ASSESSING DEGRADATIVE EFFECTS OF OPENCAST HYDRAULYC TIN MINING ON SOIL QUALITY ON BANGKA ISLAND, INDONESIA

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Abstract

Tin mining on Bangka Island, Indonesia boosts regional economy but brings social and environmental issues. This study assessed soil degradation (SDS) in tin-mining areas using a Relative Frequency of Soil Degradation (RFSD) score. We selected a minimum dataset on landscape and soil characteristics for this assessment. Converting the agroforestry fields (CSs) into the tin mining areas (ATMAs) significantly reduced plant species, vegetation coverage, and solum thickness (P < 0.01), while increasing surface rockiness. The open-pit hydraulic tin mining significantly affected soil physical characteristics (SPCs) as well as soil chemical and biological characteristics (SCBCs). Changes in landscape attributes, SPCs, and SCBCs led to varying levels of soil degradation at study sites. RFSD values ranged from 80% to 100% in all ATMAs, resulting in a total RFSD score of 32, categorizing the SDS as heavily degraded. The lack of variations in the SDS across the ATMAs indicated similar pressures from tin mining activities. In contrast, the RFSD values at the CSs ranged from 0% to 100%, resulting in a total RFSD score of 2 to 14, categorizing the SDS as slightly degraded. The low RFSD values (0% to 50%) and corresponding low total scores (2 to 14) indicated relatively undisturbed soil with optimal landscape and favorable conditions. However, elevated total RFSD scores were observed for four specific indicators at some CS locations: soil fraction (sf), total porosity (tp), soil permeability (spm), and soil acidity (sa), pointing to ongoing soil disturbances despite being designed as AF systems. These findings highlight the complexities involved in the soil degradation processes within systems intended for sustainability.

Keywords: Tini mining, CSs, ATMAs, RFSD, SDS,

1. Introduction

Soil quality (SQ) is influenced by the complex and specific relationships between soil functions and ecosystem services (Sharma *et al*., 2023). These relationships are essential for maintaining the health and productivity of soils, which in turn affects the overall well-being of ecosystems (Sharma *et al*., 2023; Telo da Gama, 2023). However, there is growing evidence that the expansion and intensification of human activities are placing increasing pressures on soil resources. These pressures can have negative impacts on food security, water quality, and overall ecosystem health (Smith *et al*., 2021; De Deyn and Kooistra. 2021).

It is widely acknowledged that mining can contribute to regional development in several ways. It can create job opportunities for local residents, enhance infrastructure development and stimulate economic growth through increased trade and investment in the area (Worlanyo and Jiangfeng, 2021). Additionally, mining revenues can also be used to fund public services and social programs that benefit local communities (Arkum et al., 2017; Worlanyo and Jiangfeng, 2021). A study by Sulista et al. (2022) reveals that tin mining in Bangka Island of Indonesia has significantly contributed to both the regional economy and the household income across the province. However, these benefits are often overshadowed by a series of adverse social and environmental impact, such as widespread land degradation, water and air pollution, and other environmental disturbances (Abdel Rahman and Arafat, 2020; AbdelRahman *et al*., 2022; Feng *et al*., 2019; Sulista et al., 2022).

The negative impacts arise from vegetation permanent loss, changes in landscape morphology, alterations in hydro-geological conditions, introduction of contaminants into the environment, loss of soil organic matter, and loss of the rich top soil, depleting nutrient stock in soil (Martins et al., 2020; Janečková *et al*., 2023). This degradation process diminishes soil productivity and health, leading to reduced vegetation cover, poorer crop yields, and diminished capacity to hold water and support biodiversity. Ultimately, these impacts collectively degrade SQ, making soil less productive and less capable of supporting healthy ecosystems and human health (Garrigues *et al*., 2012; Legaz *et al*., 2017; Benidire *et al*., 2020).

Tin mining in Bangka Belitung Islands of Indonesia has been practiced for hundreds of years and has been accelerating significantly in recent years (Sukarman et al., 2020; Sulista et al., 2022). Open-cast hydraulic tin mining typically begins with the removal of topsoil. followed by the leaching of the soil to extract tin ore. Traditionally, a large volume of water was used to remove overburden and tin-bearing debris. Current method uses high-pressure jets of water directed through hoses and nozzles. This process creates a water-sediment slurry that is then channeled through sluice boxes to separate the tin. Overall, open-cast tin mining can lead to long-lasting and detrimental impacts on soil health and productivity (AbdelRahman and Arafat, 2020; AbdelRahman et al., 2022; Martins et al., 2020; Janečková et al., 2023). Due to the complexity of these interactions, quantitatively assessing the impact of mining on SQ presents a significant challenge. The fact that soils function not only in the production of food and fibers but also in the maintenance of environmental quality has recently increased the interest in the evaluation of the degrading SQ caused by open-cast hydraulic tin mining. However, the growing demand for tin highlights the urgency of examining the ecological impacts of mining practices. This article presents an analysis of the degradative effects of open-cast hydraulic tin mining practices on SQ. By analyzing soil samples collected from areas affected by these activities. changes in landscape and soil characteristics are assessed.

