Tropical surface gold mining: A review of ecological impacts and restoration strategies

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Abstract
Surface gold mining severely degrades landscapes, causing deforestation, soil erosion and displacement, and toxic contamination. The prevalence of both large-scale and artisanal, small-scale surface gold mining in the tropics has risen over recent decades. Restoration strategies developed for less-severe forms of degradation may not sufficiently address the unique ecological conditions of former gold mines. In this review, we summarize biophysical challenges to the restoration and reforestation of large- and small-scale gold mines in the tropics and synthesize the findings of studies that test restoration strategies at these sites. Certain practices, such as the backfilling of mined pits, topsoil conservation, and the preservation of local seed sources, emerge from the literature as crucial for the timely and effective restoration of gold mines. However, because the severity of ecological degradation varies greatly within and between individual mines, and given the relatively small number (n = 42) of published tropical field studies found in our literature review, we highlight a clear need for continued research and development of restoration strategies specific to ecological conditions of former gold mines in the tropics.

KEYWORDS
ASGM, gold, mine reclamation, reforestation, surface mining, tropical restoration

1 INTRODUCTION

Restoration of degraded landscapes in the tropics has the potential to conserve biodiversity, sequester carbon, and promote sustainable livelihoods (Chazdon et al., 2009; Lamb et al., 2005; Poorter et al., 2016). However, land-use history and extent of degradation significantly influence restoration’s pace and trajectory (Chazdon, 2008). The most severe forms of anthropogenic land degradation, such as those caused by surface mining, present significant restoration challenges for practitioners and affected communities (Ahirwal & Pandey, 2020). Surface mining causes 7% of deforestation in developing nations (Hosonuma et al., 2012), and leads to intense soil disturbance such as the displacement of topsoil, loss of edaphic biological activity, heavy-metal contamination, and nutrient-leaching (Ahirwal et al., 2016; Sheoran et al., 2010). Prevailing restoration methods are generally designed to recover landscapes after agriculture and logging and are often insufficient to address degradation due to surface mining (Ahirwal & Pandey, 2020; Woodbury et al., 2020).

Within the surface mining industry, the mining of gold through ecologically destructive techniques such as open-pit mining and dredging (Halder, 2013), represents a growing environmental threat in the tropics. Regions such as the Guiana Shield, south-central...
Amazonia, West Africa, and Western Australia all have significant deposits of gold (Hammond et al., 2007), and data from 2018 indicated that tropical nations produced about 43% of the global gold supply (Alexander et al., 2019). Consequently, surface gold mining is a substantial driver of deforestation in heavily-mined areas such as French Guiana, the Madre de Dios region of Peru, the Antioquia region of Colombia (Dezécache et al., 2017; Espejo et al., 2018), and western Ghana (Schueler et al., 2011). In recent decades, successive surges in the international price of gold have driven an unprecedented expansion of both formal and clandestine gold mining, particularly operations in Amazonia (Asner et al., 2013; Hammond et al., 2007) and equatorial Africa (Armah et al., 2013; Schueler et al., 2011). It is becoming increasingly economically feasible to extract gold from low-grade deposits, threatening protected tropical biodiversity hotspots and major waterways with physical degradation and chemical contamination, and presenting grave health risks to affected rural communities (Alvarez-Berríos & Aide, 2015; Betancur-Corredor et al., 2018; Gibb & O'Leary, 2014).

Despite the severity and pervasiveness of the degradation caused by surface gold mining, this represents the first review analyzing the ecological fate of former tropical gold mines and the restoration techniques available to rehabilitate or reclaim these converted landscapes. We summarize the biophysical effects of surface gold mining, noting the differences between large-scale and artisanal, small-scale gold mining (ASGM) operations. We examine the response of the natural plant community after mine closure or abandonment and then assess potential active restoration techniques. Although we focus on gold mining here, many of the impacts and restoration options covered by our review apply to surface mines of other minerals in the tropics (e.g., bauxite, copper, and iron).

**FIGURE 1** Left—A large gold mining pit in Guyana (image by Michelle Kalamandeen). Right—An aerial photo of a large-scale opencast gold mine in Namibia. In large-scale gold mining operations, vast areas of land are converted to construct access roads, mining pits, overburden heaps, and tailings storage facilities (image by Hanspeter Baumeler) [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 2** Left—an isolated ASGM site in the Amazon (image by Sue Palminteri/Mongabay). Right—an aerial photo depicting the considerable extent of ASGM operations in the Peruvian Amazon (image by Rhett A. Butler/Mongabay) [Colour figure can be viewed at wileyonlinelibrary.com]
2 | SCALES AND MODALITIES OF OPERATIONS

Throughout this review, we differentiate between the two spatial scales of surface gold mining operations prevalent in the tropics: large-scale surface mining, and ASGM (Figures 1 and 2). These two scales of operations employ very different actors and use different mining techniques (Hammond et al., 2007), meriting separate assessments of both ecological impacts and restoration potential.

