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Research Article

Traditional gold mining in the highlands of Ethiopia: Its effect on soil loss and possible reclamation measures

Meaza Zenebe[1,2*], Emiru Birhane[2,3,5], Kassa Teka[2], Mitiku Haile[2], Tewodros Tadesse[4], Gebeyehu Taye[2]

[1] Department of Plant Science, Raya University, Maichew, Ethiopia
[2] Department of Land Resources Management and Environmental Protection, Mekelle University, Mekelle, Ethiopia
[3] Institute of Climate and Society, Mekelle University, Mekelle, Ethiopia
[4] Department of Agricultural and Resource Economics, Mekelle University, Mekelle, Ethiopia
[5] Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences (NMBU), Ås, Norway

[*]corresponding author: meazazenebe33@gmail.com

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Abstract

Traditional gold mining (TGM) is among the off-farm income sources of smallholder communities in the highlands of Ethiopia. However, information on their impact on land degradation, taking soil loss as a key indicator, was scant. Hence, this study aimed at i) analyzing local communities' attitudes toward TGM practice, ii) TGM impact on soil loss, and iii) possible restoration measures for the degraded gold-mined landscapes. For the evaluation of community perceptions, 96 beneficiaries were selected from three gold mining sites following stratified random sampling techniques. Soil loss measurement was done through measurement of i) the mass of soil excavated and transported to the river (TR) from 96 individuals and ii) soil volume excavated in 45 excavated soil pits (EP). Descriptive statistics and one-way ANOVA were used to analyze soil loss data, while community perception was analyzed qualitatively. The survey results indicated that the average soil loss from TR and EP were 6,075.97±8.9 t ha^{-1} yr^{-1} and 32,549.99±753.68 t ha^{-1} yr^{-1}, respectively. The magnitude of soil loss also showed a significant (p<0.001) difference among the three sites. Due to a lack of awareness and hiding the reality, most of the gold miners believe that TGM practice has no negative impact on the soil resource, and no post-mined reclamation strategy is implemented. It can be concluded that the existing TGM practices are not done in an environmentally friendly approach and result in adverse soil loss. Hence, stabilizing the topography of the mined sites via backfilling of mined pits and topsoil conservation and amendment measures can be suggested.

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Introduction

In developing continents like Africa, land degradation and the associated consequences become common phenomena. The continent encompasses about 30% of the world's mineral resources and possesses the largest known reserves of strategically important minerals, including gold (Edwards et al., 2014). Due to a lack of appropriate land use planning and unskilled manpower; informal, uncoordinated, and unmonitored management of the existing minerals become common circumstances (Veiga and Hinton, 2002; Rajaee et al

2015). Consequently, the intensification of traditional gold mining (TGM) practices in the continent has become widespread (Edwards et al., 2014). TGM is generally a small-scale mining practice where traditional tools and manual labor are generally used for excavation during the mining activity (Canavesio, 2014; Hagos et al., 2016). It is characterized by low productivity, lack of capital, poor technology, hazardous working conditions, and pollution (Emel et al., 2011; Emel et al., 2014; Meaza et al., 2017). Hence, due to its hideous and probabilistic working conditions, TGM results in severe land degradation in most developing countries where mining practices commonly take place (Mensah et al., 2015). For instance, as reported by Ako et al. (2014), there have been large pits, masses of rock wastes and tailings, and loss of agricultural lands generated as a result of the TGM practice in the north central parts of Nigeria. Hence, as many of the research findings, such as Léopold et al. (2016) and Babau et al. (2017), inferred, TGM practices put negative fingerprints on the soil resources that diminish and prohibit functions obtained from the land resources.

Hence, despite the fact that TGM practice has a subsistence income to the local community, it causes persistent soil removal during and after the mining practice (Ako et al., 2014; Léopold et al., 2016; Eludoyin et al., 2017) and this could cause adverse land degradation. Moreover, clearance of soil coverage and arbitrary excavation of soil materials for mining purposes and abandoned soil pits without filling out them are exposed to soil piping's and gullying, which become soil degradation hotspots (Hagos et al., 2016; Meaza et al., 2017) because the practice is performed without proposing any post-mined reclamation measures and without conducting environmental impact assessment strategies.