Accordingly, our main goal was to assess soil degradation status (SDS) in tin-mining areas based on a Relative Frequency of Soil Degradation (RFSD) score. In this study, a minimum data set on landscape attributes (number of plant species, vegetation coverage, solum thickness, and soil surface rockiness) and soil characteristics (soil fraction, bulk density, total porosity, soil permeability, and soil pH) were intentionally selected.

2. Materials and Methods

2.1. Study Site and Soil Sampling

The study site was located in four sub-districts, Kelapa, Tempilang, Parit Tiga, and Jebus Sub-districts, West Bangka District, Bangka Belitung Islands Province, Indonesia (Figure 1). This district is stretching from 105º30' E to 106º00' E and 01º00' N to 02º10' N and belongs to Type A zone with ratio of dry month to wet month <1.5 (Schmidt and Ferguson. 1951). Although there has been a seasonal shift. rainy season usually starts in September and ends in March with average annual precipitation of 2.000mm; dry season is from April to August. Air temperature is relatively similar all year long with mean annual temperature of 26.20°C to 27.80°C and RH of 80 to 87%.

Figure 1. Location of the study site in West Bangka District, Bangka Belitung Islands Province, Indonesia.

Ten agroforestry fields and ten ex-tin mining areas were randomly selected. The agroforestry fields were assigned as a Control Site (CS); while 5-year old ex-tin mining areas were assigned as abandoned tin mining area (ATMA). The over-storey layer within the CS was mixed-tree species. Some primary species included *Arenga pinnata*, *Artocarpus altilis*, *Artocarpus heterophyllus*, *Cocos nucifera*, *Dimocarpus longan*, *Durio zibethinus* Meur., *Garcinia mangostana* L., *Gnetum gnemon* Linn., *Hevea brasiliensis*. *Lansium parasiticum*, *Macaranga* sp., *Mangifera indica*, *Melastoma* sp., *Musa* sp., *Nephelium lappaceum*, *Piper nigrum*, *Schima wallichii*, and *Syzygium aqueum*.

While the ATMA was sparsely vegetated. The dominant species included *Acacia mangium*, *Dillenia indica*, *Dillenia suffruticosa*, *Imperata cylindria*, *Macaranga* sp., *Melaleuca cajuputi*, *Melastoma malabathricum*, *Mimosa pudica* L., Rhodomyrtus tomentosa, and ferns.

2.2. Soil Sample and Analytical Methods

Ten sampling points were set to represent the entire area of each site. The sampling points in the CSs were labeled as CL (CL1 to CL10), while those in the ATMAs were labeled as AL (AL1 to AL10), as illustrated in Figure 2. Each sampling point comprised five sub-sampling points that were evenly distributed, as shown in Figure 2.

Two types of soil samples—undisturbed and disturbed—were collected from a depth of 0 to 30 cm at each sub-sampling point. The undisturbed soil cores were obtained using 100-cc soil corers for measuring bulk density and hydraulic conductivity. Bulk density was calculated based on the 100-cc core and the constant dry weight of the core after it was dried at 105ºC for 24 hours. Saturated water permeability was determined using a permeameter (Daiki, DIK 4000). Additionally, soil compaction was assessed through soil hardness, which was measured in the field using a fall-cone-type soil penetrometer (Daito Green Ltd., Hasegawa type H-60) to a depth of 60 cm.