2.1 | Large-scale gold mining

National and transnational corporations operate large surface gold mines and are part of the formal economy. These large mines produce about 85% of the world’s gold supply (Metcalf & Veiga, 2012). Although the largest producers are in temperate zones, gold mining is on the rise in the tropics: between 2018 and 2019, large mines in Indonesia, Mali, the Democratic Republic of Congo, Burkina Faso, and Chile had the greatest increases in gold production (Alexander et al., 2019).

A single large-scale surface gold mine typically employs hundreds of workers, including skilled staff using advanced technologies (Bury, 2004), and processes over 500,000 Mg of ore annually (Hammond et al., 2007) using open-cast techniques, in which gold ore deposits are extracted from deep and expansive open pits. The primary method of refining, utilized by formal industrial operations since the 1880s, is ‘cyanidation’, in which the mined ore is soaked in a dilute solution of sodium cyanide (NaCN) to leach out gold (Hilson & Monhemius, 2006). Remnants of processed and leached deposits, called ‘tailings’, are transported to tailings storage facilities for long-term storage (Lottermoser, 2010). Tailings solids are often piled to construct ‘tailings dams’ which embank ‘tailings ponds’—large lagoons of effluents and slurry waste from the mining process (Festin et al., 2019) (Figure 1).

In most modern large-scale gold mining operations, over 99% of the originally mined ore eventually becomes tailings (Lottermoser, 2010).

2.2 | Artisanal and small-scale gold mining

As of 2009, an estimated 70 countries across the globe had a documented presence of ASGM, 65 of which were nations in the tropics and subtropics (Telmer & Veiga, 2009). Globally, ASGM operations produce around 350 Mg of gold per year, or about 15% of the global gold supply (Metcalf & Veiga, 2012). Up to 15 million people across the globe directly practice ASGM (Metcalf & Veiga, 2012), while 80 to 100 million people rely on ASGM for some portion of their livelihoods (Armah et al., 2013). Many artisanal gold miners come from socially and economically marginalized communities (Armah et al., 2013).

ASGM operations involve small groups of individuals, often from rural and immigrant communities, who process small volumes of ore over small areas (Hammond et al., 2007)—in some cases, illegally (Fisher et al., 2018; Naughton, 1993). While ASGM traditionally evokes images of low-impact methods like panning, it now commonly involves the removal of the soil using machinery such as excavators to dig open pits in floodplain deposits or suction pumps to dredge streambed deposits. Operations increasingly feature pressurized hydraulic jets to dislodge large volumes of deposits and wash them into sluices (flow-regulated channels where heavy metals are gravity-separated) (Byzigo et al., 2015; Hammond et al., 2007).

If gravity separation methods cannot produce concentrates with over 20% gold—the level of purity required for the smelting process—then artisanal miners use a mercury amalgamation process. Mercury forms an alloy (amalgam) with gold, chemically separating it from other minerals (Hammond et al., 2007; Telmer & Veiga, 2009). ASGM operations generally use mercury amalgamation rather than cyanidation because it is more cost-efficient and accessible (Telmer & Veiga, 2009). Often, ASGM operations abandon open dumps of mercury-contaminated tailings, allowing effluent to discharge into the surrounding environment (Fashola et al., 2016).

3 | BIOPHYSICAL DEGRADATION FROM SURFACE GOLD MINING IN THE TROPICS

We categorize degradation caused by large-scale gold mining and ASGM into three main categories: deforestation, soil degradation, and toxic contamination (Table 1). We describe how these changes to the biotic and abiotic environment, and associated social conditions, pose unique challenges to restoration efforts at former tropical gold mine sites.

3.1 | Deforestation

The degree of forest loss depends on the type and scale of mining methods employed. Large-scale projects typically involve significant deforestation at the operation level, removing vegetation to construct vast pits, tailings storage facilities, access roads, and other infrastructure (Alvarez-Berrios & Aide, 2015). While global estimates of deforestation due to surface gold mining are not available, regional studies demonstrate the industry’s impact. In Colombia, for example, large gold mining operations cleared 31,554 ha of forest between 2001 and 2018—a greater area than was deforested for any other mined mineral (González-González et al., 2021). Particularly, in Antioquia, the Country’s main gold-mining region, legal mining caused 24% of local deforestation in 2018 (González-González et al., 2021).