Ethiopia is rich in gold deposits, which are found in the north (Tigray region), south, and west parts of the country (Mencho, 2022; Nyssen and Kiros, 2022). Gold deposits in the Tigray region closely correspond to the spatial extent of the Precambrian basement rocks in the region, especially in the low-lying, rolling hills exposed along the lower Giba, Weri'i and Mereb Rivers, Tembien, Abergele, Hawzen – Nebelet – Mai Kinetal – Edaga Arbi, and the localities north and west of Shire, as well as in the deep gorges of Irob in eastern Tigray (Hagos et al., 2016; Meaza et al., 2017; Nyssen and Kiros, 2022). Following the gold deposits, many people engaged in traditional gold mining practices without considering its environmental consequences (Hagos et al., 2016; Meaza et al., 2017). TGM is, therefore, among the off-farm income sources of smallholder communities in the Tigray region, northern highlands of Ethiopia (Nyssen and Kiros, 2022) because the north Ethiopian highlands are traditionally known for gold mining, which has been a means of livelihood of the rural community (Meaza et al., 2015; Mencho, 2022). For example, more than 1,259,910 people (1.32% of Ethiopia's population) are engaged in traditional gold mining practices, which accounts for more than 74% of the gold miners' livelihood (Beyene, 2016; Hagos et al., 2016; Meaza et al., 2017). Moreover, in the Tigray region, where the study took place, more than 160,000 people are involved in mining activity and generate an estimated annual income of USD 210 per person (Beyene, 2016). Traditional gold mining in Tigray region has the potential to create land degradation and modify the natural geomorphic processes arising from modifications in the landscape, such as quarries, pits, and trenches; or overburden waste piles or rock dumps (Hagos et al., 2016; Meaza et al., 2017). Traditional gold mining practices in the region, therefore, converted abundant vegetated sites and farmlands into dysfunctional landscapes that urge regulation policies and rehabilitation efforts.

Albeit several scholars like Alvarez-Berríos and Aide (2015), Léopold et al. (2016), Eludoyin et al. (2017), Obodai et al. (2019), Ngounouno et al. (2021), Mencho (2022) endeavored studies on impacts that are associated with traditional gold mining practices, studies on the magnitude of soil loss due to the traditional gold mining practices following relevant methodology were inadequate. Instead, some of the above-mentioned scholars strongly recommended to have a scientific study on the issue. Although studies are scant on local communities' perceptions regarding TGM practice impacts on the land resources in Ethiopia, some scholars attempted to explore issues associated with traditional gold-mining practices (Hagos et al., 2016; Meaza et al., 2017; Mencho, 2022). For instance, in Asgede-Tsimbla, northern Ethiopia, Meaza et al. (2017) revealed that from the aggregate pit analysis, 104,443 t ha^{-1} soil material has been lost due to TGM practices in 2017. However, this study did not consider annual soil excavated and transported to the river by the gold miners. Another recent study by Mencho (2022) in the Guji zone, southern Ethiopia, also noted that TGM was the root cause of soil degradation due to soil erosion and environmental destruction in the area. However, the study lacks quantitative soil loss data.

As part of reversing the land degradation driven by traditional gold mining practices, there are several research experiences of post-mining landscape restoration mechanisms. For instance, followed by stabilization of the topography of the mined landscape and replacement of top soils (Byizigiro et al., 2020), the plantation of selected native plant species could be a sustainable and organic tool for the restoration of post-mined landscapes (Gairola et al., 2023). One of the key factors for the success of post-mined degraded landscapes is, therefore, the use of local indigenous species (Borbón-Palomares et al., 2023; Gairola et al., 2023; Rosa et al., 2023). These indigenous species have well adapted to the soil and climate conditions of the host site and would ensure the greatest chance for remedial success (Prasetyo et al., 2010). Providing integrated training and awareness for gold miners regarding the environmental friend mining approaches and sustainable utilization of the land resources is also essential so as to mitigate the negative impacts of TGM on the land resources (Meaza et al., 2015).

Hence, this study was designed to 1) evaluate the perception of gold mining beneficiaries on the challenges and opportunities of the traditional gold mining practice on the environment, 2) quantify soil loss rate due to traditional gold mining practices, and 3) identify possible solutions (reclamation measures) for the degraded gold-mined landscapes.

Materials and Methods

Study area

Since the Tigray region is home to various precious minerals, including gold (Hagos et al., 2016; Meaza et al., 2017; Nyssen and Kiros, 2022), most of the poor rural communities of the region are engaged in the traditional gold mining practices to fulfill their subsistence needs (Hagos et al., 2016; Meaza et al., 2017). To conduct this study, therefore, the region is selected purposefully as it is known by intensive traditional gold mining practices. Specifically, the study was conducted in the three traditional gold mining sites of Werei River located between 39°17' to 39°21' E and 13°59' to 14°04' N. The specific sites were *Guraguh, Tselim-emni,* and *Tshuf-sagla* (Figure 1), with an area of 7.2 ha, 7.6 ha, and 8.3 ha, respectively. These sites are located 132 km north of Mekelle (the Tigray capital). The study sites had a semi-arid climate in the midland agroecology with an elevation of 1,605-1,735 m above sea level. Long-term average annual rainfall was 552 mm, which falls during the main rainy season from June to September, with an unpredictable and monomodal nature. The average daily temperature of the area was 20°C.