The disturbed soil samples were collected using an auger and then scooped for physico-chemical characterization. Soil pH was measured in both a soil-to-water and

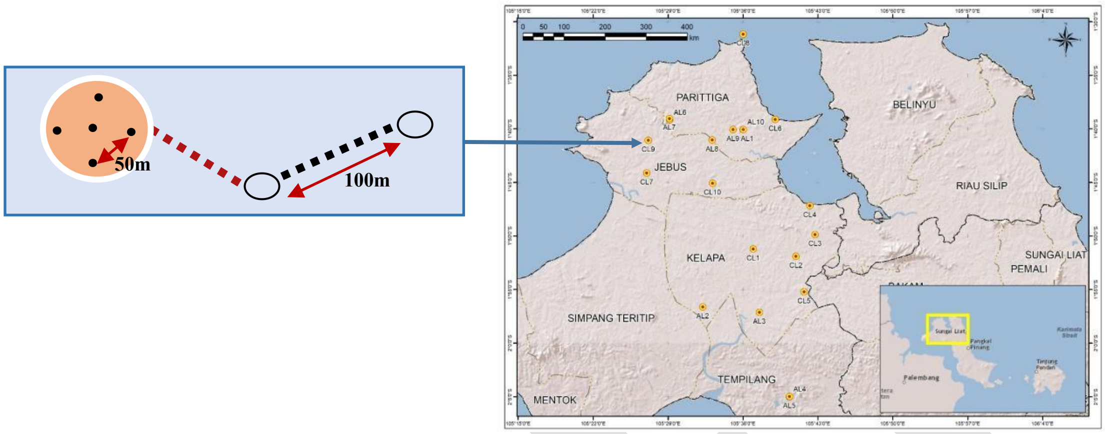

Figure 2. Sampling points

a 1 M KCl solution, using a ratio of 5 g of soil to 25 mL of solution, which are referred to as pH-H2O and pH-KCl, respectively. Exchangeable cations (Ca, Mg, K., and Na) were extracted using a 1 M NH4-OAc solution at pH 7.0. This involved reciprocal shaking and centrifugation with a soil-to-solution ratio of 1:5, and the concentrations were measured with a spectrophotometer. The resultant pellet was washed once with deionized water and twice with 99% ethanol to eliminate excess salt. The ammonium was then extracted using a 10% NaCl solution twice, with reciprocal shaking for 1 hour, followed by centrifugation for 10 minutes at 1,000 rpm. The ammonium ion content was determined as cation exchange capacity (CEC) using the Kjeldahl distillation and titration method. Soil organic carbon content was determined using the Walkley-Black chromic acid wet oxidation method. Total Nitrogen (T-N) was measured by the Kjeldahl method. Available phosphorus (Pi) was extracted using the P-Bray-1 procedure, and the extract was analyzed colorimetrically for available phosphorus using a spectrophotometer set to 660 nm.

2.3. Determination of Soil Degradation Status

The assessment of soil degradation status referred to the Minister of Environment Regulation No. 07/2006, which outlined the procedures for measuring standard criteria for soil degradation related to biomass production. The parameters collected were those related to land and soil, as illustrated in Figure 3. The assessment process consisted of four steps, detailed in Figure 4. The criteria used to evaluate soil characteristics in the soil degradation assessment are listed in Table 1.

All soil characteristics listed in Table 2 were used to calculate the Relative Frequency of Soil Characteristic Degradation (RFSD) using Equation 1. The results of the RFSD calculations were then scored to determine the land degradation status, as shown in Table 3.

Land
- Land-use, Surface rockiness, Vegetation cover and Soil erosion

Soil
- Physics (Soil hardness as a measure soil compaction, Bulk density, Total porosity, and Soil permeabilitas).
- Chemistry (pH, Total N, Available Pi, Exchangeable bases, and CEC).
- Biology (Total mirobial population) and Soil erosion.

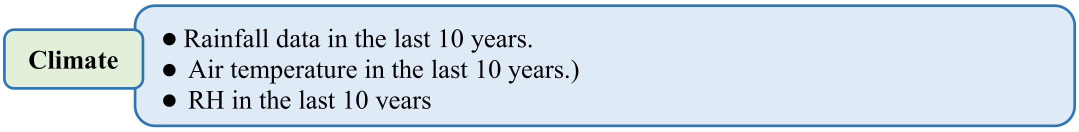

Figure 3. Parameter cluster.

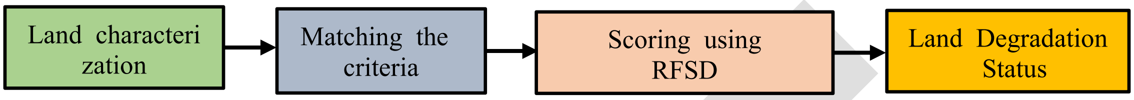

Figure 4. Steps to determine land degradation status.

Table 1. Soil Characteristics for assessing soil degradation and their tThreshold criteria.