ASGM’s contribution to deforestation is not well documented in most regions, and is likely underestimated due to the small size and/or illegality of individual projects. Moreover, ASGM often occurs in ecologically sensitive old-growth forests, riparian zones, and wetlands (Alvarez-Berrios & Aide, 2015; Román-Dañobeytia et al., 2015). In well-documented ASGM hotspots in the Guiana Shield and the Madre de Dios region of Peru, small-scale gold mining is a primary driver of land-use conversion, outpacing logging, agriculture, and ranching (Peterson & Heemskerk, 2001; Román-Dañobeytia et al., 2015).
3.2 | Soil degradation

Both large-scale and ASGM operations involve significant mechanical and chemical manipulation of the earth during the extraction and processing of gold ore. These processes result in chronic and acute forms of soil degradation in both active and abandoned surface gold mines, including soil erosion, infertility, and toxicity. This soil degradation limits the rate and form of natural recolonization of abandoned sites by plants and soil biota.

3.2.1 | Soil dislodgement and erosion

Surface gold mining involves soil dislodgement during the mining process. In large-scale gold mining operations, immense quantities of overlying soil and waste rock (called ‘overburden’) are unearthed to extract gold deposits. At the Geita Gold Mine in Tanzania, for example, a single open-pit operation excavated over 81 million m³ of overburden, altering local topography enough to divert streams nearly 3 km away from their original channels (Emel et al., 2014). ASGM operations using heavy machinery can also dislodge significant volumes of soil, often enough to destabilize riverbanks and hillsides, and wash high loads of suspended solids into streams (Byızıgıro et al., 2015; Moreno-Brush et al., 2016).

Erosion continues to be a challenge for restoration efforts even after the mining process has ceased. Steeply-sloped stockpiles and tailings dams are prone to erosion by wind and overland flow, particularly when left unvegetated (Blight, 1991; Nsiah & Schaaf, 2019a; Windsor & Clements, 2001). Erosion depletes organic content and nutrient-holding clay-size particles in topsoil stockpiles, limiting the effectiveness of post-closure soil recapping and revegetation efforts, especially in tropical areas where mineral soils are naturally weathered and nutrient-poor (Ashton & Seidler, 2014; Jordan, 1985; Sousa et al., 2008). The erosion of tailings dams can cause contaminants to seep into the surrounding environment (Daniell et al., 2019; Festin et al., 2019) and in the most extreme cases, can lead to dam collapse, endangering miners and neighboring communities (Hilson & Monhemius, 2006; Nsiah & Schaaf, 2019a).

3.2.2 | Soil fertility

In addition to erosion, surface mining reduces soil fertility by intermixing the nutrient- and organic matter-rich topsoil with newly exposed rocky, nutrient-poor subsoils, and by producing infertile tailings (Festin et al., 2019). Physically, remnant subsoils at both active and abandoned sites are typically gravelly and sandy (Eludoyin et al., 2017; Guedron et al., 2009; Román-Dañobeytia et al., 2015), while tailings are composed of fine sand and silt-sized particles (Orlekowsky et al., 2013; Rossouw et al., 2009), and lacking clay. The lack of organic matter and clay in remnant subsoils and tailings results in poor cohesion and limited capacity to retain moisture and nutrients. Some remnant substrates may also become highly compacted by the use of heavy machinery (Peláez et al., 2013), limiting plant establishment.
Chemically, remnant substrates and tailings typically have lower nutrient levels, including organic C (dos Santos et al., 2013; Eludoyin et al., 2017; Román-DañoBetyia et al., 2015), total N (Mulligan et al., 2006; Sheoran et al., 2010) and available P, Ca^{2+}, K^+, Mg^{2+}, and Na^+ (Eludoyin et al., 2017). With lower cation exchange capacity than nearby forest and agricultural lands (Eludoyin et al., 2017; Orlekowsky et al., 2013), these substrates often do not hold onto essential nutrients in plant-available forms. These substrates are typically acidic (Eludoyin et al., 2017), leading to higher levels of bioavailable toxic metals and metalloids (Bruce et al., 2003). However, tailings dams can have a wide variation in pH and may even be alkaline depending on the chemical reagents involved in mining and the substrates’ position on the dam slope (Mulligan et al., 2006; Rossouw et al., 2009).

Gold mining can also have negative impacts on soil biology. Former gold mine sites in Brazil had significantly lower soil microbial biomass than an unmined reference site (dos Santos et al., 2013). Microbial community composition also shifts, with more autotrophic and fewer heterotrophic organisms present at gold mines, slowing nutrient cycling (Prasetyo et al., 2010; Rosario et al., 2007). However, there is a need for more research on how these changes to the soil microbiome will impact restoration efforts.

### 3.3 Toxicity and contamination

Contaminants from the gold mining process can enter surrounding ecosystems through purposeful dumping, gradual leaching, and tailings dam collapses, degrading adjacent soils, polluting waterways, and poisoning organisms (Hilson & Monhemius, 2006; Miserendino et al., 2013). During the ore excavation process, heavy metals previously bound in underlying rocks are released into surface soils and waterways. Elevated levels of heavy metals such as cadmium, lead, zinc, and copper have been documented in the remnant substrates of former ASGM sites (Eludoyin et al., 2017; Salami et al., 2003), while high concentrations of arsenic, nickel, and cobalt are often present in wastes from large-scale operations (Antwi et al., 2017; Bruce et al., 2003; Fashola et al., 2016; Orlekowsky et al., 2013). After excavation, ore purification processes introduce further contaminants: mercury is primarily used in ASGM, and cyanide in large-scale operations. Contamination from gold mines can be far-reaching; at a large-scale operation in Tanzania, for example, streams carrying contaminants have affected up to 37 km² of cultivated land throughout the surrounding watershed (Emel et al., 2014).

