"Assessment of Soil Erosion, Contamination, and Rehabilitation Potential in Mongolian Mining Regions: A Case Study in the Erdenet Copper and Molybdenum, and Baganuur Coal Mining Areas"

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ZUSAMMENFASSUNG

Der Bergbau spielt eine entscheidende Rolle in der mongolischen Wirtschaft und trägt maßgeblich zum Exporterlös bei. Diese wirtschaftlichen Vorteile gehen jedoch oft mit Umweltverschmutzung einher, insbesondere in Regionen rund um wichtige Bergbaustandorte wie die Baganuur-Braunkohlenmine und die Erdenet-Kupfer-Molybdän-Mine. Diese Studie untersucht die langfristigen Auswirkungen des Bergbaus auf Bodenerosion und -kontamination in den halbariden Steppengebieten der Mongolei, mit dem Ziel, Einblicke in das Ausmaß der Degradation zu liefern und Strategien zur Milderung und Sanierung vorzuschlagen.

Die Studie quantifiziert Bodenerosionsraten in Bergbauregionen unter Verwendung des modifizierten universellen Bodenabtragsmodells (RUSLE), von Fernerkundungsdaten und bodenbasierten Beobachtungen, die sich über fast drei Jahrzehnte erstrecken (1989-2018). Dabei konnte festgestellt werden, dass ein klarer Zusammenhang zwischen Niederschlagserosivität und Bodenerosion besteht, besonders im Juli 2018 die Erosion in beiden Untersuchungsgebieten einen Höhepunkt - 7,88 t ha^{-1} $Monat^{-1}$ im Erdenet-Gebiet und 9,46 t ha^{-1} $Monat^{-1}$ im Baganuur-Gebiet - erreicht hat. Darüber hinaus unterstreicht die räumliche Verteilung der Erosion lokale Auswirkungen in der Nähe von Bergbaustandorten und angrenzenden Industriezonen. Die hohen Abtragungsleistungen der Erosion führten aufgrund der bergbaulichen Aktivitäten zu Bodenkontaminationen mit Schwermetallen und Metalloiden (HMM), die ökologische und gesundheitliche Risiken darstellen. Verschiedene Indizes wie der potenzielle ökologische Risikoindex (RI), der integrierte Nemerow-Verschmutzungsindex (P_{IN}) und der Geoakkumulationsindex (Igeo) werden verwendet, um die Kontaminationsniveaus der Böden zu bewerten. Die Ergebnisse zeigen erhöhte Konzentrationen von Elementen wie Zn und As im Bergbaugebiet Baganuur sowie erhöhte Kornzentrationen an Cu, Cr und Zn im Bergbaugebiet Erdenet, die den maximal zulässigen Grenzwert (MPL) des mongolischen Bodenqualitätsstandards (MNS 5850:2019) überschreiten. Dies unterstreicht die dringende Notwendigkeit von Bodensanierungsinitiativen zur Renaturierung von Umwelt- und Gesundheitsrisiken. Neben der Bodendegradation haben Bergbauaktivitäten breitere Umwelt- und sozioökonomische Folgen. Die Studie bewertet diese Auswirkungen und betont die Bedeutung von wissenschaftlich fundierten Renaturierungsplänen und der robusten Umsetzung von Umweltvorschriften im Einklang mit den Zielen für nachhaltige Entwicklung der Vereinten Nationen (UN-SDGs). Kontinuierliche Umweltbewertungen und Sanierungsinitiativen werden unterstützt, um die langfristige Nachhaltigkeit des mongolischen Bergbausektors zu gewährleisten und sowohl natürliche Ökosysteme als auch lokale Gemeinschaften zu schützen. Basierend auf den Studienergebnissen ergeben sich mehrere Empfehlungen zur Renaturierung der Bodendegradation und zur Förderung nachhaltiger Bergbaupraktiken in der Mongolei. Dazu gehören:

- Umsetzung von Maßnahmen zur Erosionskontrolle wie vegetativer Deckung und Terrassierung, um Bodenerosionsraten in Bergbauregionen zu reduzieren.
- Übernahme von Bodensanierungstechniken, einschließlich Phytosanierung und chemischer Stabilisierung, um Bodenkontaminationen zu bekämpfen und die Gesundheit des Ökosystems wiederherzustellen.
- Stärkung der Umweltvorschriften und Durchsetzungsmechanismen, um die Einhaltung nationaler Standards sicherzustellen und verantwortungsbewusste Bergbaupraktiken zu fördern.
- Integration von Umweltüberlegungen in die Bergbau- und Betriebsprozesse, wobei die Bedeutung kontinuierlicher Umweltauswirkungsbeurteilungen und -überwachungen betont wird.

Durch das umfassende Verständnis der Treiber und Konsequenzen von Bodenerosion und -kontamination können Stakeholder wie Bergbauunternehmen, Regierungsbehörden, lokale Gemeinschaften und Umweltorganisationen gemeinsam wirksame Renaturierungsstrategien entwickeln und umsetzen. Dieses gemeinsame Engagement zielt darauf ab, die langfristige Nachhaltigkeit des mongolischen Bergbausektors und das Wohlergehen seiner Bewohner und der Tierwelt zu gewährleisten, und fördert gleichzeitig eine nachhaltige Entwicklung.

SUMMARY

Mining plays a vital role in Mongolia's economy, contributing significantly to export revenue. However, this economic benefit often comes at the cost of environmental degradation, particularly in regions surrounding major mining sites like the Baganuur lignite mine and the Erdenet copper-molybdenum mine. This study examines into the long-term impacts of mining on soil erosion and contamination in Mongolia's semi-arid steppe zones, aiming to provide insights into the extent of degradation and propose strategies for mitigation and rehabilitation.

The study quantifies soil erosion rates in mining regions utilizing the Revised Universal Soil Loss Equation (RUSLE) model, remote sensing data, and ground truth observations spanning nearly three decades (1989-2018). Results show a clear correlation between rainfall erosivity and soil erosion, particularly noting peak erosion in July 2018 in both study areas reaching 7.88 t $ha^{-1}month^{-1}$ in the Erdenet area and 9.46 t $ha^{-1}month^{-1}$ in the Baganuur area. Additionally, the spatial distribution of erosion underscores localized impacts near mining sites and adjacent industrial zones. In addition erosion due to mining activities have led to soil contamination with Heavy Metals and Metalloids (HMM), posing ecological and health risks. Various indices such as the Potential Ecological Risk Index (RI), Nemerow Integrated Pollution Index (PI_N), and Geoaccumulation index (I_{geo}) are used to assess contamination levels of the soils. Findings reveal elevated concentrations of elements such as Zn and As in Baganuur mining area and elevated concentrations of Cu, Cr, and Zn in Erdenet mining area. This concentrations exceed Maximum Permissible Level (MPL) of Mongolian Soil quality standard (MNS 5850:2019), particularly in proximity to mining and industrial areas. This underscores the urgent need for soil rehabilitation initiatives to mitigate environmental and health hazards.

Beyond soil degradation, mining activities have broader environmental and socioeconomic consequences. The study evaluates these impacts, emphasizing the importance of science-based rehabilitation plans and robust implementation of environmental regulations aligned with United Nations Sustainable Development Goals (UN SDGs). Continuous environmental assessments and rehabilitation initiatives are supported to ensure the long-term sustainability of Mongolia's mining sector, safeguarding both natural ecosystems and local communities.

Based on the study findings, several recommendations emerge for mitigating soil degradation and promoting sustainable mining practices in Mongolia. These include:

- Implementation of erosion control measures, such as vegetative cover and terracing, to reduce soil erosion rates in mining regions.
- Adoption of soil remediation techniques, including phytoremediation and chemical stabilization, to address soil contamination and restore ecosystem health.
- Strengthening of environmental regulations and enforcement mechanisms to ensure compliance with national standards and promote responsible mining practices.
- Integration of environmental considerations into mine planning and operation processes, emphasizing the importance of continues environmental impact assessments and monitoring.

By comprehensively understanding the drivers and consequences of soil erosion and contamination, stakeholders such as mining companies, government agencies, local communities, and environmental organizations can collaboratively devise and implement effective mitigation and rehabilitation strategies. This concerted effort aims to ensure the long-term sustainability of Mongolia's mining sector and the well-being of its inhabitants and wildlife, all while promoting sustainable development.