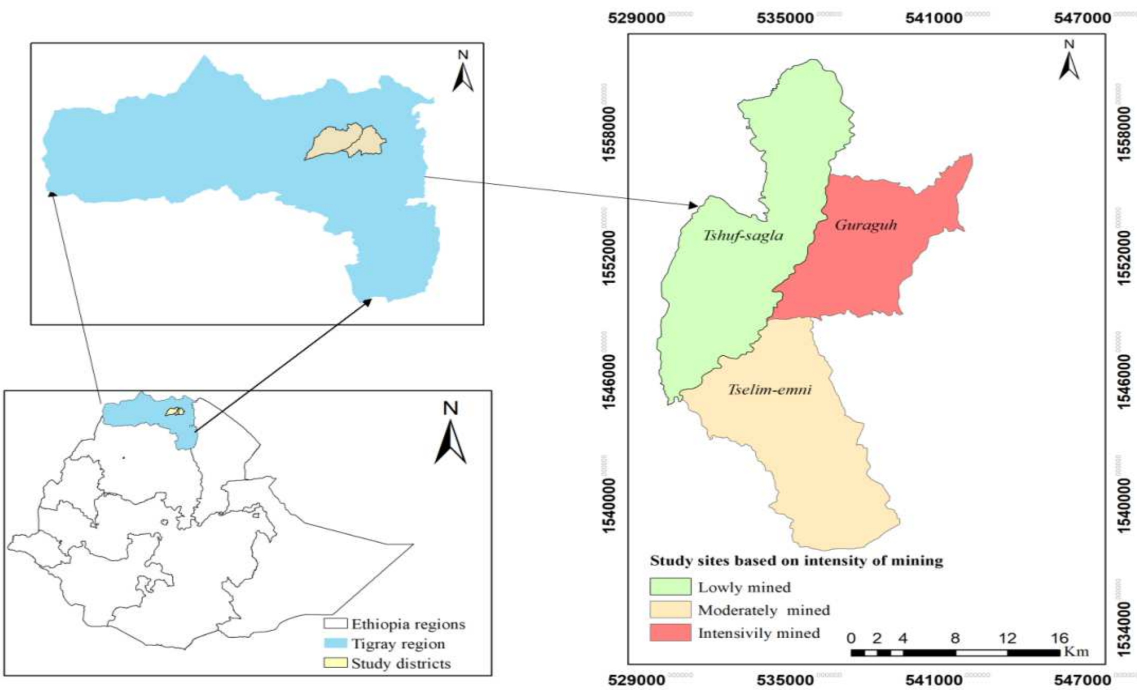

Figure 1. Location of the study sites in Tigray (northern Ethiopia).

Topographically, it is characterized by rugged nature, including mountains, plateaus, valleys, and gorges (Nyssen and Kiros, 2022). The Werei River draining through the study area is deeply incised and transports large amounts of runoff and sediment during the rainy season (self-observation). The area is also characterized by three major land use types, including cultivated, exclosures, and woodland. Moreover, the dominant vegetation species are *Acacia tortilis, Balanites aegyptiaca, Sauromatum venosum, Vachellia etbaica,* and *Faihderbia albida.* Mixed farming, which comprises crop and livestock production, is the common farming system in the study area. Geologically, the area is classified into low-grade metamorphic, meta-sediment, and quarzitic formations (Williams, 2016). The major reference soil group in all the study sites is Eutric cambisols (Figure 2), which is highly affected by erosion and deposition processes (FAO, 1971).

Study site selection and sampling method

A reconnaissance survey had been made to get overview information on the gold mining sites of the Tigray region before site selection. The top five gold-rich Woredas in Tigray are Asgede-Tsimbla, Laelay-Adiabo, Mereb-Leke, Embasneytiy, Hawzen, and Tselemti (Nyssen and Kiros, 2022). A multi-stage sampling procedure was used to select the study sites and design the study method. Among the aforementioned gold potential Woredas, Embasneytiy, and Hawzein districts were selected purposefully considering their accessibility and the presence of intensive traditional gold mining practices. In the second stage, three kebeles, namely *Baleda* and *Debreselam* from *Hawzein* and *Gonek* from *Embasneytiy* were chosen randomly. Thirdly, the existing mining sites within the kebeles were classified into three categories based on mining intensity.