Rainfall patterns can influence the spread and severity of contamination from gold mines. For instance, intense rainfall increases the erosion of contaminant-bearing surfaces and the dispersion of toxins (Winde & Jacobus van der Walt, 2004; Zaidi et al., 2012). Gold mines in areas of the wet tropics that receive high levels of year-round rainfall, therefore, may be at higher risk of contaminant spread compared to drier tropical and temperate regions. However, hourly changes in precipitation can affect the delivery of contaminants into streams, with very heavy rainfall events temporarily diluting contaminant concentrations (Davies et al., 2011).

#### 3.3.1 Acid mine drainage

Gold-bearing ore and surrounding rock often contain high concentrations of heavy metal sulfides, particularly pyrite (FeS₂) (Lottermoser, 2010). When heavy metal sulfides previously bound in rock are brought to the surface during ore excavation, they react with oxygen in air and water to create sulfuric acid. This oxidation process leads to acid mine drainage (AMD), which exacerbates the leaching of heavy metals into surrounding ecosystems and acidifies streams (Fashola et al., 2016). AMD disrupts aquatic food webs from the bottom-up, destroying habitat and food access as streambeds become coated with solid precipitates (Kefeni et al., 2017; Naicker et al., 2003; Oberholster et al., 2013). AMD can affect expansive areas surrounding gold mines; in South Africa, for example, groundwater over 10 km from a gold mining area was found to be contaminated by AMD (Naicker et al., 2003).

#### 3.3.2 Mercury

Mercury used to refine gold in ASGM operations represents the largest global source of anthropogenic mercury emissions (US EPA, 2014), released into both the atmosphere and lithosphere (Telmer & Veiga, 2009). While miners are directly exposed to mercury vapor during amalgamation, neighboring communities that consume fish from contaminated rivers are also affected (Fréry et al., 2001; Gibb & O’Leary, 2014). In acidic, organic matter-rich river sediments, elemental mercury used in ASGM undergoes abiotic and biotic (bacteria-mediated) methylation reactions to form methylmercury, a toxic organic compound that is readily absorbed by aquatic organisms and biomagnifies at higher trophic levels (Veiga, 1997). Chronic and acute exposure to methylmercury harms the central nervous system, and can irreversibly damage neurodevelopment of fetuses in utero (Poulin et al., 2008). Despite the risks of mercury accumulation in humans and animals from ASGM, concentrations in river water and sediment at ASGM sites are often variable, and difficult to distinguish from background mercury levels from natural emission sources (Howard et al., 2011; Moreno-Brush et al., 2016; Pfeiffer et al., 1989), though recent advances in isotopic analyses promote more accurate tracking of ASGM-associated mercury movement through aquatic ecosystems (Schudel et al., 2019). Depending on local hydrology, downstream areas may experience higher levels of contamination than mined sites (Marrugo-Negrete et al., 2015; Miserendino et al., 2013).

#### 3.3.3 Cyanide

Cyanide is used to extract gold from ore in large-scale mining operations and is often present in tailings and leached ore (Lottermoser, 2010). Cyanide is toxic to all animal life and can be absorbed through the lungs, skin, and mucous membranes, preventing cellular oxygen utilization (Kulig & Ballantyne, 1991). While most contaminants present in gold mines are heavy metals or metalloids,
cyanide is a notable exception. In contrast to these other contaminants, cyanide is capable of being degraded into non-toxic components by acclimatized microbiota (Akcil et al., 2003). While cyanide can be lethal to plants when present in high concentrations, at lower doses, some plants can metabolize cyanide into an amino acid, asparagine (Trapp & Christiansen, 2003). Despite its lesser persistence in the environment, the management of cyanide-laden waste is very important, because breaches and failures in tailings dams can release high concentrations of cyanide into adjacent soils and waterways, which can be lethal to wildlife and people (Hilson & Monhemius, 2006). Animals that come in contact with unnetted cyanide-containing tailings ponds are also at risk of poisoning and death (Donato et al., 2007; Eisler & Wiemeyer, 2004).