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1 INTRODUCTION

1.1 Rationale

Especially since the last few decades, Mongolia has been facing with a increasing environmental degradation issues such as soil erosion, desertification, and various forms of pollution. This alarming situation is attributed to both climate change and anthropogenic activities, including mining, overgrazing, agriculture, urbanization, and off-road transportation (Lehmkuhl and Batkhishig, 2003; Knippertz, 2005; Karthe et al., 2014, 2017; Timofeev et al., 2016; Kosheleva et al., 2018; Han et al., 2021). Among various industrialization processes, in particular irregular mining has a negative impact on environmental degradation. Farrington et al. (2005) and Dagys et al. (2020) highlighted that despite the mining sector being crucial for Mongolia's economic development through revenues from mineral exports mainly coal, gold, and copper, it has unfortunately emerged as a primary driver of environmental degradation. This impact is notably reflected in the estimated total damaged land area within the country's mining regions, reaching approximately 8.1 thousand hectares (ha) (Batmunkh, 2021). According to the Mineral Resources Petroleum Authority of Mongolia (2020), extensive areas, covering around 4.6% of Mongolia's territory, are adversely affected by mining activities, supported by over 2,700 valid mining licenses. The accumulation of heavy metal substances in the soils primarily results from anthropogenic activities, including mining, agricultural industrial processes, air dust due to traffic, overburden dump and mining process, domestic emissions, heavy industry, and chemical manufacturing (Knippertz, 2005; Hu et al., 2013; Pusz et al., 2021; Rasulov et al., 2013; Wang et al., 2020). Mining activities contribute significantly to the elevated presence of heavy metals in river loading, leading to bioaccumulation in plants and freshwater fish species, thereby posing ecological risks and public health concerns (Karthe et al., 2017; Jarsjö et al., 2017; Kaus et al., 2017; Kosheleva et al., 2018; Nottebaum et al., 2020). Furthermore, detailed studies of mining effects on water resources has addressed significant challenges such as water scarcity, ground and surface water pollution (Timofeev et al., 2016; Batbayar et al., 2017; Jarsjö et al., 2017; Nottebaum et al., 2020; Schoderer et al., 2021). Despite this focus, there has been a notable gap in assessing mining-related erosion and exploring the complicated connections between soil erosion and soil pollution (Sodnomdarjaa et al., 2023). For instance, numerous studies have conducted into the sources and impacts of sediments in the Mongolian river system, pinpointing high livestock densities along the rivers as a central challenge (Hartwig et al., 2016; Theuring et al., 2015). Onda et al. (2007), Kato et al. (2010), and Batkhishig et al. (2019) utilized cesium-137 radionuclides to measure soil erosion and sediment accumulation. Batkhishig et al. (2019) found that in the non-mining impacted mountainous area (Ikh Bogd Mountains), the average soil erosion rate was 12.57 ± 1.08 t ha^{-1} $year^{-1}$, reaching a maximum of 40.87 t ha^{-1} $year^{-1}$, primarily attributed to precipitation as the main driver of increased erosion. In mining regions, the creation of barren lands, mine tailings, and stored overburdens has resulted in heightened erosion, especially during the rainy season (Kayet et al., 2018). Some authors, including Khishigjargal et al. (2015), have mentioned concerns about mining's contribution to land degradation, while others, like Batkhishig (2013), have observed a substantial expansion of soil erosion due to mining activities. Previous studies have predominantly concentrated on soil and water contamination. However, there is a notable scarcity of research addressing soil erosion, especially in mining regions. In the Tuul river basin in central part of Mongolia, Jarsjö et al. (2017) utilized the WATEM/SEDEM model to quantify the input of metal-contaminated sediments from the Zaamar Goldfield mining area into the river system. Their findings indicated that mining activities significantly exacerbate natural soil erosion, with a reported soil loss rate of 10 t km^{-2} $month^{-1}$ around the mining area, and highlighted that these soil losses contribute to the transport of pollutants within and around the mining area. Especially, soil losses in the vicinity of mining sites has resulted in the dispersion of contaminants throughout the environment, facilitated by factors such as rainfall, and anthropogenic influences (Sodnomdarjaa et al., 2023). Heavy Metals and Metalloids (HMM) contamination spread outs from mining dumps, tailings storage facilities, and other accumulated pollution generated by mining processes. Additionally, soils contaminated with HMM can lead to decreased fertility, emerging as a primary cause of heightened soil degradation (Lehmkuhl and Batkhishig, 2003; Knippertz, 2005). In the pursuit of sustainable development for Mongolia's mining sector, particularly considering its substantial global ranking as the seventh-largest mineral and ore producer by 2012 (Hatcher, 2016), strategic prioritization of environmental sustainability is crucial. Considering the ongoing and future importance of the mining sector in Mongolia's economic landscape, there is an urgent importance to conduct thorough investigations and closely monitor environmental degradation. Highlighting the crucial necessity for accurately estimating soil erosion in Mongolia, particularly in mining regions, Batkhishig (2013) points out a knowledge gap regarding the spatiotemporal pattern of erosion and the differentiation of predominant driving factors, underscoring the essential for comprehensive research and monitoring efforts in this area. Although recent studies have addressed mining-related environmental degradation and contamination in Mongolia (Pecina et al., 2023), there remains a notable gap in providing a comprehensive overview of the mining impacts on HMM soil pollution. This knowledge deficit poses challenges in prioritizing national-level mitigation measures, as it relies on a thorough understanding of pollution and the associated ecological risks (Rong et al., 2022) stemming from exposure to contaminants in soil, water, air, and sediments (Saha et al., 2022).

1.2 Objectives and outline

The primary objective of this dissertation is to quantify and evaluate the spatiotemporal patterns of soil contamination and erosion in Erdenet and Baganuur, two open-pit mining cities in Mongolia, known for their significance in the country's mining sector. Special priority is placed on the areas surrounding the open-pit mining sites, utilizing remote sensing and in-situ based data during the period from 1989 to 2018. The research is structured around three primary objectives, each aimed at addressing crucial questions within the mining regions:

1. What is the primar source contributing to the increases of soil erosion and contamination around the open-pit mining sites in the cities of Erdenet and Baganuur? This objective seeks to understanding the primary sources responsible for the intensify of soil erosion and contamination around mining sites. Through an analysis of the factors contributing to these environmental challenges, the research aims to provide a detailed understanding of the forces driving soil degradation within the study areas.
2. What is the correlation between contamination and distance in the mining cities of Erdenet and Baganuur? The second objective is to investigate the relationship between soil pollution and the distance to potential sources of pollution. By analyzing the obtained data, the research Through the examination of the data, the research aims to determine whether these two characteristics are connected or operate independently. Understanding such relationships is crucial for formulating effective strategies to reduce the adverse effects on soil quality.
3. Can rehabilitation plans be formulated effectively by considering the overlapping spatial distribution of soil erosion and contamination in the mining cities of Erdenet and Baganuur? The third goal is focused on exploring the possibility of creating rehabilitation plans based on the spatial distribution of soil erosion and contamination in the study regions. By identifying and mapping the areas most impacted by these environmental challenges, the research aims to derive site specific rehabilitation strategies. This contributes to a more sustainable and environmentally conscious approach to mining activities, particularly at the Erdenet copper-molybdenum mine site.

The dissertation consists of eight main chapters designed to address the above mentioned questions and present the following findings.

Chapter 1 introduces the primary reasons for conducting this research, highlighting the importance of defining soil erosion and contamination. It outlines the main goals guiding the research toward a thorough understanding of the issues. This chapter serving as an introductory framework, providing a clear guide for moving through the following chapters of this dissertation.

Chapter 2 outlines the evolution of Mongolia's mining sector from its inception to the present day, emphasizing key milestones such as the establishment of geological research, substantial contributions to the country's economy, and the attraction of foreign investment through legal frameworks. The chapter also brings attention to environmental challenges, including water and soil contamination, water scarcity, underscoring the urgency for sustainable practices. It concludes by introducing interconnected issues such as agriculture, workforce dynamics, health, and gender equality, laying the foundation for further exploration.

Chapter 3 introduces the Erdenet copper and molybdenum mine and the Baganuur lignite mine in Mongolia, highlighting their significant contributions to the country. The chapter references previous studies focusing on soil erosion, heavy metals and metalloids content, and contamination zones. It examines the economic impact, workforce dynamics, and environmental challenges of both mining operations. Additionally, it emphasizes the crucial need for sustainable mining practices and immediate rehabilitation measures, underscoring the importance of continuous support, research, and community collaboration to ensure effective environmental management.

Chapter 4 describes the process of data collection, fieldwork, and data analysis. The Revised Universal Soil Loss Equation (RUSLE) is introduced for assessing soil erosion on a broader scale using remote sensing and long-term data. Additionally, the chapter discusses the use of geochemical indices for soil quality evaluation. It highlights the study's alignment with United Nations Sustainable Development Goals (UN SDGs) for mining and rehabilitation, focusing on the importance of transparency, stakeholder engagement, and environmental concerns in the rehabilitation mine sites.

Chapter 5 focuses on soil degradation in the oldest and biggest open-pit mining sites in Mongolia such as Erdenet copper-molybdenum and Baganuur lignite coal mines, using the Revised Universal Soil Loss Equation (RUSLE) model at three-year intervals from 1989 to 2018, focusing on spring, summer, and fall seasons. Rainfall erosivity and mining activities are identified as key factors, with the highest erosion rates in both study areas. The integrated approach of the RUSLE model, remote sensing data, and GIS proves cost- and time- effective for monitoring for larger scale area and facilitating effective planning of preventive actions in mining areas, despite some limitations.

Chapter 6 addresses soil contamination in the Erdenet copper-molybdenum and Baganuur lignite coal mines. The study uses the Potential Ecological Risk Index (RI), Nemerow Integrated Pollution Index (PI_N), and Geoaccumulation Index (I_{geo}) to assess concentrations of Ni, Cu, Zn, As, Cr, and Pb. The analysis includes three analytical methods: portable X-ray fluorescence (pXRF) at the German-Mongolian Institute for Resources and Technology in Mongolia for the initial assessment of all 98 soil samples from both study areas; stationary X-ray fluorescence (sXRF) at RWTH Aachen University's Laboratory for 48 samples from the same set; and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) at the SGS laboratory in Mongolia for an additional 36 soil samples near the initial sampling points, considering the stream network line from the open-pit mine site (both study areas) and the tailings storage facility (Erdenet mining area). The research reveals a predominantly low level of contamination; however, it highlights notable elevations in specific elements. For instance, concentrations of As and Zn are 2.8-3.0 times greater in the Baganuur mine area, while Cu is 8 times higher than the MPL of the national standard, particularly in the mining and industrial zones. Approximately 3.6-4.9% of Baganuur area and 3.1-4.9% of Erdenet area show high pollution levels based on PI_N. The findings stress the crucial need for soil rehabilitation, essential for Mongolia's economic growth and environmental stability. The lack of documented rehabilitation initiatives emphasizes the immediate necessity for enhanced environmental responsibility in the expanding and developing mining sector in the country.

Chapter 7 examines into the environmental and socioeconomic impacts of mining activities in Mongolia, with a focus on Erdenet copper and molybdenum mine. The study identifies land degradation issues, including land cover change, soil erosion, and heavy metal contamination, stemming from inadequate mine land rehabilitation practices. The analysis highlights the need for continued environmental assessments, science-based mitigation plans, and improved implementation of laws and regulations, aligning with UN SDGs. The study highlights the significance of addressing soil erosion and contamination, especially in areas around tailings storage facilities (TSF) and industrial zones. Exceedances of Cu, As, and Cr than the MPL of the national standard are highlighted, particularly near mining sites and residential areas. The study reveals the contribution of Cu production to environmental degradation, essential mitigation measures were recommended. These recommendations include chemical stabilization, phytoremediation for soil contamination, and reforestations. Ongoing environmental assessments, adherence to laws and UN SDGs, and a "Climate change adaptation and mitigation plan" are crucial for successful rehabilitation. The chapter underscores the importance of prioritizing rehabilitation efforts, deepening soil erosion analysis, and enhancing environmental monitoring for sustainable development and mitigating environmental concerns in the Erdenet mining area.

Chapter 8 addresses to effectively tackle the three key questions concerning soil erosion, contamination, and rehabilitation strategies in Mongolia's major open-pit mining sites: 1) The primary sources identified as contributing to soil erosion and contamination include intensified rainfall and human activities, particularly mining activities and industrial operations. 2) Significant correlations are found between contamination levels and proximity to mining sites, with elevated levels of heavy metals and metalloids were observed closer to the mining areas. 3) Despite existing rehabilitation efforts, there is a scarcity of research on effective rehabilitation plans, highlighting the need for sustainable practices aligned with the UN SDGs. Future studies should focus on exploring pollution and rehabilitation methodologies within Mongolia's mining sector.

1.3 A brief introduction about the PhD sandwich program

This program, introduced in December 2018, represents a unique initiative aimed at enhancing the capabilities of young academic lecturers and researchers at the German-Mongolian Institute for Resources and Technology (GMIT) in Mongolia. The initiative enables participants to pursue a Doctoral degree with integrated research opportunities in partner universities in Germany, facilitated through collaboration with the German Academic Exchange Service (DAAD). Referred to as the "sandwich model" the program involves dual supervision by a GMIT professor and an academic adviser at the host institute in Germany. The announcement indicated that the research phases of the call will be conducted at GMIT's German partner universities, including TU Bergakademie Freiberg and RWTH Aachen University. The program facilitates stays at German universities for a duration of up to six months per year over the course of three years.