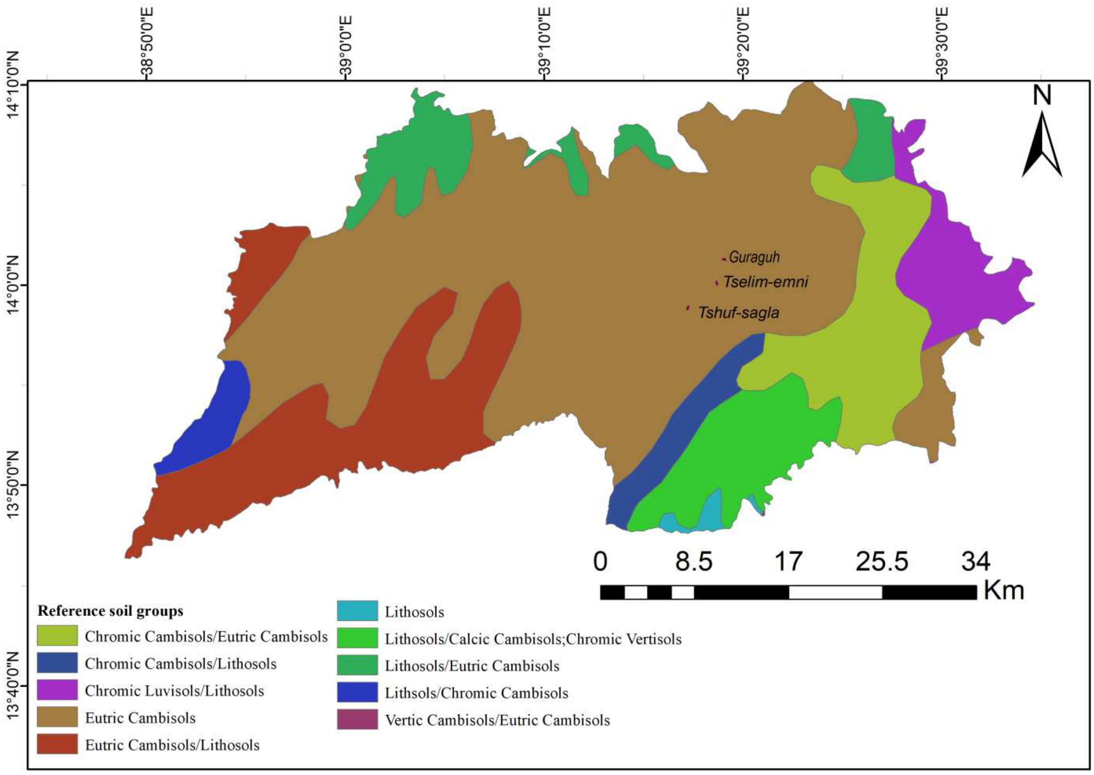

Figure 2. Soil map of the study area (FAO, 1971).

The mining intensities were characterized based on the number of excavated pits, the dimensions of the pits, and the number of people involved in the mining practice. Accordingly, three sites, namely, *Guraguh* from *Baleda, Tselim-emni* from *Debreselam,* and *Tshuf-sagla* from *Gonek* were systematically selected from intensively, moderately, and low-mined sites, respectively. These areas had been used for gold mining for about two decades. The boundary of each site was delineated using GPS, and the area coverage of each site was estimated.

Data collection

Primary data such as the history of the mining activity, the number of participants in the activity, and soil loss due to mining were obtained from field observations and interviews using semi-structured questionnaires. Based on the pilot survey conducted in the areas, people between the ages of 20 and 40 could mine the gold intensively, while people above 40 could not mine intensively. Hence, following the age-based stratified random sampling method, a total of 96 households were selected for interview using Eq.1 developed by Glenn (1992).

$$n = \frac{N}{1+N(e)^2} \text{………………………………... (Eq. 1)}$$

where: n = sample size; N = household size of the population (gold miners); e = acceptable sampling error (5%).

Secondary data such as research experiences on post-mined degraded landscape reclamation measures, major mining sites in Ethiopia, and other traditional gold mining-related research experiences were also collected from published journals, book chapters, organization reports, unpublished district offices, and regional bureau documents.