3.3.4 Contamination and plant growth

The impact of contamination on plant growth is of particular concern for restoration projects. At low concentrations, common gold mine contaminants like mercury and cyanide appear to have a negligible effect on terrestrial plant growth (Ekyastuti et al., 2016; Kalamandeen et al., 2020; Trapp & Christiansen, 2003). However, higher concentrations of some forms of cyanide can be lethal to plants, while a build-up of mercury in soil and water can reduce germination rates, root development, and aboveground growth of plants (Patra & Sharma, 2000; Trapp & Christiansen, 2003). High concentrations of other heavy metals can also directly limit plant establishment and growth, or indirectly affect vegetation productivity by making soils inhospitable to the soil microbiota supplying nutrients to plants (dos Santos et al., 2013). Even when not at phytotoxic levels, the presence of contaminants can still limit the range of feasible restoration approaches. For example, establishing agroforestry projects on contaminated soils can endanger human and livestock health when there is significant biomagnification in harvested plant parts (Marrugo-Negrete et al., 2015; Terán-Mita et al., 2013). Management activities such as prescribed fires also have to be carefully planned, because they can re-release contaminants already absorbed by vegetation (Abraham et al., 2018).

3.4 Social challenges

3.4.1 Social challenges to ASGM restoration

In 2013, the Minamata Convention on Mercury was signed by more than 130 nations with the goal of limiting anthropogenic mercury emissions. The trade of mercury for gold processing was not banned by the Convention, but signing nations were required to develop action plans to reduce mercury use (Kessler, 2013). However, attempts to regulate the ASGM sector and educate communities on the dangers of mercury use have been largely ineffective (Hilson, 2006; Jønsson et al., 2013; Miserendino et al., 2013; Puluhulawa & Harun, 2019). The informal and remote nature of ASGM makes it difficult to regulate at the national level (Miserendino et al., 2013; Sousa, Veiga, Van Zyl, et al., 2011). Additionally, mining communities tend to experience high rates of extreme poverty, violent crime, and disease (Betancur-Corredor et al., 2018) and have few alternative sources of income (Schueler et al., 2011). Alternative gold refining methods often require knowledge, technology, and investment that is not accessible to miners (Hilson, 2006; Veiga, 1997).

3.4.2 Social challenges to large-scale gold mine restoration

In many regions, laws require large mining companies to rehabilitate mine sites after closure. However, legal requirements vary greatly between nations, enforcement may be haphazard, and successional trajectories may not be headed towards the proposed reference ecosystems (Ahirwal & Pandey, 2020; Hayati et al., 2021; Woodbury et al., 2020). Many developing nations in the tropics have weaker environmental legislation and enforcement, and in some cases, corruption within governing bodies limits the effectiveness of mine reclamation policy (Hayati et al., 2021; Holden & Jacobson, 2008). In Brazil, for example, mining companies are required to restore ecosystems to as close to pre-mine conditions as possible, but the current legal structure provides limited guidance on appropriate restoration targets and techniques (Gastauer et al., 2019), and environmental fines for noncompliance are rarely enforced (Volckhausen, 2020). In Cameroon and Ghana, enforcement of mine rehabilitation policy is also inconsistent, and illegal ASGM often continues even after large mines are officially closed (Essapo & Ekedi, 2020; Owusu-Nimo et al., 2018). In Australia, most large-scale mines can be held indefinitely in a ‘care and maintenance’ phase, where active mining has ceased, but the land has not been fully rehabilitated (Vivoda et al., 2019). In Indonesia, despite legislation, restoration of mined lands is rarely enforced by government officials, and corruption in the mine licensing process has been documented (Hayati et al., 2021). Inconsistency in mine rehabilitation policy and enforcement further hinders attempts to restore these landscapes.

4 RESTORATION AND REHABILITATION OF GOLD-MINING SITES IN THE TROPICS

Due to the extensive environmental impacts of large-scale and ASGM operations, standard forest restoration techniques, developed to recover the land after agriculture, ranching, or logging, may not be sufficient for mined areas. We identified 42 tropical, field-based studies that specifically examined gold mine restoration techniques (see Annex A: Literature Review Methods). These were primarily from South America (n = 15) and Africa (n = 18), with far fewer in Asia (n = 4) and Australasia (n = 5) (Figure 3). Overall, more field studies were conducted at large-scale gold mines (n = 26), than at ASGM (n = 15); one study examined mines of both scales. Most studies in South America and Asia were conducted at ASGM sites. In Africa and
Australasia, most studies focused on large-scale gold mines. All studies from Asia took place in Indonesia, and all Australasian studies took place in Australia (Figure 3). While most studies we found to occur in countries with both documented ASGM and large-scale mining, many gold-producing countries in the tropics lack any published field-based restoration research (Figure 3). Additionally, the restoration goals of these studies varied. In some cases, the goal was rapid revegetation for sediment and contaminant control rather than restoration to natural forest conditions (Weiersbye et al., 2006). Other projects had further objectives involving agriculture or agroforestry (Tetteh, Logah, et al., 2015), silviculture (Sousa et al., 2008; Tetteh, Ampofo, & Logah, 2015), or livestock production (Bruce et al., 2003). In this section, we summarize the findings to examine the effectiveness of various site preparation, natural regeneration, and tree-planting methods. We also briefly discuss phytoremediation, a strategy for restoring heavily contaminated landscapes.