This doctoral research's topic was approved by both supervisors, Prof. Dr. Frank Lehmkuhl, the supervisor from the Department of Geography at RWTH Aachen University, and Prof. Dr. Daniel Karthe, former Environmental Engineering Professor at German-Mongolian Institute for Resources and Technology (GMIT). The PhD research study began with the field studies conducted in the Baganuur and Erdenet mining areas in June and September in 2020. Throughout the study, regular meetings with supervisors were conducted every 14-21 days to seek guidance and instructions regarding the progress of laboratory results, studies, and writing. Currently, three papers were produced during this period.

1. "Assessment of soil loss using RUSLE around Mongolian mining sites: a case study on soil erosion at the Baganuur lignite and Erdenet copper-molybdenum mines" published in the Environmental Earth Sciences journal on April 27th, 2023.

2. "Resource Conundrum in Mongolia: Soil contamination from coal and copper-molybdenum mining" published in Soil Use and Management on February 22th, 2024.

3. "Aligning Erdenet copper-molybdenum mine rehabilitation with SDGs by mitigating soil erosion and contamination" submitted to an international journal on April 22nd in 2024.

2 ENVIRONMENTAL ISSUES IN MINING REGIONS OF MONGOLIA

2.1 Overview of the mining industry

Mongolia’s offical mining sector commenced in 1922 with the establishment of its first mining industry, Nalaikh coal mine (WMC, 2022). This event stands as a crucial milestone, playing a vital role in establishing the foundations for the expansive development of Mongolia’s mining industry. Geological research in Mongolia began in 1923 with a group led by Rachkovsky, a scientist from the Russian Academy of Sciences. In 1925, the “Mongolian Commission of Geological Survey” for organizing geological research in Mongolia was created by Komarov, the president of the Russian Academy of Sciences. This step led the fundamental work for a more structured and cooperative approach for understanding the geological features of Mongolia. Beginning from this period, Russian geologists conducted surveys to systematically collect essential data on geological formations, minerals, and underground water sources in the eastern and southern regions of Mongolia. This effort led to the successful identification of numerous deposits of iron, coal, lead, copper, and zinc minerals. In 1938, the Department of Geological Research Institute was established in Mongolia, beginning of the first generation of the countries geologists, taking on all aspects of geological research and analysis under the guidance and trainings provided by Russian scientists. Since then, Mongolia has observed a notable increase in both the intensity and scope of geological research and exploration activities. During the period from the 1960s to the 1990s, major mining operations, including the Erdenet copper-molybdenum mine, Baganuur coal mine, Bayanteeg coal mine, Khar Tarvagatai coal mine, Ulaan Tsair lead mine, Shariin-Gol coal mine, and Bor-Undur ore mine, were established. These industries played a crucial role in Mongolia’s economy. In the early 1990s, the government stopped spending funds for geological exploration and relevant research, as well as cut support for light and heavy industries due to the country’s transition from a centrally planned economy (a communist state) to a market-based economy. As a result, numerous of geological research institutes specializing in exploration and relevant scientific investigations, alongside associated industries underwent closure (MRPAM, 2011). In response, the Mongolian government introduced new legal frameworks in the mid-1990s to standardize neoliberal procedures and governance, giving priority to large-scale mining over small-scale and informal mining. The primary focus was on establishing a stable legal foundation to facilitate the development of the mining sector, including exploration and the attraction of foreign investment. These measures included enacting specific laws, such as the Minerals Law in 1997 (which was amended later in 2017) and the Foreign Investment Law in 2002, by recommendations from international financial institutions such as the World Bank, Asian Development Bank, and the International Monetary Fund (Hatcher, 2016). This shift provided the foundation for foreign companies to commence investments in Mongolia's mining sector. In the early 2000s, there was a remarkable and rapid growth in the production and investment of mining products. A significant milestone occurred in 2009 with the commencement of operations at the Oyutolgoi copper-gold mine and Tavantolgoi coal mine, representing a crucial advancement in Mongolia’s economic development (MRPAM, 2011). By 2012, Mongolia ranked the seventh-largest mineral and ore producer in the world, with mining contributing to 30% of the country’s GDP (Hatcher, 2016). These positive changes had a significant impact on the country’s economic development, as evidenced by the mining sector contributing 25% to the annual Gross Domestic Product (GDP), 87% to exports, 72% to industrial production, and 75% to foreign direct investment (FDI) (Krusekopf, 2023). Furthermore, the stable operation of the Erdenet copper-molybdenum mine since 1978 played a notable role in these positive economic changes. Noteworthy achievements include its contribution of 7.5% to the country’s GDP and 12.5% to total exports in 2017 (erdenetmc.mn).

Mongolia has a diverse mineral landscape, including over 500 deposits and 6,000 mineral occurrences spanning 80 different mineral commodities (Lkhamsuren et al., 2002), with prominent resources including copper, molybdenum, gold, coal, silver, fluorspar, iro ore, phosphate, zinc, and rare earth elements (Gerel et al., 2021). As of 2023, the Mongolian Mineral Resources and Petroleum Authority reported a total of 2,680 valid mining and exploration licenses, covering

4.2% of the country's total territory. Among these, 1,714 licenses are dedicated to mining, including various deposits such as 26.8% for gold, 17.8% for coal, 12.5% for fluorite, 5.4% for gold ore, 4.7% for iron, 4.7% for limestone, 1.9% for tungsten, 1.1% for copper, 0.5% for molybdenum, 0.5% for rare earth elements and others, while 966 licences are dedicated for exploration purposes (MRPAM, 2023). In Figure 2.1, the mining licensed area and main producing provinces in Mongolia are shown.

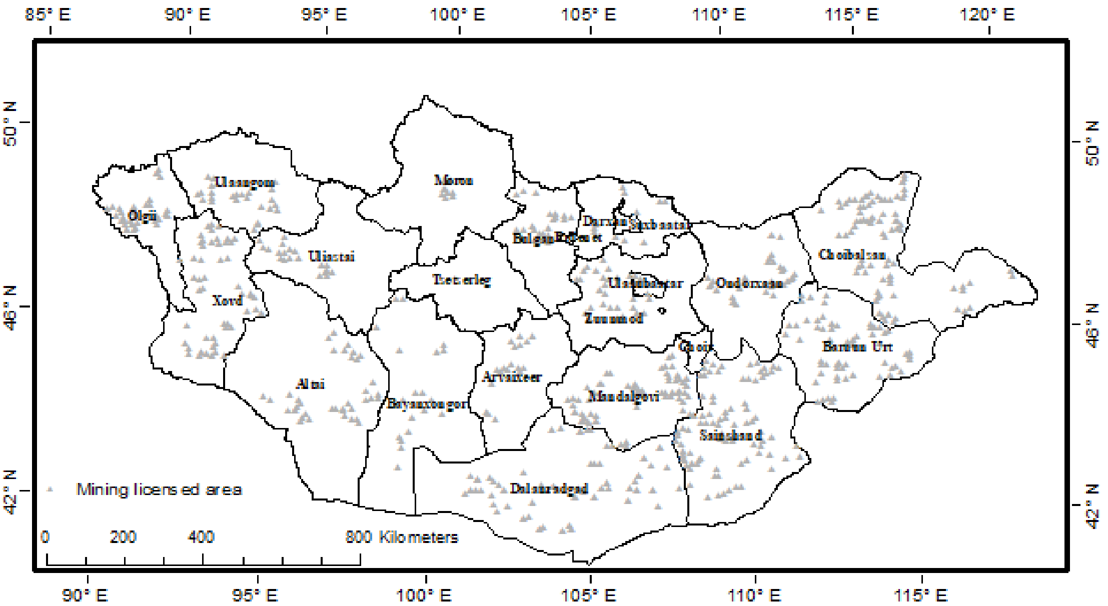

Figure 2.1 The licensed mining areas and primary producing provinces in Mongolia (MRPAM, 2020; Sternberg and Ahearn, 2023)

Foreign Direct Investment (FDI) is vital for Mongolia's economic growth and stability. In recent years, the country has been successful in attracting FDI, reaching a record high of 2.3 billion USD in 2019, with its 80% for the mining sector. However, in 2020 during the COVID-19 pandemic period severely impacted Mongolia's economy, leading to a 41% drop in FDI inflows. This decline underscores the importance for Mongolia to diversify its sources of FDI and invest in various sectors to make the economy stronger and less affected by unexpected events on the economy (Interesse, 2023). The leading investors in Mongolia's mining sector include the Netherlands (46%), China (18%), Luxembourg (4.3%), Japan (3.5%), the USA (2.4%), Great Britain (2.3%), Australia (2.1%), and several other countries, including Canada, Germany, France, South Korea, contributing to a total of 21.4% of the FDI in 2023, as reported by the National Statitistical Information in 2023 (NSO, 2023). Main destinations for Mongolian exports include China and Switzerland, representing 79.7% of the total exports went to China, distinguished by 63% is coal, 18.2% is copper, and 15% of the total exports were directed to Switzerland, predominantly consisting of 99.9% gold (NSO, 2023).

2.2 Environmental issues related to mining regions

Despite being a crucial pillar of Mongolia's economy, the mining sector has been associated with various environmental challenges, such as water pollution, water scarcity, soil contamination, erosion, air pollution, and deforestation. Furthermore, public health issues are arising as a significant concern in mining regions (Kosheleva et al. 2010; Timofeev et al. 2016; Karthe et al. 2017; Jarsjö et al. 2017; Pecina et al. 2023).

Mongolia has ecologically sensitive environments, characterized by a subarctic climate, featuring extended winters and short summers, alongside low annual precipitation levels ranging from 50 mm in the southern Gobi Desert to over 500 mm in the northern mountainous regions (Lee et al., 2019). Given the restricted and irregular precipitation distribution across the Gobi and steppe regions, which encompass 69% of the country's total territory, surface water is scarce, groundwater recharge is limited, and water quality remains inadequate for supply purposes (Batsukh et al., 2012). The country's total water resource is approximately 600 km^3, distributed as follows: 82.1% in lakes, 10.3% in glaciers, 5.7% in rivers, and 1.9% in groundwater (Batnasan, 2003; Batsukh et al., 2012). Surface water accounts for 78% of the total, with groundwater sources contributing the remaining 22%. Nonetheless, groundwater resources persist as a crucial water source, supplying over 80% of the Mongolia's total water consumption (Batsukh et al., 2012; World Bank, 2021).