No.	Soil Characteristic	Critical Threshold
1.	Soil solum	<20 cm
2.	Soil fraction	<18% Clay; >80% Quartz sand
3.	Bulk density	>1.4 g cm^{-3}
4.	Permeability	<0.7 cm hr^{-1}; >8.0 cm hr^{-1}
5.	$pH_{(H2O)}$ 1:2.5	<4.5; >8.5
Source: Indonesian Government Regulations of the Republic of Indonesia No. 150/2000.		

$$\text{RFSD }(\%) = \frac{X}{Y} \times 100\% \quad \ldots\ldots\ldots \text{(Eq.1)}$$

Where:

RFSD : Relative Frequency of Soil Characteristic Degradation (%)
X : Number of sub-sampling points whose soil characteristics were categorized as degraded.
Y : Total number of sub-sampling points. There 5 sub-sampling points in one sampling point.

Source: The Minister of Environment Regulation of the Republic of Indonesia No. 07/2006 Indonesian Government Regulations of the Republic of Indonesia No. 150/2000.

Table 3. Land degradation status and their symbols based on the RFSD. total soil characteristic degradation score

RFSD (%)	Score	Score	Land Degradation Status
0-10	0	0	Not Degraded
11-25	1	1-14	Slightly Degraded
26-50	2	15-24	Moderately Degraded
51-75	3	25-34	Heavily Degraded
76-100	4	35-40	Extremely Degraded

3. Result and Discussion

In our study, we typically measured soil degradation by evaluating various landscape and soil characteristics. The characteristics assessed to determine the extent of soil degradation included the number of plant species, land cover, and the physical and chemical properties of the soil.

3.1. Landscape Characteristics

Long-term mining operations significantly contribute to deforestation and the loss of plant biodiversity (Sun et al., 2024; Werner et al., 2019). Table 4 shows the number of plant species, vegetation coverage, soil thickness, and surface rockiness across the study sites. Our findings indicate that converting the CSs into the ATMAs had a significant impact ($P < 0.01$) on these four indicators. Specifically, tin mining activities led to a reduction in plant species, with losses ranging from 33.33% to 57.14%. While the CSs supported 6 to 8 species, the ATMAs only contained 3 to 4 species (Table 4). Additionally, a clear shift in vegetation composition was observed. All plant species identified in the CSs were indigenous, including *Durio zibethinus*, *Lansium parasiticum*, *Artocarpus heterophyllus*, *Artocarpus altilis*, *Syzygium aqueum*, *Garcinia mangostana* L., and *Arenga pinnata*. In contrast, the vegetation in the ATMAs consisted solely of invasive species, primarily *Acacia mangium*, *Melastoma* sp., and *Imperata cylindrica*, none of which were present in the CSs.

Table 4. Plant species richness and land coverage at the study sites.

Landscape Characteristics	Sites	Location									
		L.1	L.2	L.3	L.4	L.5	L.6	L.7	L.8	L.9	L.10
Number of plant species	CS	7a	8a	7a	6a	6a	6a	8a	7a	8a	8a
	ATMA	3b	4b	3b	3b	3b	4b	4b	4b	4b	4b
	Changes (%)	-57.14	-50.00	-57.14	-50.00	-50.00	-33.33	-50.00	-42.86	-50.00	-50.00
Vegetation coverage	CS	95a	95a	95a	95a	95a	95a	65a	95a	65a	95a
	ATMA	20b	20b	20b	20b	20b	20b	20b	25b	20b	20b
	Changes (%)	-78.95	-78.95	-78.95	-78.95	-78.95	-78.95	-69.23	-73.68	-69.23	-78.95
Solum thickness (cm)	CS	120a	120a	120a	120a	120a	120.a	97a	92a	100a	100a
	ATMA	15b	15b	15b	15b	7b	15b	15b	15b	15b	12b
	Changes (%)	-87.50	-87.50	-87.50	-87.50	-94.17	-87.50	-84.54	-83.69	-85.00	-88.00
Soil surface rockiness (%)	CS	18.75	0	0	0	0	6.25	0	0	0	12.50
	ATMA	50.00	62.50	56.25	43.75	62.50	62.50	62.50	62.50	56.25	56.25

Note: - = decreases
+ = increases

3.2. Soil Physical Characteristics

Opencast hydraulic tin mining results in both structural and functional changes in soils. These changes include increased soil compaction, reduced water holding capacity, and an imbalanced distribution of soil fractions. To assess the impact of tin mining on soil physical characteristics (SPCs), we examined several indicators, including soil bulk density (SBD), soil penetrability (SP), soil fraction (SF), and soil permeability (SPm). Our findings indicate that converting the CSs into the ATMAs significantly affects SBD, SP, SF, and SPm ($P<0.01$). All SPCs at the ATMAs differed significantly from those at the CSs, as shown in Table 5.