Soil loss due to TGM was estimated following two methods. Measurement of the mass of soil excavated and transported to the river at a round by an individual was employed using a sensitive balance. Based on the responses of those traditional gold miners, the annual soil loss due to TGM was derived using (Eq. 2);

$$SL = (NP * F * MS * D)/A \text{...…………………. (Eq. 2)}$$

where: SL = soil loss (t ha^{-1} yr^{-1}); NP = number of people involved in the mining activity per day; F = frequency of mining activity by an individual per day; MS = average amount of soil mass (ton) at one excavation by an individual; D = average number of days that an individual is involved in gold mining activity per year; A = area of the mining site.

To complement and validate the above method (Eq. 2), soil loss estimation from the mined site was performed by measuring the dimensions of opened soil pits that were excavated during the survey year. The number of pits for measuring the soil volume was selected using a systematic random sampling method. Three transects were laid at intervals of 100 m, and five pits were taken from each transect randomly. Thus, based on the systematic random sampling method, a total of 45 pits were considered for soil loss measurement. Finally, soil loss was estimated from the volume (m^3) of each pit following Eq. 3 (Meaza et al., 2017). The volume of excavated soil was converted to mass (t ha^{-1}) of soil by multiplying the volume with the mean bulk density. Bulk density was determined by taking undisturbed soil samples from each of the mined soil pits that were classified based on their depths following Eq. 4 (Klute, 1986).

$$\mathrm{SL} = \mathrm{VL} * \mathrm{BD} \ldots\ldots\ldots\ldots \text{(Eq. 3)}$$

where SL is soil loss (t ha^{-1}); VL is the volume of the pit representing the volume of excavated soil (m^3) determined based on the dimensions (depth, length, and width) of the soil pits; BD is bulk density (g m^{-3}).

$$\text{Bulk density} = \frac{\text{mass of dry soil}}{\text{total volume}} \ldots\ldots\ldots\ldots \text{(Eq.4)}$$

Data analysis

Soil loss data were checked via Shapiro-Wilk for normality distribution and via Levene's test for homogeneity of variance. Hence, data were normally distributed and had equal variance. Accordingly, data were subjected to parametric tests. Soil loss is the dependent variable, while site or intensity of mining which has three levels, is the independent variable. Hence, a one-way ANOVA method of analysis was undertaken in the statistical package for social science (SPSS) version 20 statistical software. A post hoc test using the Tukey HSD test was also undertaken to determine a significant difference of means between the three mined sites that had different mining intensities. Data obtained from social surveys regarding the community perceptions and opinions on the challenges and opportunities of TGM were analyzed quantitatively and qualitatively. Quantitative data was described using descriptive statistics like frequency and percentages, while qualitative data was analyzed qualitatively by explaining, refuting, enriching, and confirming the data.

Results and Discussion

Perception of households on traditional gold mining

The majority of the respondents, more than 62%, revealed that the location of gold mining sites is traced by trial and error, in which the miners have to excavate sites randomly until they get a satisfactory result. Similarly, findings from *Asgede-Tsimbla* of northern Ethiopia Hagos et al. (2016) and southern Ethiopia Mencho (2022) reported that traditional gold miners destruct areas, including sites that have no gold potential as the miners do not use modern technologies to identify potential sites. So, the trial and error method exaggerated the land degradation, thereby destruction of additional non-gold potential areas.

The landless and unemployed youth were highly involved in the gold mining practice. The unemployment rate in the area was as high as 60% during the survey year, and the TGM practice serves as a temporary income source. The same is true in other parts of the Tigray region, such as Asgede-tsmbla district (Redehey, 2017) and in the Western Region of Ghana (Attuquayefio et al., 2017) TGM practices are a means of income for most of the poverty prone rural society of Tigrians. Hence, unlike the negative impacts of the TGM practice on land resources, this finding highlighted that the income generated from traditional gold mining plays an important role in reducing rural poverty. Because artisanal gold mining has been a source of subsistence for the rural poor society of the Tigray region (Meaza et al., 2015). To fulfill their temporary needs, youth students also participated in the traditional gold mining practices by dropping out of their studies. The same is true (Redehey, 2017), who suggested that in Asgede-Tsmbla, Tigray region, many young people (school-aged) in the district are involved in such mining practices, which exacerbates school dropout, over-age enrollment, and lower rates of school completion.

A considerable number of respondents, more than 95%, believe that the mining activity has no negative impact on the environment and that no rehabilitation effort needs to be put in place (Table 1). However, the reality on the ground is different. During the study, the researchers observed a huge destruction of vegetation cover and removed soils that could have the potential to support agriculture and other land uses. Only a few numbers of respondents (not more than 6.3%) agree with the notions indicated by (Alvarez-Berríos and Aide, 2015; Eludoyin et al., 2017) that traditional gold mining practice has a serious environmental impact. Because, it destroys plant covers, removes excessive soil materials, and disturbs the soil properties of the mined area. A similar case was reported in the southwestern part of Nigeria (Eludoyin et al., 2017) and northern Ethiopia (Meaza et al., 2017). The lack of awareness of the miners on sustainable land management issues and the focus on the subsistence income gained from the activity were the reasons behind hiding the reality.