Mongolia's agricultural sector stands as the primary consumer of water, accounting for 54% of the country's total water demand, while mining operations represent 13%. Over the last two decades, the South Gobi region of Mongolia has witnessed significant mining activities, notably in copper and gold extraction. However, this region faces with the challenge of limited surface water resources, heavily relying on groundwater to fulfill its needs. Projections indicate that mining activities will increasingly become a significant consumer of water resources in the future (Fan, 2020). According to the national statistic, the mining industry accounted for 12.6% of Mongolia's total water demand in 2022 (NSO 2023). The impact of mining activities, as highlighted in the findings by Sternberg et al. (2022), extends to the depletion of shallow groundwater and the disappearance of springs and surface-level water, furthermore, despite notable recycling efforts by mining industries in the country, the slow recharge of groundwater, attributed to low precipitation and high evapotranspiration, has resulted in ecological imbalances (IESC, 2023). Water scarcity and pollution, increasingly prevalent in mining regions, have negatively effects on surrounding environments, including soil, air, living organisms, and human health. For instance, in the vicinity of mining operations in Baganuur coal mining and Erdenet copper-molybdenum, elevated concentrations of heavy metals and metalloids exceeding the Maximum Permissible Level (MPL) set by the national soil quality (MNS 5850:2019) and water quality (MNS 4586:1998) standards were detected in both water and soil, particularly in close proximity to the tailings storage facility and mine sites (Kosheleva et al., 2010; Battogtokh et al., 2014; Timofeev et al., 2016; Karthe et al., 2017; Jarsjö et al., 2017; Tsetsgee et al., 2021; Park et al., 2022; Narangaravuu et al., 2023). Furthermore, irresponsible and small-scale mining operations, particularly in gold mining operations in Mongolia, significantly contribute to elevated concentrations of heavy metals in river systems. In the northern part of the country, in the Zaamar gold mining area, soils show heightened levels of As, Sr, Mn, V, Ni, Cu, and Cr. These heavy metal-contaminated soils were eroded due to an intensified natural erosion process and subsequently flowed into the Tuul river, resulting in the detection of heavy metals in the river (Jarsjö et al., 2017). Sodnomdarjaa et al., (2023) observed an increased soil erosion rate in the vicinity of mining and industrial zones, including both the Erdenet copper-molybdenum and Baganuur coal mining operations. While precipitation remains the primary factor contributing to increased erosion, the proximity to mining areas raises concerns. Erosion near mining sites has the potential to flow into river systems, leading to the dispersion of heavy metals and metalloids contamination originating from tailings and other mining waste into the surrounding environments. Moreover, road erosion stands as a major contributor to land degradation, although precise data on road erosion are unavailable. This erosion is directly linked to the escalating number of vehicles, particularly heavy machinery used in mining, which proves to be highly destructive in terms of soil erosion, underscoring the crucial need for accurate estimation (Batkhishig, 2003). Also, the operation of heavy driving tracks generates dust in mining regions, particularly during the transportation of coal to China on unpaved dirt roads. The absence of paved roads can initiate erosional processes and serve as source material for dust transport (Sternberg, 2023). In mining operations, particularly in copper mining regions like the Erdenet mining area, one of the most concerning issues involves the escalation of "white dust" originating from the tailings storage facility (TSF) surrounding the mining site. Despite efforts by the Erdenet mining operation to address this problem through the implementation of mitigation measures, visible improvements have been limited. Studies have identified significant contamination of both ground and surface water in downstream areas near the TSF (Battogtokh et al., 2014; Solongo et al., 2021). The incidence of white dust intensifies notably during dry conditions, especially in warm seasons, posing environmental and health concerns (Lkhagvajargal et al., 2018).

The complex challenges stemming from Mongolia's mining sector, including water pollution, scarcity, soil contamination, and other environmental degradations, bring the critical importance of implementing comprehensive and sustainable practices to reduce the ecological disruptions in the country's mining regions. Addressing these challenges requires using different approach. Firstly, there is a pressing need to prioritize sustainable water management strategies, given that Mongolia's agriculture sector is the primary water consumer, and mining is also becoming a major water consumer. This requires implementing efficient water usage methods, promoting responsible water consumption in mining operations, and investing in technologies that enhance water recycling and conservation. Additionally, measures must be implemented to tackle soil erosion caused by mining activities, particularly heavy machinery and road networks. Paving roads, controlling dust emissions, and adopting erosion prevention techniques can significantly mitigate the adverse impacts on soil quality and prevent the dispersion of contaminants into surrounding environments (Batkhishig, 2003). Furthermore, regulatory frameworks should be strengthened to ensure responsible mining practices, with a focus on minimizing the release of pollutants. Strict enforcement of environmental standards, continuous monitoring, and transparent reporting mechanisms can contribute to mitigating the environmental impact of mining activities. In conclusion, the urgency to adopt sustainable practices in Mongolia's mining regions requires a comprehensive strategy that addresses water management, soil conservation, and strict regulatory implementation.

2.3 Highlighting social and economic challenges

The mining sector has become a cruical part of the economy in Mongolia. Its contribution is 2.4 times higher than the agriculture sector, and consisting 27% of the total Gross Domestic Product (GDP) in 2023 and Figure 2.2 illustrates the composition of Mongolia's GDP by primary sectors in 2023 (NSO, 2023). Examining the social and economic challenges within Mongolia's mining sector shows a complicated influenced by various factors. The following outlines the primary effects and results influenced by the mining sector over the last two decades.

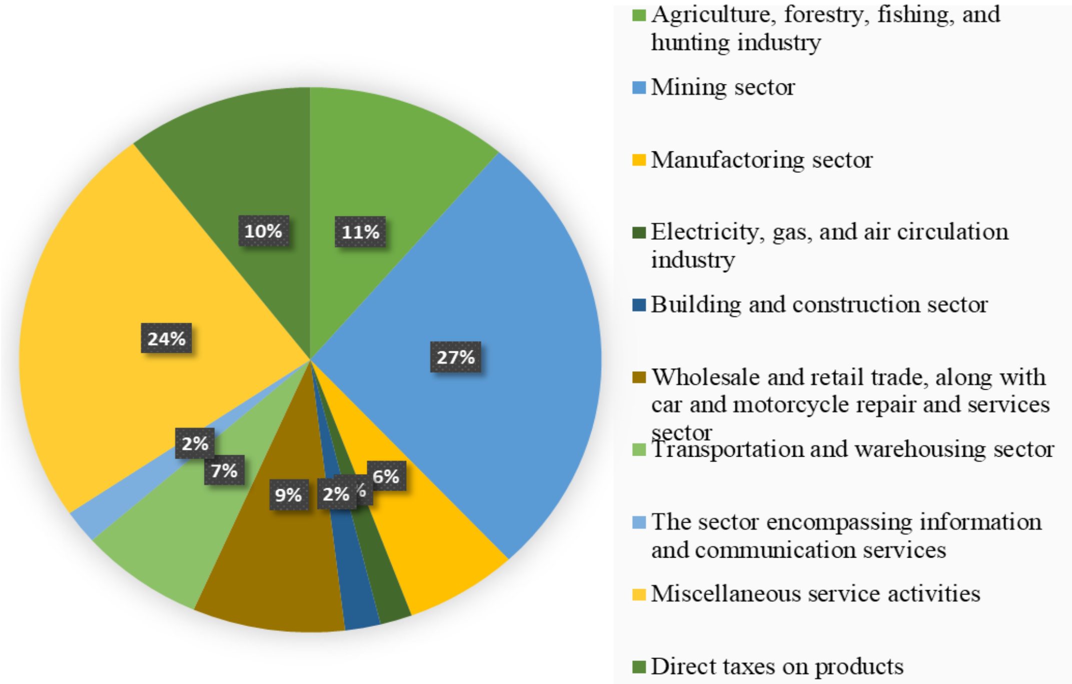

Figure 2.2 Mongolia's GDP by primary sectors in 2023 (NSO 2023)

2.3.1 Impact on the agricultural sector

In 2023, the national statistics reported that around 15% of Mongolia's total workforce is involved in the mining sector including its main activities of mining, processing, and transportation. The continuous growth of the mining industry has resulted in an annual expansion of the workforce in this sector. Since 2003, a noticeable trend has revealed, depicting rural herdsmen transitioning from the livestock sector to employment in mining, corresponding with a consistent decrease in herder households. This transition contributes to the migration of herder households to nearby urban centers, leading to a noteworthy increase in the urban population. According to research conducted by Amartuvshin et al. (2021) on migrants, this corresponds to approximately 1,494 individuals, with 909 (60.8%) moving to urban areas, 324 (21.7%) to aimag (province) centers, 151 (10.1%) to soum centers, and 110 (7.4%) to pastoral locations. Also, in certain instances, this contributes to an increased unemployment rate in local areas, primarily due to the mismatch in skills between local herders and the requirements of mining companies. For instance, in Khanbogd soum in Umnugobi province, herding practices have changed, evidenced by a decline in traditional nomadic lifestyles, and a substantial number of active herder households (17%) have now established permanent residences within seasonal camps (Sternberg et al., 2022). Furthermore, the increases of environmental degradation, pollution, and the depletion of water resources resulting from mining activities has expanded to rural landscapes, leading to direct and indirect consequences for parturelands, livestock, and the well-being of herders (Burchard-Dziubińska et al., 2019; Amartuvshin et al., 2021).

2.3.2 Impact on the smallest social units (families or households)

Despite the impact of the mining sector on the nomadic lifestyle of Mongolia over the past two decades, one significant consequence is the heavy workload faced by mining workers. Typically, one partner from a family is employed by a mining company, which is often situated in remote rural areas of the country. The husband or wife, usually the wife, remains at home to take care for the children. According to the initial Labor law of Mongolia, the work schedule for miners was consisting of 20 working days and 10 days off in shift work at remote mine sites. However, this arrangement resulted in an increase in mine accidents and other social concerns, including extended periods away from home, which contributed to a rise in divorce rates, suicide rates, and other related social problems. In addressing these challenges, the government, in collaboration with the Federation of energy, geology, and Mining workers' trade unions of Mongolia, implemented changes to the work roster through the amended Labor Law. These changes took effect on January 1, 2022. Under this new arrangement, the work roster for employees in mining companies consists of 14 working days followed by 14 days off. This adjustment aims to promote a healthier work-life balance for miners (IndustriAll, 2022). Since the implementation of the amended Labor law, there has not been any research related to the impact of these changes and their influences on families. Further investigation is necessary to understand the implications better. There is a crucial need for a thorough investigation into the impact on mining workers' families, with a focus on developing practical solutions, including the construction of schools and kindergartens for miners' children. Additionally, implementing suitable systems for establishing new workplaces, affordable family apartments, and attracting businesses to create recreational spaces like cinemas, libraries, and restaurants. Special attention should be given to families residing in remote areas, where mining operations are often located. The goal is to identify and implement measures that enhance the overall well-being of these families and provide them with the necessary support structures.