SBD and SP

The SBDs in the ATMAs were significantly higher than those in the CSs. Specifically, the SBDs in the ATMAs ranged from 1.48 to 1.63 g/cm^3, as shown in Table 5. These values exceed the critical threshold for bulk density (greater than 1.4 g/cm^3), indicating that the soil in the ATMAs has experienced compaction. In contrast, the SBDs in the CSs ranged from 0.78 to 1.29 g/cm^3, remaining below the critical threshold. The higher SBD in the ATMAs suggests that the soil in these areas is more compacted compared to the CSs.

FSP

The soils in the ATMAs showed a significantly ($P < 0.01$) lower proportion of fine soil particles (silt and clay) compared to the control sites (CSs). As indicated in Table 5, the clay content in the ATMAs ranged from 0.00% to 7.60%, which is well below the critical threshold of 18%. In contrast, the sand content in the ATMAs increased significantly, ranging from 90.95% to 100%, exceeding the critical threshold of 80% for sand content.

SPm

Soil permeability (SPm) at the ATMAs was significantly faster ($P < 0.01$) than that in the CSs. Specifically, the SPm in the ATMAs ranged from 75.69 to 163.04 cm hr^{-1}, far above the critical threshold of 8.00 cm hr^{-1} for SPm. In contrast, the SPm at the CSs showed a significantly slower SPm, ranging from 8.04 to 33.00 cm hr^{-1} (Table 5). It was still much lower compared to the levels observed at the ATMAs and did not exceed the critical threshold of 8.00 cm hr^{-1}.

The SPm is influenced by various factors, most notably soil bulk density (SBD) and porosity. As previously indicated in Table 5, the SBDs at the ATMAs are significantly higher, ranging from 1.48 to 1.63 g cm^{-3}, compared to those at the CSs, which range from 0.78 to 1.29 g cm^{-3}. This suggests that the soil at the ATMAs is more compacted than that at the CSs.

3.3. Soil Chemical and Biological Characteristics

The chemical and biological components of soil play a crucial role in assessing the degradative effects of open-cast hydraulic tin mining on SQ. In this study, we measured eight soil indicators related to the impact of open-cast hydraulic tin mining on soil chemical and biological characteristics (SCBCs), as detailed in Table 6. These indicators included soil pH, total nitrogen (N-tot.), available phosphorus (Pi), as well as exchangeable potassium (K), calcium (Ca), and magnesium (Mg). We also analyzed soil cation exchange capacity (CEC) and total microbial population (TMP) (Table 6). The results showed that the SCBCs in the ATMAs were significantly lower than those in the CSs, indicating the negative impact of open-cast hydraulic tin mining on soil quality in the study areas.

3.4. Soil Degradation Status

Assessing soil degradation in tin-mining areas requires an integrated approach because the effects on landscape attributes and soil characteristics are interrelated (Bhaduri et al., 2022; Bongiorno, 2020; Ghimire et al., 2023). In this study, a minimum data set was intentionally selected, which includes erosion, solum thickness, soil fraction, bulk density, total porosity, soil permeability, and soil pH. Each chosen indicator was then compared against relevant criteria to calculate the Relative Frequency of Soil Degradation (RFSD). The soil degradation status (SDS) was determined based on the cumulative score of RFSD. These two metrics provide a quantitative assessment of soil degradation: lower values indicate a more stable and

productive soil environment, while higher values signify increased soil disturbance, which can adversely affect soil health and productivity. The results of the soil degradation assessment at the study sites are presented in Table 7.
Changes in landscape attributes, soil physics, soil chemistry, and soil biology, as described previously, collectively contribute to varying states of soil degradation at the study sites. The minimum data values in the ATMAs were significantly lower than those in the CSs and fell below critical thresholds (Tables 4 and 6). As a result, the RFSD values range from 80% to 100% across all locations in the ATMAs (Table 7). These RFSD values correspond to a score of 4 for each measured soil characteristic, indicating that each characteristic is heavily degraded. Consequently, the total RFSD score reaches 32, categorizing the SDS as heavily degraded across the ATMAs (Table 7).

4. Conclusion

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