4.1 Basic site preparation: Backfilling and topsoil conservation

Surface mine restoration is significantly more feasible and effective when planning occurs well before mining even begins. Basic site preparation steps can greatly improve restoration trajectories, including (1) conserving topsoil removed during the mining processes, (2) backfilling mining pits and contouring steeply sloped areas, and (3) promptly re-spreading conserved topsoil at the site (Ahirwal et al., 2016; Parrotta & Knowles, 2001). Topsoil conservation is particularly crucial in the tropics, where soil already tends to be naturally weathered, with limited available nutrients (Ashton & Seidler, 2014; Jordan, 1985; Sousa et al., 2008). In addition to its nutrient content, conserved topsoil also contains mycorrhize, soil microbes and fauna, and plant propagules (present in the buried seed bank) that help native plants to spontaneously establish under favorable moisture and light regimes (Sousa et al., 2008).

Stockpiling topsoil for re-application after mine closure is the most common and feasible conservation method. However, biological activity and restoration utility—including nutrient availability, the abundance of soil microbes, and the viability of buried seeds—wanes with long-term (over 1-year) stockpiling, due to erosion and anaerobic conditions at the center of the stockpile (Block et al., 2020; Ghose, 2001; Parrotta & Knowles, 2001; Valliere et al., 2022). These impacts can be mitigated by including biomass, such as tree roots and stumps, in the stockpiles to retain more organic content (Nsiah & Schaaf, 2019), and by establishing vegetation on stockpile surfaces (Windsor & Clements, 2001) to help facilitative soil microbes persist until mine closure (Bell et al., 2003). Steeply-sloped stockpiles can also be protected from erosion by contouring and grading down their slopes (Windsor & Clements, 2001) and covering their surface with biogeotextiles (Nsiah & Schaaf, 2019).

After mine closure, filling open pits with waste rock and subsoils excavated during mining is an essential step to promote the restoration of these sites. While backfilling is already a common practice at large mine sites, ASGM pits are often left unfilled, which slows and prevents the establishment of woody species (Ramkat, 2017). Unfilled pits typically have gravelly bottoms and often accumulate standing
water, preventing seedlings from taking root (Peterson & Heemskerk, 2001). Refilling improves the likelihood of natural regeneration, particularly at small ASGM sites surrounded by a rich forest seed source (Salami et al., 2003).

Some areas may require additional site preparation steps. Very compacted surfaces may require plowing to allow plant establishment and root development (Peláez et al., 2013), while sites with poor soil aggregate stability may have to be treated with binding agents like oxides (Tetteh, Ampofo, & Logah, 2015). Highly contaminated areas, such as tailings storage facilities, will need additional site preparation steps, such as the installation of impermeable liners, to contain runoff and leachate (see Annex B: Treatments for Tailings Dams - Containment Strategies).

4.2 | Restoration using natural regeneration

4.2.1 | Natural regeneration without topsoil conservation

Studies indicate that without topsoil conservation, natural regeneration at former gold mines is significantly delayed (Ekyastuti et al., 2016; Román-Dañobeytia et al., 2015; Sousa et al., 2008) compared to sites abandoned after less severe land conversions, such as agriculture. Tailings, eroded waste rock, and pit bottoms can remain unvegetated or hold standing water for years, if not decades, in both large-scale (Mulligan et al., 2006; Okerefor et al., 2020; Rossouw et al., 2009) and ASGM sites (Peterson & Heemskerk, 2001; Schimann et al., 2012). The sparse recolonizing vegetation is often entirely herbaceous (Haagner et al., 2008; Salami et al., 2003; Weiersbye et al., 2006) and includes fewer woody species seedlings than nearby forest floors (Eludoyin et al., 2017; Peterson & Heemskerk, 2001). In some cases, trees may not regenerate even when surrounded by seed sources from adjacent forests due to staked tree root establishment from poor drainage, subsurface compaction, and soil infertility (Peterson & Heemskerk, 2001). Natural regeneration is even less vigorous and more transient on rapidly eroding, steep slopes of heaped overburden and tailings (Weiersbye et al., 2006).

When operations dig small pits (e.g., around 1.5 m2) and leave good seed sources, the natural regeneration of trees is more likely (Adesipo et al., 2020; Eludoyin et al., 2017; Salami et al., 2003). The unexcavated areas around pits may support the regeneration of some pioneer species, but often these are non-native species as natives are excluded by soil and water pollution (Adesipo et al., 2020; Eludoyin et al., 2017; Salami et al., 2003). Thus, even when natural regeneration occurs, the complete recovery of species diversity may take decades or longer (Baez et al., 2022; Valois-Cuesta et al., 2017). Furthermore, trees are still less speciose and abundant at such sites, with most of the vegetation dominated by herbs, climbers, creepers, and tuber plants, unlike adjacent reference forests that mostly feature trees, shrubs, and ferns (Haagner et al., 2008; Salami et al., 2003; Weiersbye et al., 2006).