2.3.3 Health issues

The working conditions in mining industries not only adversely affect those within the mines but also extend their negative impact through the release of heavy metals and metalloids in tailings dumps, which can be dispersed by wind and water erosion, ultimately affecting the surrounding environment. In Mongolia, the nomadic way of life is being influenced by expanding mining activities (Amartuvshin et al., 2021; Sternberg et al., 2022). For instance, herder households are settling down in one place more frequently, and as a result, livestock animals are grazing on grass and drinking water contaminated by mining processes, including tailings water near the fences around mining sites. Given that livestock forms a primary source of food in Mongolia, this shift in nomadic lifestyle near mining sites raises concerns about its potential adverse effects on local people' health, as well as its impact on wild animals and other natural conditions. Furthermore, concerns have arisen regarding environmental issues such as white dust generated from mining activities and the transportation of deposits by heavy vehicles on paved roads. These practices contribute to increased airborne dust and the dispersion of coal and other deposits in the surrounding areas. Numerous studies have been conducted to examine health-related issues associated with major mining operations in Mongolia, including the Erdenet copper-molybdenum mine, Oyu Tolgoi copper-gold mine, Tavantolgoi coal mine, Baganuur coal mine, and small-scale artisanal gold mines. Burchard-Dziubińska et al., (2019) found that heavy vehicles on unpaved roads generate significant dust, negatively impacting herders' health and leading to respiratory illnesses like bronchitis. This dust, along with noise and water pollution, directly harms livestock health, causing poor weight and fat gain. Animals near roads face increased mortality, often exhibiting black lungs due to dust inhalation, making survival in the harsh winter. In 2021, environmental health survey conducted for children residing near mining areas in the South Gobi region of Mongolia, elevated concentrations of blood lead were observed in children. However, these elevated levels were attributed to factors beyond direct mine exposure (Surenbaatar et al. 2021). In the Baganuur and Erdenet mining regions, elevated levels of heavy metals and metalloids have been detected in both soils and water, necessitating further investigation into potential public health risks and impacts on wildlife (Battogtokh et al., 2014; Park et al., 2020). Consequently, comprehensive assessments are crucial for understanding and addressing these issues. The existing health risks associated with pollution from both mining and non-mining activities are inadequately quantified, emphasizing the need for additional investments in further monitoring, as highlighted by McIntyre et al. in 2016. Also, improved understanding of these risks through comprehensive monitoring efforts is crucial for developing effective mitigation strategies and safeguarding public health.

2.3.4 Gender equality

The worldwide mining workforce shows women accounting for less than 15% of employees in large-scale mining (Ochir et al., 2023). In Mongolia, this proportion is even lower than the global average, with females comprising an average of 11% of total mining employees over the last 15 years, as indicated in Figure 2.3.

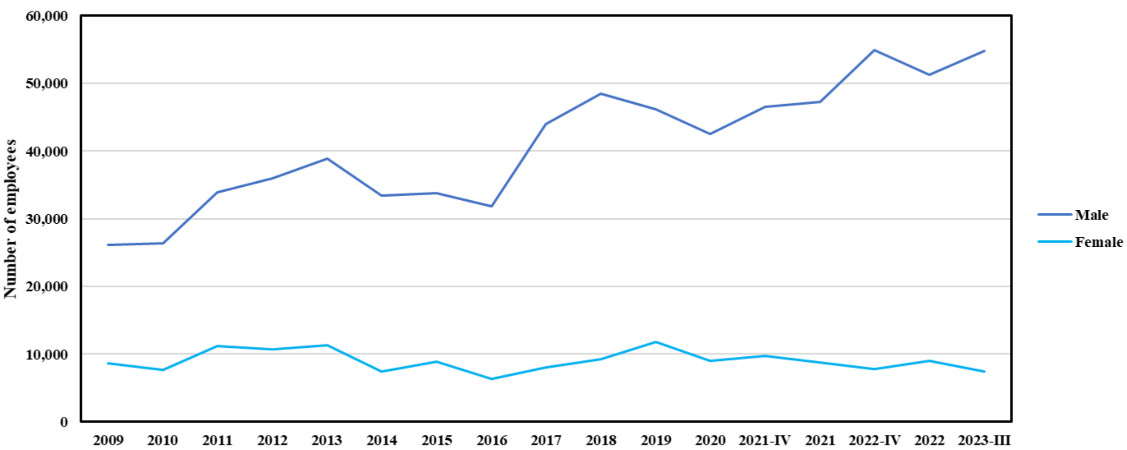

Figure 2.3 The number of male and female employees working in the mining sector over the past 15 years (NSO 2023).

In Mongolian coal mining, female representation in total employment consistently remains at the lowest levels, averaging 12%. In contrast, metal ore mining, which employs the largest workforce, exhibits a higher proportion of female workers, reaching 20% in both 2020 and 2021. The overall participation of women in mining employment tends to be higher in the under-30 age group, declining with increasing age, while the trend is reversed for males. One contributing factor to this pattern might be the family-related challenges that women face during the transition into adulthood, leading to their withdrawal from the workforce (Weldegiorgis, 2022). As of 2023, approximately 19% of the total workforce in the Mongolian mining sector comprises female employees (mmhi.gov), and the female participation is notably lower: female mining professionals account for 2%, contrasting with male professionals at 14%; in plant and machine operation, females represent 2%, while males make up 45%; within the "Craft and Related Trades Workers" category, women comprise 1%, compared to 8% for men; management positions show 2% female representation and 3% male representation. Additionally, females in mining tend to possess a higher proportion of advanced-level education (47%) compared to their male counterparts (37%). Across all age ranges, female workers are underrepresented, reporting an average of 6.3 fewer working hours than their male counterparts (Ochir et al., 2023). Therefore, promote gender equality, mining companies should adopt inclusivity and diversity policies implementing programs for equal career advancement, along with policies as flexible working hours and parental leave, can support women in balancing work and family responsibilities. These steps are essential for fostering equal opportunities in the mining sector (Daley et al., 2018; Kroll, 2021; Ochir et al., 2023).

2.3.5 Education demand for mining industry

In the last century, Mongolia's mining sector has seen significant development, with vital contributions from foreign investments and educational initiatives. These efforts have been provided comprehensive education, empowering individuals with the essential skills to independently sustain mining activities. Mongolia's mining education started with the establishment in 1938, by the first Mongolian geologist educated abroad (MRPAM, 2011). The National University of Mongolia initiated the education of the country's first "Mining Engineer" in 1960. Subsequently, since 1971, the Mongolian University of Science and Technology has also played a role in educating mining engineers. In total, these two universities have collectively educated approximately 10,000 mining engineers to date (guus.edu). Since the 2000s, increased foreign direct investment in the country's mining sector has spurred the adoption of advanced technologies. This transition demanded mining engineers proficient in both new technologies and English language skills to operate modern equipment and collaborate with foreign experts. Initially, many locally educated engineers lacked the required proficiency, requiring time to fulfill these demands. As a result, foreign-invested mining companies often mitigated these gaps by bringing in foreign experts. According to national statistics in 2023 (NSO, 2023), approximately 38% of the total foreign experts working in Mongolia are employed in the mining sector, encompassing both mining processing industries and transportation. To address challenges in the country's mining sector, focus should be placed on enhancing local education programs from the highschool and college, particularly in advanced technologies and English proficiency. Initiatives promoting gender diversity, supportive government policies, and collaboration with industry stakeholders can collectively contribute to building a skilled and diverse workforce. Additionally, implementing technology transfer programs will facilitate the integration of modern practices, reducing dependence on foreign experts over time. Hence, it is crucial to prioritize the improvement of local education programs, with a specific emphasis on improving high school and college education and extending thse improvements to higher education levels. This enhancement should specifically target advanced technologies and English proficiency to better equip the workforce for the demands of the industry (Shatz et al., 2015).

2.4 Regulatory framework and current environmental protection measures

Mongolia is governed by approximately 30 laws and 40 regulations, rules, and guidelines (UNDP, 2016) related natural resources and mineral exploration, outlined as follows: State Policy in the Natural Resource Sector (2014), Common Minerals Act (2014), Control of Explosives and Blasting Law (2013), Investment Law (2013), Law on Environmental

Impact Assessment (2012), Mineral Exploration Prohibition Act in River Flow Irrigation Source, Protected Area with River Basins, and Forest Reservation Areas (2009), Law on Nuclear Energy (2009), Tax Laws (2008), Minerals Law (2006), Land Law (2002), Industrial Activities Licensing Act (2001), Environmental Laws (1995), Special Protected Areas Act (1994), and Law on Subsoil (1988).

Despite the presence of sufficient laws and regulations addressing mining and environmental protection in Mongolia, the actual implementation of these measures remains notably slow (Schoderer et al., 2021). Over the past two decades, numerous donor organizations and environmental protection initiatives have played a crucial role in assisting Mongolia to achieve sustainable environmental management and protection. Despite active participation in these global efforts, Mongolia currently holds the 157th position in the worldwide Environmental, Social, and Governance (ESG) index (Sternberg and Ahearn, 2023). The legislative environment governing the mining sector in Mongolia is characterized by its dynamic and unstable nature. For instance, since the approval of the Minerals Law in 2006, it has experienced a total of 18 amendments (UNDP, 2016). Mongolia's ranking at 116 out of 180 countries is partly due to corruption, delaying law enforcement, with limited progress in combating corruption in the mining sector emphasizing the urgent need for enhanced transparency (UNDP, 2016; Tradingeconomics, 2022).

According to the sections 3.1.4 and 14.1.3 of the Law on Environmental Impact Assessment (EIA) enacted in 2012, an Environmental Impact Assessment (EIA) is mandatory for assessing the prevailing environmental conditions before the initiation and three years prior to the closure of a mining project. This assessment is carried out by the EIA assessing authority, often typically professional companies. This stage also involves the development of a rehabilitation plan by the mining companies. Furthermore, mining companies are obligated to submit annual reports on the environmental impacts of their mining activities to both local authority and environmental administration of Mongolia. These reports serve the purpose of suggesting amendments to both the EIA and the environmental management plan of the mining companies as required by the Minerals Law of Mongolia (IGF, 2017). Despite land degradation reaching 23,000 hectares due to mining activities, there was a positive development with the rehabilitation of 12,000 hectares of mining areas in 2019, as reported in Mongolia's Environmental Status Report 2019-2020 (MESR, 2020). In 2023, according to the National Statistics information (NSO 2023), a total of 14,300 hectares of land were degraded due to mining activities. Even with efforts in rehabilitation planning and implementation, there has been a concerning increase in environmental degradation, including soil, water, and air pollution, as well as inreasing soil erosion. This situation is attributed to the inadequate enforcement and implementation of mining regulations, with insufficient monitoring studies exacerbating the problem.

So far, there has been limited studies, guidelines and concepts, exist for mine rehabilitation planning in open-pit mining areas in Mongolia. Knippertz (2005), GROM (2019), and Frauenstein et al. (2021) have contributed technical guidance to the rehabilitation planning of open-pit coal mine areas in the country. These instructions encompass critical components, including land restoration, public engagement in projects, continuous environmental impact assessments during mining operations, landscape re-utilization through the rehabilitation of abandoned mine areas, and biodiversity conservation to identify pollution-sensitive zones. The lack of a systematic approach to monitoring, planning, and regulating mine closure and rehabilitation, along with the absence of financial assurances for these processes, has led to a significant and growing legacy of inadequately rehabilitated mine properties in Mongolia (IGF, 2017). Hence, it is essential for enhancing mining rehabilitation and its effective implementation based on the active involvement of mining companies, local residents, and local authorities. This collaborative effort should be rooted in comprehensive monitoring by all parties, related laws and regulations enforcement, and the incorporation of scientifically informed studies to assess environmental impacts. Through this collective engagement, valuable insights can be gained, leading to informed suggestions for amendments to both the EIA processes and relevant laws and regulations.

