived environmental harm among different primary sectors of work for mining activities and products with statistically significant ($p < 0.1$) difference in responses between sectors. Scale ranges from 1 (no environmental harm) to 5 (extremely harmful to the environment).

Environmental risk perception of old mine tailings illustrates the difference in perception between stakeholder groups. In interviews, miners and ore-processing center managers indicated that they were aware of the presence of mercury and other heavy metals in tailings. However, through a series of follow-on questions and site observations, it was evident that few were aware of proper tailings management options. For example, several ore-processing centers left tailings exposed to the environment, potentially allowing hazardous materials to leach from the tailings piles into the surrounding soil. Other ore-processing centers constructed rudimentary shelters over tailings piles to reduce exposure to rainfall, but these shelters were often poorly maintained. The extent of the tailings in the region is widespread, with one ore-processing center manager stating, "This earth [where the ore-processing center sits] was made with old mud from mining," implying that the existence of tailings is so pervasive that the soil on which ore-processing centers were constructed consists of old tailings. Because these old tailings piles accumulate over decades, miners may not see them as an imminent threat to environmental safety and human health. Coffee farmers and other sectors see the environmental risk differently, with some perceiving the tailings to pose a moderate environmental risk and others perceiving the risk to be significant.

Gold refining, where the gold is heated to a high temperature to volatilize any remaining impurities, was also an activity perceived differently across the examined stakeholder groups. Members of the agriculture sector saw the refining process as being environmentally harmful, with a median and mode perceived environmental harm of 4 and 5 out of 5, respectively. The reason that refining ore was perceived to be significantly harmful to the environment could be linked to the knowledge of health risks posed by heating mercury and gold amalgams. As mercury amalgamation also requires refining the metals by vaporizing impurities, participants may have equated the two practices as being interlinked, especially if the participants do not work primarily in the mining sector.

The combination of an attentive, stable local government and environmental regulatory agency and the pressure to make mining environmentally responsible to protect the interests of neighboring coffee farmers form the central features of the context that gave rise to the three positive deviance projects we identified. The "vigilant" environmental regulatory agency likely pushed miners to implement sedimentation basins to meet water quality requirements. In contrast, environmental concerns from individuals in the agricultural sector may have prompted miners and ore-processing center managers to amend ore refining and tailings management practices to maintain the conflict-free, albeit tense, relationship between the two sectors. The positive deviance projects found within Andes emerge from this context by addressing the concerns of stakeholders and regulatory agencies that were held during the time of the study.

4.3. Mechanisms

Our research shows that the success of the identified positive deviance projects in Andes was dependent upon the project innovator's use of social capital. In all three examples of positive deviance, different levels of bonding and bridging social capital were utilized to either enhance the performance of the positive deviance project or to share the positive deviance project among other miners within the community. For example, bonding and bridging social capital significantly affected the development and amplification of the sedimentation basins.

Collaborations with local universities facilitated miners' self-organization into the "*Mesa Minero Ambiental*" or the Environmental Mining Board, and these relationships allowed for the dialogue between miners and universities to continue throughout our study period (CIMEX, 2021). Through participation with "*Mesa Minero Ambiental*," miners had a local network with which to collaborate on strategies to meet formalization requirements. This process of self-organization is an example of bonding social capital. As the network grew in size and influence, technical experts were sought to help address the environmental requirements of formalization. By obtaining technical experts from outside of Andes to assist with environmental projects, "*Mesa Minero Ambiental*" enhanced their bridging social capital. This ultimately allowed for new project ideas to be introduced and different designs to be implemented.

Similarly, the mine tailing recycling project utilized both bonding and bridging social capital to improve its performance and increase awareness. The innovator of the mine tailing recycling initiative applied his bridging social capital by engaging five different universities to assist with the technical challenges of his project. His involvement in "*Mesa Minero Ambiental*" led to him serving as president of the local mining organization, thereby enhancing his bonding social capital. The status associated with his position expanded his network, developing bridging social capital to engage with universities both in Colombia and the United States. His bonding social capital also explains why his work on recycling mine tailings is so well known among the miners and ore-processing center managers in Andes even though they are not experimenting with tailings.

The fume hood emphasizes the dependence of positive deviance projects on bridging social capital. The creator of the fume hood in Andes explained that his inspiration for the fume hood design was based on a similar device he had seen at mine sites in other regions of Colombia. By having connections with another mining community and repurposing coffee farming equipment, the creator of the fume hood was able to draw on outside sources of knowledge and resources to build a fume hood using locally available materials. This demonstrates the importance of inter-community collaboration and is another example of how utilizing bridging social capital affects the development of positive deviance in Andes.