The majority of the respondents (*Guraguh 81.3%, Tselim-emni 100%, and Tshuf-sagla* 87.5%) agree that after the gold miners operated gold mining, they do not reclaim or rehabilitate the mined site. Likely, Ako et al. (2014) stated that most artisanal gold miners abandon the mined area without any post-mining restoration effort. Although a small number of respondents (18.8% and 12.5% respondents from *Guraguh* and *Tshuf-sagla,* respectively) mentioned that the gold miners intervened in rehabilitation measures after they explored the gold ore, there was no indication of rehabilitation effort in all of the studied mined sites. Similar findings were also reported in other African countries, such as Geita district in Tanzania (Kitula, 2006) and the southwestern part of Nigeria (Eludoyin et al., 2017), where traditional gold mining activities are operated by people who have not any consideration to the sustainable land resource management.

Table 1. Community perception on the status of traditional gold mining.

Traditional gold mining status indicators	**Respondents (%) at *Guraguh***	**Respondents (%) at *Tselim-emni***	**Respondents (%) at *Tshuf-sagla***
Who is highly involved in the mining activity?			
Landless and unemployed youths	87.5	90	85
School dropout youth	12.5	10	15
What are the impacts of the activity?			
Vegetation, soil, and water degradation	6.3	0	3.5
No impact	94.7	100	96.5
Do you support the continuation of the activity?			
Yes	56.2	60	60
No	43.8	40	40
Do you have an interest in conserving the land resources?			
Yes	6.2	0	0
No	93.8	100	100
Recommendations towards achieving a sustainable mining activity?			
Better to stop the activity	18.8	10	18.8
Continue as it is	37.5	50	43.8
Mining by implementing management activities	12.5	8	12.5
Working by groups	31.3	32	25

Fear of miners that the government might change the land to exclosures if rehabilitation activities were in place was another reason to hide the reality (Hagos et al., 2016).

Soil loss due to traditional gold mining practice

Traditional gold mining activity in the studied sites removed soil and rock fragments. There was a significant difference ($p<0.001$) in soil loss among the three mining sites. The highest soil loss was estimated at *Guraguh,* while the lowest was at *Tshuf-sagla* (Table 2). The average soil loss of the studied sites was found to be 6,075.97±8.9 t ha^{-1} yr^{-1} from soils transported to rivers (TR) and 32,549.99±753.68 t ha^{-1} yr^{-1} from excavated pit measurements (EP). Mining intensity varies between the three mined sites which high mining activity was performed in Guraguh site while relatively moderate and low gold mining activity is practiced in Tselim-emni and Tshuf-sagla sites, respectively. Soil loss estimated in this study is far beyond the maximum soil loss threshold, which is 50 t per ha^{-1} yr^{-1}, recommended by Haregeweyn et al. (2017). This is due to the destructive and unmanageable process of the gold extraction method. TGM activity in the study sites was performed by the excavation of both surface soils and deep soils until the miners reached the gold-rich soil material, and the gold-bearing material was transported manually to the nearby river. Ako et al. (2014) also suggested that in Nigeria TGM activity is the main cause of the destruction of natural landscapes and land degradation resulting from TGM-driven soil erosion. Even though the soil loss result is quite low compared to the findings of Meaza et al. (2017) from Asgede-Tsimbla (104,443 t ha^{-1} yr^{-1}) in northern Ethiopia, the rate is too high to sustain environmental rehabilitation activities. Hence, the magnitude of annual soil loss estimated in this study (6,075.97±8.9 t ha^{-1} yr^{-1}) is quite higher than the tolerable soil loss rate of 11 t ha^{-1} yr^{-1} (Renard et al., 1996) and far beyond the average soil loss rate estimated for the highlands of Ethiopia (Tamene et al., 2022). TGM activity in the study area not only leads to the estimated amounts of soil loss. Such mining practices also exposed the mined site to further land degradation hotspots by exposing the mined site to further erosion agents like water and wind erosion. Because, based on the majority of the respondents and field observation, after the miners accomplished the gold mining activities, they did not rehabilitate the degraded mined area. Instead, the gold miners abandoned the former mining sites without any rehabilitation effort and continued searching for other gold potential sites. As a result, in the study sites, vast gullies and degraded lands were observed which are expanded following the excavated mining pits. Besides, mining activities in all the studied sites removed huge amounts of soil as compared to soil loss caused by water and tillage in areas with similar agroecological zones (Table 3). Study results in May Zeg-zeg area of northern Ethiopia (Nyssen et al., 2009) and Mayleba of northern Ethiopia (Taye et al., 2013) revealed a soil loss of 17.4 t ha^{-1} yr^{-1} and 38.7 t ha^{-1} yr^{-1} due to water erosion, respectively. Another study by Bewket and Teferi (2009) also reported a water-induced soil erosion rate of 125 t ha^{-1} yr^{-1} for the upper Blue Nile (Ethiopia). Soil loss due to tillage erosion in Dogu'a Tambien (northern Ethiopia) was found to be 20 t ha^{-1} yr^{-1} (Gebremicael et al., 2005). Another recent study by Girmay et al. (2020) in the Wag-Himra zone, northern Ethiopia, also reported 25 t ha^{-1} yr^{-1}. These all-reported results are still far below that of soil loss driven by traditional gold mining activity (Table 2). Thus, all of the research experiences integrated with the results of this study (Table 3) confirmed that TGM activity is the main and most human-induced erosion agent, which converts the natural landscape drastically into degraded and bad land due to the mining-induced erosion incident.