3 STUDY AREA AND REGIONAL OVERVIEW

This study investigated the Erdenet copper and molybdenum mine, situated in Erdenet city, roughly 360 kilometers northwest of Mongolia's capital, Ulaanbaatar. Additionally, it examined the Baganuur lignite mine located in the remote Baganuur district, approximately 140 kilometers east of the capital (Figure 3.1).

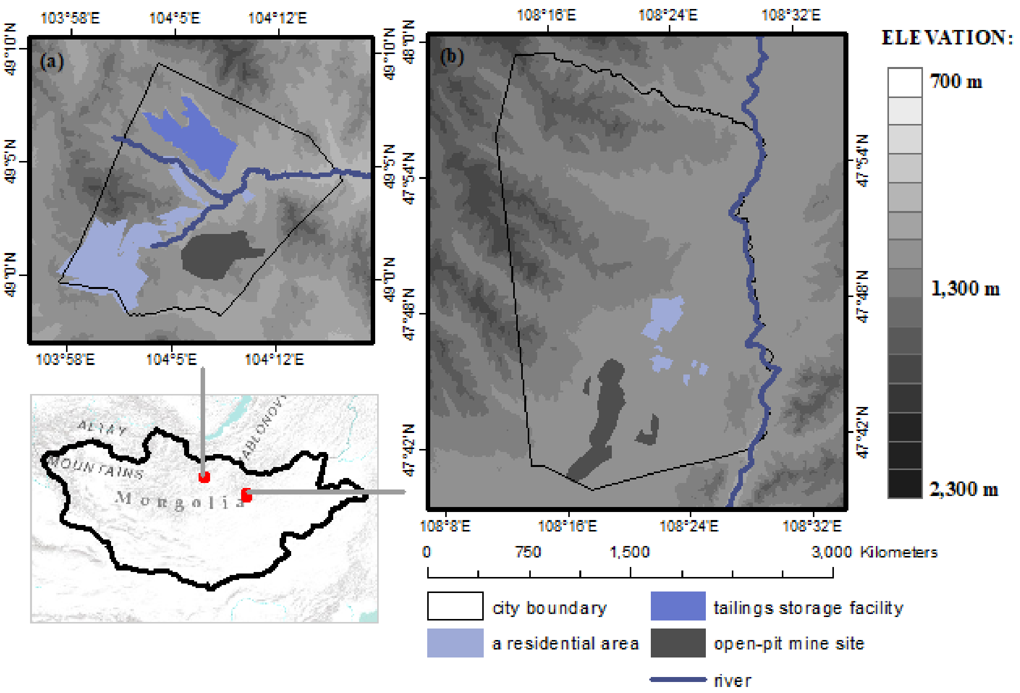

Figure 3.1 The study area with elevation (m) and its location in Mongolia. (a) illustrates the Erdenet mining site situated in Erdenet city while (b) the Baganuur mining site located in Baganuur city. The data source: the Digital elevation model (www.earthexplorer.usgs.org)

These mining sites are pivotal to the economy and infrastructure of Mongolia, making substantial contributions to mineral extraction. By concentrating on these open-pit mining sites, the research aims to conduct a thorough assessment of soil erosion patterns and the content of heavy metals and metalloids. It also aims to delineate contamination zones, offering crucial insights for environmental management and the development of mitigation strategies. The subsequent sections provide a more detailed geographical and environmental overview of the two mining sites as follows.

3.1 The Erdenet mining area: Geography and environmental aspects

3.1.1 Introduction to the Erdenet copper-molybdenum mining operation and its location

The Erdenet copper and molybdenum mine, a significant contributor to both the mining industry and the economy of Mongolia, underwent geological exploration starting in the late 1950s, which led to its discovery between 1964 and 1968. Following this discovery, the first explosion was conducted at the site in 1976, and it was officially established in 1978 (Potravny et al., 2023). This mining operation annually extracts approximately 580,000 tons of copper concentrate and 5,000 tons of molybdenum concentrate (erdenetmc.mn). Following the continued development of the Erdenet copper-molybdenum mine operation, Erdenet city has became one of the largest urban centers in Mongolia, with an estimated population of around 100,000 by 2022. The city has a diverse range of industries, including both light and heavy manufacturing, agriculture, and various urban development projects (Figure 3.1).

3.1.2 The role of the Erdenet mining in the country's mining sector and social development

The Erdenet mine significantly impacted the country's GDP, contributing around 7% to its economic output. It also played a crucial role in employment, providing jobs for over 7,000 individuals, with more than 90% of them being local residents. Noteworthy is the mine's contribution to the financial well-being of the region, offering salaries that are approximately 33% higher than the country's average, thus ensuring greater financial stability (NSO, 2023). In addition to employment opportunities, the mining company has made step in enhancing the living conditions of its employees by providing affordable housing options through projects such as the "Miner 1, 2, 3" apartment complexes. Furthermore, the company has been a key supporter of the "Erdenet Complex" University since 1978, playing a crucial role in preparing skilled workers for the mining sector in Erdenet city. Moreover, the mining operation collaborates with the local administration to support citizens and small businesses.

Its operational lifespan has been extended by an additional 30 years. This extension is attributed to the discovery of a 37 million-ton ore exploration capacity through geological research conducted between 2017 and 2021. Consequently, the projected total operational period now stands at 70 years (erdenetmc.mn). The ongoing global trend shows a consistent increase in demand and prices for refined copper, against depletion of deposits and a decline in the balance reserves of copper ores. As a result, mining companies worldwide, including those in Mongolia, are actively exploring new production resource through the utilization of secondary raw materials. This approach also addresses the challenge of mitigating accumulated environmental damage. The waste rock within the tailings dump of the Erdenet mine, containing significant residual quantities of copper, molybdenum, rhenium, silver, and other associated metals, along with flotation reagents used in technological processes, constitutes a valuable resource in these efforts (Potravny et al., 2023).

Since its establishment, the Erdenet mine site has seen the creation of more than 10 stockpiles for leaching, and starting in 2014, the mining operation entered into a lease agreement with Achit-Ikht Co., Ltd. for a secondary tailings dump. Through the application of hydrometallurgical methods, these deposits are transformed into economically valuable materials, specifically A-grade copper cathodes. This initiative has resulted in the production and export of copper, contributing over 250 billion MNT (Mongolian tugrug) to the country's economy since 2014 (achit-ikht). The sustainability and continued success of the Erdenet mining operation underscore its significance for Mongolia's economic resilience and development in the expected future.

3.1.3 Environmental features of the Erdenet mining region

The climate of Erdenet is classified as cool continental, subarctic (Dwc) according to the Köppen-Geiger climate classification, with noticeable seasonal variations. The average annual temperature of Erdenet city is about 0.8℃, with January being the coldest at temperatures dropping to an average of -17℃, while July is the warmest month, with an average temperature of 17℃. The rainfall in this area gradually increases from late May to September, with annual precipitation ranging from 260 to 590 mm as reported by the National Agency of Meteorology and Environmental Monitoring (NAMEM).

In the Khangay Mountains, tectonic activities and folding created plutonites, rocks exposed through erosion, while mudstones around the Middle Orkhon Valley represent remains from the Late Jurassic to early Cretaceous, with the valley also featuring Quaternary deposits, including flat areas shaped by rivers (fluvial terraces) (Lehmkuhl and Lang, 2001). In the Erdenet city region, chernozem soils predominate, with thin sandy to loamy compositions on steep slopes, while in foothills and valleys, thicker layers of weathered soil containing rocky material are found, suggesting a mixture of original and sediment deposits (colluvial deposits), thus ruling out the possibility of being pure and undisturbed (Schwanghart et al., 2008; eic.mn). Short grass vegetation is preserved at altitudes below approximately 1,200-1,400 meters above sea level (m a.s.l.), while natural larch forests are found nearer to the mountain peaks. Urban areas feature isolated larch and poplar plantations, with grass cover limited primarily due to the effects of intensive livestock grazing, as emphasized by Yembuu et al. (2021).

Erdenet city is located in a valley between the Selenge and Orkhon River basin areas, yet the city experiences relatively low water resources (Figure 3.2). Within the city's territory, three rivers flow through the landscape: the Erdenet, Gavil, and Khangal. Originating from mountain valleys, the Gavil and Erdenet rivers merge to form the Khangal River, which subsequently joins the Orkhon River in Mongolia (Solongo et al., 2021)

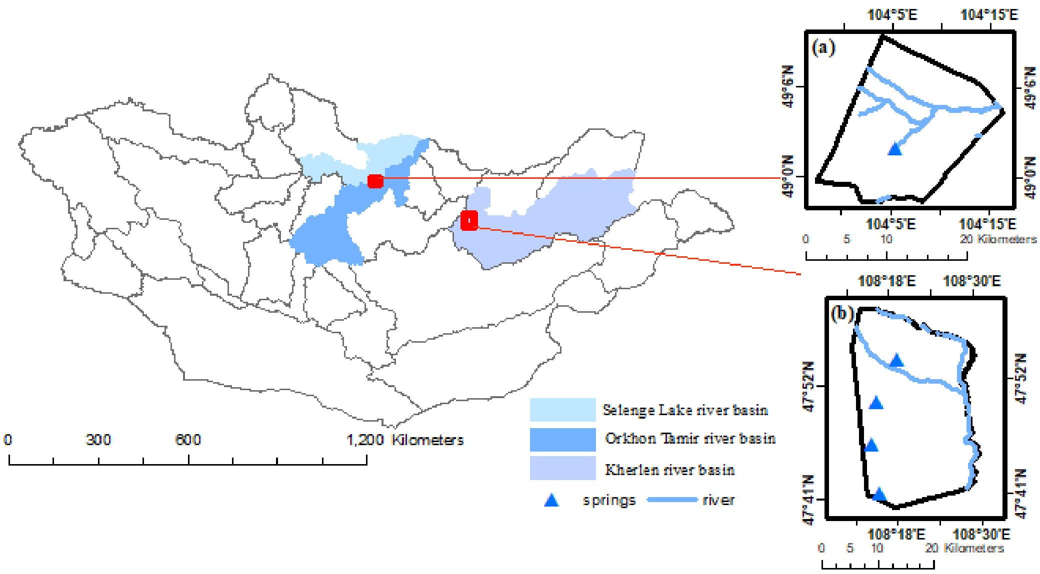

Figure 3.2 Surface water resources in (a) Erdenet city and (b) Baganuur city. The data source: a metadata on surface water resources in Mongolia, including springs, rivers, and lakes (www.eic.mn)

3.1.4 Current environmental challenges in Erdenet city

Since the inception of the Erdenet mine industry due to the Erdenet city area has faced a shortage of water resources, it relying solely on 16 groundwater wells along the Selenge River to fulfill its drinking and industrial water needs. This water is transported through a 60 km pipeline and elevated by 600 meters. The wells exhibit a yield ranging from 99 to 145 liters per second, with the depth of the groundwater wells ranging from 41 to 44 meters. The water table experiences fluctuations of 0.67 to 27 meters, and hydrogeologists determine the height of water resource deposits to be approximately 38 meters (Tumursukh, 2013). Also, the city of Erdenet is facing with severe environmental issues, including air, water, soil pollution, and land degradation, primarily attributed to the tailings storage facility (TSF). These challenges have arisen from over four decades of intensive mining activity and a substantial increase in the population, which currently stands at approximately 102,000 residents (NSO, 2022). A large amount of the waste generated during the rock processing is directed to the TSF situated approximately 4 km in the north of the mining processing plant. This facility is a major source of airborne particulate matter (PM), commonly referred to as "white dust" posing risks to both the environment and human health (Lkhagvajargal et al., 2018) despite boilers, copper concentrate driers of the proccessing plant are also major source of dust generation around the mining area. Furthermore, the rate of soil loss was higher in the vicinity of the TSF and the mining areas of the Erdenet mining operation, primarily attributed to factors such as rainfall intensity, transportation, and other mining activities. These findings are based on field observations, scientific literature, and erosion modeling utilizing the Revised Universal Soil Loss Equation (RUSLE) (Sodnomdarjaa et al., 2023). It leads to water contamination in the ground and on the surface downstream from the storage site. While the soil near the storage area exhibits higher concentrations of copper and molybdenum, it appears to be less polluted compared to the sediment in streams. For example, the Khangal River shows elevated levels of sulfate, calcium, magnesium, and arsenic, with a relatively milder impact on groundwater quality due to the recharge process (Battogtokh et al. 2014; Karthe et al. 2017).