4.2.2 | Natural regeneration with topsoil conservation

Few field studies examine the impact of backfilling and topsoil conservation practices on natural regeneration at former gold mines in the tropics. However, such landscaping efforts can restore drainage and fertility to conditions more favorable to tree regeneration, particularly when seed sources are also nearby. The studies we assessed found that backfilling and topsoil conservation at gold mine sites near forest fragments had faster and more diverse natural regeneration of trees (Rodrigues et al., 2004; Sousa et al., 2008) and higher soil microbial activity (Schimann et al., 2012) than in areas without these site preparation steps. While these preliminary findings suggest that backfilling and topsoil conservation can improve natural regeneration success, more field-based experimentation is needed.

4.3 | Restoration using planting approaches

Because of the slow and limited natural regeneration process at most abandoned tropical gold mines, it may take decades or longer to achieve desired ecosystem functions or species compositions without active planting (Baez et al., 2022; Couic et al., 2018; Rossouw et al., 2009). Restoration approaches involving tree planting vary widely in level of intensity, ranging from lower-input enrichment planting techniques (Haimbili et al., 2016; Pollo et al., 2011; Román-Dañobeytia et al., 2015) to the creation of exclusive plantations of desired species (Schimann et al., 2007; Tetteh, Ampofo, & Logah, 2015; Tetteh, Logah, et al., 2015). Overall, most tree planting studies on mine sites tended to focus on a mix of exotic and native legumes (in the Fabaceae family; see Section 4.3.2). Non-woody plants, such as grasses and herbaceous groundcovers can also be incorporated into planting strategies, but are not discussed in-depth in this section (see Annex D for a complete list of species planted in tropical field experiments).

As with natural regeneration approaches, soil management plays a crucial role in determining the success of tree-planting efforts (Nsiah & Schauf, 2019b; Parrotta & Knowles, 2001; Sousa et al., 2008). Sites without conserved topsoil need to ameliorate poor nutrient content and coarse soil texture. The application of fertilizer or organic amendments is one approach to improve the growth and survival of tree plantings in some field studies (Ekyastuti et al., 2016; Román-Dañobeytia et al., 2015; Sousa et al., 2008), while plantings of leguminous, nitrogen-fixing tree species capable of growing in a poor substrate is another commonly-studied approach.

4.3.1 | Leguminous tree planting

Leguminous (Fabaceae) trees are commonly planted to counteract the deficiency of nutrients in mined substrates, particularly at sites without topsoil conservation practices (Sheoran et al., 2010; Woodbury et al., 2020). In general, leguminous trees have relatively high survival
rates, even in the least fertile substrates of former gold mine sites, though there is variability based on site conditions and species (Baez et al., 2022; Haimbili et al., 2016; Mulligan et al., 2006; Tetteh, Ampofo, & Logah, 2015). For example, after one year, planted Acacia seedlings had a survival rate of about 45% in unamended tailings in one field experiment (Haimbili et al., 2016), whereas up to 100% of Acacia and Mimosa seedlings still survived five years after being planted on fertilized and limed overburden in another study (Assis et al., 2011) (see Annex D for summaries of field-based planting experiments). Plantings of legumes can improve mine substrates by fixing nitrogen into the soil, and may also serve as a sustained source of organic matter by providing leaf litter (Peláez et al., 2013; Schimmann et al., 2012; Thomas, 2014). Established plants also improve soil quality by increasing soil pH, soil organic carbon, available phosphorus, exchangeable potassium (Peláez et al., 2013; Tetteh, Logah, et al., 2015), cation exchange capacity, microbial activity (Coul et al., 2018; Schimmann et al., 2007; Velásquez Ramírez et al., 2021) and aggregate stability (Peláez et al., 2013). Plantings of leguminous trees can also increase soil biomass and microbial activity (dos Santos et al., 2013), although their impact may be higher in clay-based soils than in sandier ones (Schimmann et al., 2007).

### 4.3.3 | Tree planting on overburden and tailings

Woody species may not readily establish on the steeply sloped, particularly infertile growing substrate of tailings dams and overburden heaps. Initial fertilization (Mulligan et al., 2006;Nsiah & Schaaf, 2020; Weiersbye et al., 2006), irrigation, and transplantation of nursery-hardened containerized (rather than bare-root) seedlings (Mulligan et al., 2006; Weiersbye et al., 2006), liming (Assis et al., 2011), and the incorporation of B-horizon subsoils into the growing substrate (Assis et al., 2011; Nsiah & Schaaf, 2020) can all improve the survival of planted trees. However, many introduced woody species cannot survive long-term in these environments without continued amelioration, and in particularly unsteady surfaces, perennial herbs and shrubs may be more effective than trees at stabilizing these systems (Assis et al., 2011; Rossouw et al., 2009) (see Annex B: Treatments for Tailings Dams).