Table 2. Soil loss due to traditional gold mining practices in each study site.

Site	**Soil loss (t ha^{-1} yr^{-1}) from excavated and transported to the river**	**Soil loss (t ha^{-1}) from aggregate pit analysis**
Guraguh	8,294.15±4.46c	48,512.39±878.94a
Tselim-emni	5,258.41±1.18d	33,932.58±1265.88b
Tshuf-sagla	4,675.37±3.15e	15,205±116.22c
Average	6,075.97±8.9	32,549.99±753.68
p - value	**	**

Note: Different letters within the column indicated significant differences, while ** stands for the significant difference of soil loss between the three mined sites at a 0.001 level of significance.

Table 3. Comparison of soil loss due to traditional gold mining practices with water and tillage erosion process reported elsewhere in the highlands of Ethiopia.

Land use	**Soil loss**	**Erosion agent**	**Study areas**	**Method of study**	**Source**
Mixed	6,075.97 t ha^{-1} yr^{-1}	gold mining	Northern Ethiopia (Werie area)	Field measurement and interview	This study
Mixed	32,549.99 t ha^{-1}	gold mining	Northern Ethiopia (Werie area)	Aggregate pit analysis	This study
Mixed	104, 443 t ha^{-1}	gold mining	Northern Ethiopia (Asgede-Tsimbla)	Aggregate pit analysis	Meaza et al. (2017)
Cropland	20 t ha^{-1} yr^{-1}	Tillage	Northern Ethiopia (Dogu'a Tembien)	Plot experiment	Gebremicael et al. (2005)
Cropland	72.6 t ha^{-1} yr^{-1}	Water	Eastern wollega	RUSLE	Adugna et al. (2015)
Mixed	566 t ha^{-1} yr^{-1}	Water	Hararghie (Wabishebelle)	Aerial photo	Daba et al. (2003)
Mixed	4.4 t ha^{-1} yr^{-1}	Water	Northern Ethiopia	Aeria photographs	Frankl et al. (2012)
Cropland	37 t ha^{-1} yr^{-1}	Water	Western Ethiopia (Gojjam)	USLE	Bewket (2003)
Mixed	17.6 t ha^{-1} yr^{-1}	Water	Northern Ethiopia	Aerial Photographs	Frankl et al. (2013)
Mixed	6.2 t ha^{-1} yr^{-1}	Water	Northern Ethiopia (Geba catchment)	Field survey and interviews	Nyssen et al. (2006)
Cropland	7.2 t ha^{-1} yr^{-1}	Water	Northern Ethiopia (Mayleba)	Plot experiment	Taye et al. (2013)
Rangeland	17.4 t ha^{-1} yr^{-1}	Water	Northern Ethiopia (May Zeg-zeg)	Plot experiment	Nyssen et al. (2009)
Rangeland	38.7 t ha^{-1} yr^{-1}	Water	Northern Ethiopia (Mayleba)	Plot experiment	Taye et al. (2013)
Mixed	31 t ha^{-1} yr^{-1}	Water	Wabishebelle (Alemaya)	AGNPS model	Muleta et al. (2006)

Note: Mixed land use indicates that a study reported from comprised of more than two land uses; USLE stands for universal soil loss equation; RUSLE stands for revised universal soil loss equation, and AGNPS stands for agricultural non-point pollution sources.