Moreover, extending downstream from the Erdenet mining area by approximately 10 km, the water continues to be affected by heavy metal contamination, specifically, with molybdenum concentrations consistently surpassing the health-based guidelines established by the WHO during the summer (Solongo et al., 2021). Therefore, immediate action is required for mitigation and rehabilitation to protect the well-being of wildlife, livestock, and the city's residents, addressing the multifaceted environmental issues stemming from decades of intensive mining activity.

3.1.5 The current status of rehabilitation measures and environmental management practices in the Erdenet mining operation region

A scarcity of literature exists on mine rehabilitation planning, especially concerning the open-pit mining area of Erdenet. The Rehabilitation Pyramid, introduced by Knippertz (2005), provides a foundational framework for developing a rehabilitation plan and expanding monitoring activities, ensuring alignment with the unique environmental conditions and socioeconomic needs specific to the Erdenet mining area. Schwarz et al. (2016) underscore the importance of focusing on the tailings storage facility (TSF) in ensuring a sustainable future for the Erdenet mining operation, highlighting the significance of addressing environmental concerns, particularly through TSF rehabilitation. This is especially crucial given that existing TSFs operate at approximately 60% capacity (Dagva et al., 2016). Additionally, advancing the current situation requires for the crucial promotion of modern technologies and research aimed at developing construction materials from the TSF, as emphasized by Jargalsaikhan et al. (2023).

The Erdenet mining operation, expected to continue for another 30 years (eic.mn), necessitates the establishment of an environmental management and rehabilitation plan for both ongoing mining activities and eventual closure to ensure responsible and sustainable practices aligned with the United Nations Sustainable Development Goals (UN SDGs). This involves ongoing support for recycling tailings dump around the mining area, researching new material production, and collaborating with local residents at both community and governmental levels. Active participation in environmental monitoring studies focusing on water, soil, and air quality is crucial. Moreover, the establishment of a centralized information is essential to unify projects related to environmental sustainability, rehabilitation, and new material production, enhancing effective processing industrialization. The key objective is to sustainably continue mining operations, contributing significantly to the Mongolian economy while concurrently fostering a sustainable environment around the mining industry.

3.2 The Baganuur mining area: Geography and environmental aspects

3.2.1 Introduction to the Baganuur lignite mining operation and its location

The Baganuur lignite mine, situated around 130 kilometers east of the Mongolian capital city, Ulaanbaatar, is within one of the city's remote districts (Figure 3.1). The topography of the area is characterized by expansive valleys, bounded by small hilly mountains to the west and east, with an average elevation ranging from 1,350 to 1,376 meters above sea level (Park et al., 2020). The discovery of around 600 million tons of lignite in Baganuur in 1973 paved the way for the establishment of the Baganuur coal mine in 1978. Two years later, in 1980, the Baganuur district was officially founded (MRPAM, 2011).

3.2.2 The role of the Baganuur mining in the country's mining sector and social development

Despite the transition to clean energy, the coal industry remains a major player in the global economy (Ivanova et al., 2022), as coal, being a cheap and abundant resource, is responsible for approximately 40% of global greenhouse gas emissions from fossil fuel use (c2es, 2008). In Mongolia, coal plays a crucial role as the primary energy source, driven by its widespread availability and cost-effectiveness in production (Alyeksandr et al., 2020). This dependence is evident in the significant contribution of coal-fired combined heat and power plants, accounting for 98% of the overall electricity supply. Notably, the Baganuur lignite coal mine stands out as a key player, providing 50% of Mongolia's total coal demand and fulfilling 70% of the coal requirements for the central region of the country, with an annual extraction of 3 million tons (ctc-n, 2013). The Baganuur mine employs around 1,100 individuals, with roughly 90% being local residents of Baganuur city. Recent initiatives by the mine include supporting education for employees and their children, offering opportunities for higher education in mining-related subjects and other engineering fields, utilizing the local environment for professional internships, and inviting successful graduates to pursue careers within the Baganuur mine (baganuurmine.mn). In the 2014-2015 research focused on detailed exploration and resource assessment of the Baganuur coal deposit, it was discovered that the total reserves of the Baganuur Mine increased to around 800 million tons (MIE, 2015). The increased reserves contribute to the understanding of the mine's capacity for sustained extraction. The ongoing coal extraction, reaching an annual output of 3.6-3.8 million tons by the end of 2023 (baganuurmine.mn), underscores the significance of these reserves in supporting continued production.

To better align with sustainable mining practices, despite coal's global reputation as a less preferable energy source, Mongolia's future trajectory continues to indicate an increased dependence on coal as the primary energy source. However, there is a growing emphasis on exploring alternative opportunities that prioritize environmental conservation, and both the Baganuur mine and the Mongolian government should consider actively participating in these efforts.

3.2.3 Environmental features of the Baganuur mining regions

Baganuur city region exhibits a cool continental subarctic (Dwc) climate according to the Köppen-Gieger classification, characterized by notable temperature extremes. The coldest temperatures typically occur in January, reaching around -24°C, while the warmest temperatures in July reach 16°C. Precipitation patterns similar with Erdenet city, with levels increasing from May to September and ranging between 220 and 380 mm annually, as observed through in-situ measurements conducted by NAMEM.

In geological terms, Baganuur city is located within the Choir Nyalga Coal basin, characterized as a rift-type basin that hosts a variety of sediment types, including fluvial-swamp, fluvial-lacustrine, deltaic-fluvial, and fluvial deposits. The basin axis aligns in a southwest-northeast direction. The Baganuur Basin is predominantly filled with Jurassic and Cretaceous sediments, which are further overlaid with Quaternary alluvial, deluvial, and aeolian sediments (Erdenetsogt et al., 2009).

Baganuur city is situated in the mountain steppe region, chernozem soil is predominantly distributed based on metadata from the Environmental Information Center of Mongolia (eic.mn), and the area hosts approximately 31 different types of vegetation, with a majority of species demonstrating semi-drought resistance and drought resistance (Yembuu et al., 2021). In the city, research conducted by Park et al. (2020) reveals that the sampled soils predominantly exhibit silty loam or sandy loam textures, with primary components including quartz, microcline, and albite. This geological composition, as reported on the official website of the Baganuur coal mine company (baganuurmine.mn), attributes these soil textures to a Quaternary sand and gravel layer with a thickness of 6 meters covering the underlying clastic sedimentary rock.

The prevalent vegetation comprises Festuca plants and shrubs, covering a significant portion of the plain. Stony Festuca and wormwood herbs populate the mountainous sections, while the riverside area features a blend of willow groves, herb grass, and marshy sedge bent herbs. Larch, birch, and spruce trees dominate in the region (eic.mn).

Regarding the location of Baganuur city within Mongolia's 29 river basin administrations, it is situated within the Kherlen River basin (Figure 3.2), characterized by numerous small surface water streams, with the Kherlen River being the largest, boasting a watershed area of approximately 7,000 km² (eic.mn). Both the industrial and household drinking water needs of the area primarily depend on groundwater as the main water source, supplemented by water pumped from the nearby Kherlen River, situated 13 km east of the mining area (baganuurmine.mn). The mine usess advanced water removal systems with in-pit pumping to manage water levels, and the extracted water is conveyed through pipes to the Baganuur thermal plant and nearby rivers. The water supply for the mine comes from public water supply wells managed by the Baganuur Water company, while wastewater discharge is directed to the local wastewater treatment plant (Park et al., 2020).

3.2.4 Current environmental challenges in the Baganuur city

The persistent demand for raw materials and energy in production contributes to a significant environmental crisis, marked by a rise in greenhouse gas emissions, particularly in mining regions (Ivanova et al. 2022). This is evident in the current environmental degradation around the mine region in Mongolia. The open-pit coal mining process in the Baganuur Coal Mine area could have major impacts on the environment, particularly in terms of desertification. It has been observed that the process can degrade forests and prairies, thereby accelerating desertification, especially in areas with dry climates such as Mongolia. This degradation is attributed to the potential for desertification in the waste soil excavated and removed during the mining process. Over 80% of the soil particles, measuring smaller than 150 µm, contain As levels surpassing Mongolian soil pollution standards (MNS 5850:2008). The pH of the soil samples varies, ranging from 6.17 to 7.50 (Park et al. 2020). Furthermore, signs of contamination and pollution are primarily visible in the original town center characterized by paved roads and buildings. The assumption is that increased traffic, linked to higher emissions of metals, has contributed to this issue. Additionally, the extensive coverage of soil with impermeable surfaces may intensify the occurrence of pollution hotspots in specific areas that have long allowed the retention and accumulation of contaminating particles (Pecina et al. 2023). Metal leaching may initiate from the waste sediments that are directly exposed to air and rainfall at the land surface (Jarsjö et al. 2017). Urgent action is needed for rehabilitation and environmental protection both during and after mining operations to ensure sustainable management.