Three primary mechanisms were used for utilizing bonding and bridging social capital to both develop positive deviance projects and amplify them in Andes: miner-to-miner interaction, miner-to-technical expert communication, and community-to-community interaction. Miner-to-miner communication was used the most frequently when utilizing bonding social capital, either through participation in "*Mesa Minero Ambiental*" or through ongoing communication via social media platforms. Miner-to-technical expert communication occurred less frequently than miner-to-miner communication, but acted as the bridging social capital between miners and outside universities and engineers. A combination of site visits, communication via social media, and collaboration with the miners' organizations facilitated miner-to-technical expert communication. Finally, although observed less frequently, community-to-community interaction served as bridging social capital. In particular, the fume hood was the result of an ore-processing center manager drawing on resources and knowledge from outside mining communities. However, other miners involved in the identified positive deviance projects discussed how they too had connections with outside mining communities. This experience in other mining communities not only provides the context in which the miners' environmental perceptions were shaped, but also provides a network that reaches beyond Andes in which miners would be able to draw from.

4.4. *Areas of improvement*

Grassroot initiatives or positive deviance projects in Andes are often well intentioned but fall short in different areas. For example, the difference in the performance of the sedimentation basins at ore-processing centers indicates that best practices involving sedimentation basins have not been developed or widely communicated. Some ore-processing facilities have already developed strategies to overcome the largest challenges associated with the system, but this information is not widely distributed across the entire municipality. The technical constraints due to limited access to expertise, lack of testing methods, and the non-existent communication between ore-processing centers illustrate how some limitations in the bonding and bridging social capital are inhibiting further improvement of sedimentation basins. By building on the pre-existing bonding and bridging social capital, we suggest that these constraints could be overcome and improve the performance of the sedimentation basins.

The difference in fume hood technologies among different ore-processing centers can be attributed to limitations in bonding social capital. The creator of the functioning fume hood, though affiliated with "*Mesa Minero Ambiental*" is not as active a member as are the other innovators and creators of the positive deviance projects. As such, few miners are aware of the fume hood systems. This illustrates how a lack of bonding social capital leads to the uneven distribution of technologies for protecting the environment and human health within a community. Failure to communicate how to build and operate such a system has resulted in limited uptake of the system and illustrates the need for a forum in which this information can be widely shared. It is likely that enhancing bonding social capital would improve awareness and community buy-in for this project.

The practice of repurposing mine tailings into construction materials, while well studied at laboratory scales (Kawatra, 2017), has not often been implemented at the field scale (Amedjoe and Gawu, 2013). Numerous technical and social limitations limit the uptake of this practice for addressing mine tailings, calling for increasing bridging social capital through collaboration between the ore-processing center owners and technical experts, and between the ore-processing center and the general, non-mining community. The technical advice from local experts would provide the environmental and health assurance that such bricks could safely be adopted into construction products, while collaboration with community members could help increase local support in the project. Collaboration with other ore-processing centers, or utilizing bonding social capital, would also prove to be beneficial, as many have also expressed an interest in addressing old mine tailings despite having no knowledge of how to properly do so.

5. Conclusion

This case study illustrates the application of the concept of positive deviance to community-led environmental management and remediation projects in ASGM communities. By identifying which environmental problems are of concern to miners and members of the agriculture sector and by establishing a baseline of mining practices, we identified ore-processing methods and systems that directly address community concerns. Connecting the concept of positive deviance with theories of bridging and bonding social capital, we suggested ways forward to expand the reach of such projects in a community. Isolating the context and mechanisms that facilitated the creation of the positive deviance projects provides guidance on logical next-steps for amplifying their adoption and use. Through enhancing bonding and bridging social capital, miners and technical experts could likely improve upon and implement environmental systems or methods, ultimately amplifying the effect of the initiative.

Members within the ASGM community have innovative ideas to make ASGM cleaner and safer. However, they need a socially and technologically appropriate forum to vet and communicate these ideas with others. Miner-to-miner collaboration (i.e., bonding social capital) is vital for sharing important information regarding the existence of initiatives while also providing local support to individuals interested in replicating a positive deviance initiative at their own mine or ore-processing site. Pre-existing networks of miners, such as "*Mesa Minero*

Ambiental" in Andes, may help to facilitate miner-to-miner communication regarding these initiatives, and such networks could be expanded to connect miners across multiple mining communities for collaboration (i.e., bridging social capital). By creating a network of local expertise, miners could draw on past projects in other regions as examples to address environmental concerns. In addition to miner-to-miner interactions, opportunities need to be created so that knowledge exchange can happen between technical and local experts, as many of the identified positive deviance and grassroot initiatives still have many technical limitations that prevent them from performing as desired. Regardless of the technique used to continue the dialogue between technical and local experts, local initiatives to address environmental concerns can be enhanced by ensuring that miners can access a network of technical and local experts.

CRediT authorship contribution statement

Michelle Schwartz: Conceptualization, Methodology, Investigation, Writing - original draft, Visualization. **Kathleen Smits:** Conceptualization, Writing - review & editing, Supervision, Funding acquisition. **Jessica Smith:** Conceptualization, Methodology, Writing - review & editing, Funding acquisition. **Thomas Phelan:** Writing - review & editing, Funding acquisition. **Oscar Jaime Restrepo Baena:** Resources, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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