Possible restoration mechanisms to rehabilitate degraded gold-mined landscapes

Understanding traditional gold mining-driven soil mass movement and the associated geomorphic processes and the control of these processes is a fundamental prerequisite toward a successful restoration of mined sites. Hence, prior to the revegetation of the post-mined sites, stabilizing the topography of mined sites so as to reverse the TGM-induced soil loss and create a favored environment for plant growth in the mined-driven degraded land is a prerequisite post-mining restoration mechanism (Byizigiro et al., 2020). Certain practices, such as the backfilling of mined pits, topsoil conservation, and plantation of native species, are, therefore, crucial for the timely and effective restoration of gold mining sites (Timsina et al., 2022). Post-mined restoration, hence, includes the management of all types of physical, chemical, and biological disturbances of soils, such as soil pH, fertility, microbial community, and various soil nutrient cycles that make the degraded land productive. Productivity of the mined soil can be increased by adding various natural amendments such as sawdust, wood residues, sewage sludge, and animal manures, as these amendments stimulate microbial activity, which provides nutrients and organic carbon to the soil. Revegetation of mined sites is also the most widely accepted and useful way to reduce erosion and protect soils against degradation during reclamation (Byizigiro et al., 2020). Mine restoration efforts have focused on N-fixing species of legumes, grasses, herbs, and trees (Sheoran et al., 2010).

The plantation of selected native plant species could, therefore, be a sustainable and organic tool for the restoration of post-mined degraded land (Gairola et al., 2023). In case of this, A native *Stylosanthes guianensis* cover crop in the TGM Amazonian Forest, Peru thrived in the degraded post-mined area (Velásquez Ramírez et al., 2021). One of the key factors for the success of post-mined degraded landscape reclamation with phytoremediation technology is, therefore, the use of local indigenous species (Borbón-Palomares et al., 2023; Gairola et al., 2023; Rosa et al., 2023). These indigenous species have well adapted to the soil and climate conditions of the host site and would ensure the greatest chance for remedial success (Prasetyo et al., 2010).

Metal-tolerant plants can also be effective for acidic and heavy metal-bearing soils (Mendez and Maier, 2008; Sheoran et al., 2010). Phytoremediation of mined tailings requires metal-tolerant plants with minimal accumulation in above-ground organs to minimize the incorporation into local food webs (Mendez and Maier, 2008). A study in mining tailings of northwestern Mexico noted that the plantation of R. communis (native plant to the area) in the mined tailings clearly showed that the concentration of potentially toxic elements (PTE) in above-ground organs significantly reduced by adding compost and nutrients to the growing substrate (Borbón-Palomares et al., 2023). The occurrence of AMF in mined lands can promote plant growth by increasing nutrient absorption as well as protecting plants from the harmful effects of toxic metals (Husna et al., 2021; Adyari et al., 2022). AMF species have the potential to restore degraded mined areas and developed as a bio-fertilizer for kalapi (an endangered endemic legume) cultivation in gold mine tailings of Sulawesi, Indonesia (Husna et al., 2021). A study by Marcelo-Silva et al. (2023) in South Africa demonstrated that Aloe plants showed potential for the phytoextraction and bioaccumulation of potentially toxic metals (PTMs) in contaminated soils from platinum and gold-mined tailings. In the Ghanaian gold-mined tailings re-vegetated with Acacia species improved soil physical characteristics such as bulk density, moisture holding capacity, and infiltration rates to levels comparable with the un-mined soils (Frimpong et al., 2014). Re-vegetation of mined areas using Acacia species, therefore, is a good strategy for restoring the fertility of gold-mined soils.

Conclusion

Traditional gold mining activity in the area led to severe soil loss. The soil loss is also related to the direct transport of the soil to – and damping in the rivers, which leads to sediment transport by rivers. As the gold miners have not used technology to identify and select gold potential sites, they dig out all the soils randomly until they find gold. Based on the evidence of the field observation and miners' perception, the gold miners have not reclaimed or rehabilitated the mined area after they explored the gold ore. Moreover, this destructive process of gold exploration causes land degradation, and rehabilitation efforts are needed to protect the mined areas from further degradation. Therefore, stabilizing the topography of the mined sits through backfilling of the mined pits; topsoil conservation and amendment so as to protect soil erosion and create fertile land for plant growth; plantation of native species integrated with arbuscular mycorrhizal fungi inoculation are among the most relevant reclamation measures to be intervened in the gold mining sites. Further research on the effectiveness of the aforementioned post-mined reclamation measures in the study sites is required.

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