### 4.3.4 | Phytoremediation

Phytoremediation is a restoration approach that uses living plants to immobilize, metabolize, and extract contaminants from water and soil (Salt et al., 1998). It is rapidly emerging as a cost-effective method of ameliorating mine substrate, particularly tailings (Wang et al., 2017). In some phytoremediation approaches, plants that metabolize or immobilize toxins may be planted and indefinitely left on-site to help prevent the spread of contaminants throughout the site. In other cases, plants that hyperaccumulate contaminants, often heavy metals, are planted and then removed from the site to prevent the reentry of contaminants into the ecosystem through decomposition, or consumption by people and wildlife.

While phytoremediation species can sometimes naturally regenerate in contaminated sites, their growth may be too sparse for them to stabilize and effectively remediate the soil (Okereke et al., 2020), and therefore usually need to be actively planted to achieve desired densities. However, we found very few field-based planting trials of potential phytoremediator species (see Annex C for species used in gold mine phytoremediation).

### 4.4 | Restoration pathways for former gold mines in the tropics

Field-based experimentation at former gold mines in the tropics is still limited, but studies conducted at these sites reveal important findings for restoration. In the diagram below (Figure 4), we highlight that restoring these landscapes depends greatly on the degree of degradation present at a particular site, particularly the quality of growing substrate and availability of local seed sources. If mining companies and small-scale miners plan ahead and complete integral site preparation steps before mine closure, including backfilling and topsoil conservation, lower-input revegetation strategies, such as natural regeneration and enrichment planting, become much more feasible. However, at sites where substrate is highly contaminated and few seed sources remain, more intensive, multistep approaches will often be necessary to recuperate the fertility of the substrate and kickstart reforestation. These potential pathways are not intended to be prescriptive or all-encompassing; restoration options will depend on the goals, budget, and timeline of a given project. Ultimately, surface gold mining, even in its less-severe forms, degrades tropical ecosystems, and forest recovery in these landscapes will likely be slower and require much more active restoration intervention than in unmined areas.
5 CONCLUSIONS AND RECOMMENDATIONS

While the ecological impacts of tropical surface gold mining are well-documented, we see a clear need for more field-based experimentation to develop a methodology for restoring these degraded landscapes. The continued identification of suitable woody species (in particular, a greater diversity of non-leguminous native species) and effective substrate amelioration processes are essential. Many earlier rehabilitation efforts wasted substantial resources by temporarily altering mine land substrates for species of plants that failed to persist beyond the initial years of tending (Weiersbye et al., 2006). Long-term establishment of self-sustaining vegetation requires a careful and adaptive selection of species that can persist in the often harsh conditions of former mine sites (Ahirwal & Pandey, 2020). There is a strong need to develop sequential, longer-term restoration treatments to determine the best methods for transitioning these landscapes from mine closure to recovery. Field studies indicate that restoration to pre-mine species composition may not be possible at more degraded former gold mine sites, at least not without a lengthy and costly series of plantings, soil amendments, and monitoring.

Given the evident difficulties involved in reforesting former surface gold mines in the tropics—and the importance of proper planning and site preparation for effective restoration—governing agencies, land managers, miners, and local communities need to understand the challenge and monetary expense involved in such efforts. Tropical gold mine restoration is unlikely to succeed without more active involvement from mining communities (Antwi et al., 2017; Betancur-Corredor et al., 2018), the incentivization and enforcement of small-scale mine restoration (Ramkat, 2017; Sousa, Veiga, Meech, et al., 2011), and more in-depth and long-term monitoring of large-scale mine restoration projects (Betancur-Corredor et al., 2018). While this review focuses on strategies for restoring mined landscapes, slowing the spread of tropical gold mining, or modifying some of the more harmful practices involved in operations, is essential for limiting long-term forest loss and ecological degradation. Along with continued field-based research, a combination of increased outreach to mining communities, governmental regulation of rehabilitation projects, and consumer education on the ethical and environmental impact of gold can all play a role in improving restoration outcomes.

FIGURE 4 Restoration options at former mine sites are influenced by initial site conditions. Sites with plentiful local seed sources and well-conserved growing substrates are the best candidates for natural regeneration methods. Sites with more degraded substrate and few seed sources may require active restoration efforts, including basic site preparation, substrate amelioration, and plantings. The most degraded sites, such as tailings storage facilities, may also require additional steps to sequester or remove contaminants. However, it is important to note that more active restoration methods could still be applied to sites with less degraded conditions, depending on specific restoration objectives, budgets, and timelines. Options flow top to bottom from most to least degraded initial site condition, and most to least resources (e.g., money, labor, etc.) required.
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