3.2.5 The current status of rehabilitation measures and environmental management practices in the Baganuur mining operation region

Between 1999 and 2017, the Baganuur mining company implemented biological rehabilitation both inside and outside the mining fence, covering a total area of 180.5 hectares, with plans to rehabilitate an additional 100 hectares. As part of these initiatives, the company planted approximately 25 thousand trees, including species such as *Poplar, Elm*, and Yellow shrub (erdenesmongol.mn). To mitigate the impacts of activities such as waste soil excavation and metal leaching, which contribute to environmental degradation including desertification and soil pollution, it is crucial to implement sustainable mining practices, conduct ongoing monitoring, and establish effective waste disposal and pollution prevention measures. Furthermore, implementing measures like water recycling to lower groundwater pumping expenses can help preserve valuable resources and prevent pollution hotspots. Sustainable development requires the establishment of ongoing monitoring practices and the formulation of mining strategies based on field monitoring data to ensure safe disposal and prevention of environmental pollution. Effective environmental management from both the mining company and the government is crucial in this regard (Park et al. 2020). Park et al. (2020) and Pecina et al. (2023) recommended increasing the number of soil and water samplings in the Baganuur mining area and considering more appropriate methods to anticipate long-term expansion. A comprehensive assessment of heavy metal contamination is crucial, with investigations prioritizing drinking water and mining dust pollution.

4 METHODS AND APPLICATIONS

4.1 Data collection

4.1.1 Fieldwork and sampling

Fieldwork was conducted at the Baganuur mine site from June 25 to 27, 2020, and at the Erdenet mine site from September 17 to 20 of the same year. A total of 50 soil samples were collected from the Baganuur mining area and 48 samples from the Erdenet mining area, selected using simple randomization technique. Simple randomization, as defined by Abbott (2010), involves selecting individuals for measurement in each population element with an equal probability of selection. This method provides economic and time-saving advantages, allowing for more accurate results when increasing the number of sampling points in the study area. In this study, the soil samples were obtained from the top layer of the surface (0-10 cm) at different locations, including the vicinity of open-pit mine sites, the tailings storage facility, human settlement areas, and industrial zones within the territories of each city. In 2022, an additional 18 soil samples were taken from each study area, with a specific focus on the stream network lines where smaller streams merge with major rivers such as the Kherlen River in Baganuur city and the Khangal River in Erdenet city. This collection focused on areas passing through open-pit mines and the tailings storage facility, aiming to assess the negative impact of mining on sediment in rivers. Geospatial coordinates were recorded using the Garmin 64 GPS, and photographic documentation of the sampling points is available in the Supplemental material for Chapter 4, Table S4.1 and Table S4.2.

4.1.2 Remote sensing and long-term data collection

In this study, the long-term soil loss rate was calculated based on the Revised Universal Soil Loss Equation (RUSLE) using the following data. Long-term precipitation data obtained from Global climate and weather data (worldclim.org) were utilized to define the rainfall intensity factor (R factor). Landsat 4-5 and 7-8 data with a 30 m spatial resolution were employed to calculate the land cover management factor (C factor) based on the Normalized Difference Vegetation Index (NDVI). Additionally, the Digital Elevation Model (DEM) with a 30 m spatial resolution was obtained from the United States Geological Survey (earthexplorer.usgs.gov) to determine the topographic steepness factor (LS). The datasets cover the period from 1989 to 2018, excluding DEM, and the calculations were carried out throughout various seasons, excluding winter.

4.2 Laboratory work

4.2.1 Grain size analysis

The soil sample preparation were executed in alignment with the Mongolian standard for Soil Quality and the preliminary processing guidelines for physiochemical analysis (MNS ISO 11464:2002). This including air drying, separation of organic matter, sieving with a diameter less than 2 mm, and grinding. The determination of particle size employed the dry sieve method, wherein 100 grams of soil was distributed across three sieves with different diameters (0.05-2.0 mm, 0.002-0.05 mm, <0.002 mm), aligning with particle size classifications by the U.S. Department of Agriculture (USDA). Utilizing a triangular diagram representing fundamental soil textural classes based on USDA particle size classifications is a comprehensive approach to determining soil particle sizes, ensuring accuracy in the assessment of soil characteristics.

4.2.2 Soil pH analysis

Maintaining an optimal soil pH is essential for healthy plant growth and contamination prevention. In this study, air-dried soil samples from each location were mixed with distilled water in a 5:1 ratio, shaken for one hour in the shaker, and the pH was determined using a pH meter (Hanna HI2002 pH meter).

4.2.3 Soil organic matter content analysis

In this research, the determination of Soil Organic Matter (SOM) content played a crucial role in establishing the soil erodibility factor for the RUSLE calculation. SOM levels were assessed based on the soil texture, and the majority of the sampled soils exhibited sandy composition (92% in Erdenet and 94% in Baganuur), with some instances of loamy and sandy loam textures in the Erdenet area, and loamy sand as well as sandy loam textures in Baganuur. The selection of K values (0.12 for loamy sand, 0.25 for sandy loam, and 0.27 for sandy soil) was influenced by the SOM content and soil texture.

4.2.4 Soil heavy metal and metalloid concentration analysis

The concentrations of heavy metals and metalloids (HMM) in the soils of the Baganuur and Erdenet areas were determined using portable X-ray fluorescence (pXRF) at the German-Mongolian Institute for Resources and Technology in Mongolia (GMIT), with 50 samples from Baganuur and 48 from Erdenet. Following this, 20 and 24 samples from each site (a total of 44) were evaluated using stationary X-ray fluorescence (sXRF) analysis at the laboratory of the Department of Physical Geography and Geoecology at RWTH Aachen University in Germany. Additional samples collected in 2022 at both locations were analyzed using Inductively coupled plasma optical emission spectrometry (ICP-OES) at the SGS Mongolia laboratory. The pXRF analysis identified a total of 16 elements, while both sXRF analysis and ICP-OES revealed more than 30 elements. Challenges arose with pXRF's limit of detection (LOD), particularly when the desired element concentration exceeded the device's range, resulting in potentially inaccurate values, often showing 0. For further interpretation of the study, elements such as Ni, Cu, Zn, As, Cr, and Pb were selected. These elements were chosen due to their detection by all three methods, and they are recognized as potentially toxic heavy metals. Previous studies have also highlighted the significance of these elements in environmental assessments.

4.3 Evaluating soil erosion and soil quality

4.3.1 The Revised Universal Soil Loss Equation (RUSLE)

In this study, the Revised Universal Soil Loss Equation (RUSLE) served as the primary tool for assessing annual soil loss around the Erdenet and Baganuur mine sites. RUSLE stands out as the most practical model for predicting erosion, particularly well-suited for application at the local or regional scale. Moreover, various parameters, including slope, aspect, and Land Use Land Cover (LULC) data derived from Digital Elevation Models (DEM) and satellite images, seamlessly integrate with RUSLE. The model is specifically designed to predict long-term average annual soil erosion. However, it is important to note a limitation of RUSLE, it does not possess the capability to route sediment through channels, which restricts its applicability to smaller areas, as pointed out by Ganasri and Ramesh in 2014.

Originating in the late 1950s, the Universal Soil Loss Equation (USLE) was formulated by Wischmeier et al. It has since become a widely adopted and practical methodology for soil conservation and management, implemented in over 100 countries (Alewell et al., 2019). However, recognizing some limitations in the original USLE, was revised as the the Revised Universal Soil Loss Equation (RUSLE) by Renard et al. in 1991. The RUSLE represents a significant enhancement, providing a more robust tool for the assessment of soil erosion. Its adaptability is evident in its capacity to integrate with remote sensing and Geographic Information System (GIS) tools, which have become standard practices for mapping soil erosion risks in recent years (Zerihun et al. 2018). The computation of the Revised Universal Soil Loss Equation (RUSLE) involves climate erosivity, represented by R (rainfall runoff erosivity factor); soil erodibility, represented by K (soil erodibility factor); topography, expressed as LS (slope length and steepness factor); and land use and management, indicated by C (cover management factor). Additionally, the supporting practices factor is considered, represented by P (supporting practices factor), as defined by Renard et al. in 1991.

$$A = R \times K \times LS \times C \times P \tag{4.1}$$

Although the RUSLE is used worldwide to estimate soil erosion, it hasn't been used much in Mongolia, with only a few studies utilizing this model in the region. This might be due to local conditions, such as distinctive soil types, land use practices, or climatic patterns. Also, not having enough data about the RUSLE model in Mongolia might be a reason it's not used much there. Given the global recognition of the RUSLE model, exploring ways to enhance its utilization in Mongolia could contribute to better defining soil erosion rates on a larger scale and improving environmental management in the region.

4.3.2 Assessing soil quality

In this study, widely recognized geochemical indices, including the Potential Ecological Risk Index (RI), Geoaccumulation Index (Igeo), and Nemerow Integrated Pollution Index (PIN), were employed to assess the level of HMM contamination in the soils.

The Potential Ecological Risk Index (RI) was calculated using the equation proposed by Hakanson in 1980:

$$RI = \sum_{i}^{n} E_r^i \tag{4.2}$$

where E_r^i is the ecological risk factor of the substances, E_r value classified as no pollution (<2), moderate pollution (2-5), moderate to severe pollution (5-20), severe pollution (20-40) and extreme severe pollution (>40).

The Geoaccumulation Index (Igeo) was calculated based on the following equation by Müller in 1969:

$$I_{geo} = log_2 \left[\frac{C_n}{1.5B_n} \right] \tag{4.3}$$

where C_n is the measured concentration of metal n in the soil, B_n is the geochemical background concentration or reference value of the heavy metal n, and 1.5 is a constant specified by Müller in 1969 to compensate geochemical variations.

The Nemerow Integrated Pollution Index (PI_N) was calculated using the following equation by Nemerow in 1974:

$$PI_N = \sqrt{\frac{PI_{max}^2 + PI_{ave}^2}{2}} \tag{4.4}$$

where PI_i is the pollution index of HMM in each sample, PI_{max} is the maximum value, and PI_{ave} is the mean value of PI_i for all heavy metals in each sample.

Table 4.1 Soil contamination categories by Igeo and RI

Igeo	Categories of contamination	RI index classes	Categories of contamination risk	PI_N	Categories of contamination
<0	Unpolluted	<150	Low ecological risk	≤0.7	no pollution
0 – 1	Unpolluted to moderately polluted	150-300	Moderate ecological risk	0.7-1	precautionary pollution
1 – 2	Moderately polluted	300-600	Considerable ecological risk	1-2	slight pollution
2 – 3	Moderately to highly polluted	>600	Very high ecological risk	2-3	moderate pollution
3 – 4	Highly polluted			≥3	severe pollution
4 – 5	Highly to extremely polluted				
5<	Extremely polluted				

4.4 Sustainable Development Goals (SDGs) for sustainable mining and rehabilitation

In September 2015, the United Nations adopted the "2030 Agenda for Sustainable Development" outlining 17 Sustainable Development Goals (SDGs) for 2015-2030, which address social, environmental, and economic progress, requiring collaboration among governments, NGOs, businesses, and communities.

Mining, as related to the SDGs, can bring both positive and negative consequences. Positively, it contributes economic growth by creating jobs, fostering business expansion, generating revenue, and improving infrastructure. Conversely, it has also been associated with issues like environmental degradation, displacement of communities, inequality, conflict, gender-based violence, corruption, health hazards, and human rights abuses.

Therefore, it is crucial for mining industries to actively align with the SDGs during their operations, supporting the goals and mitigating any adverse impacts, as defined by the UNDP Atlas 2016.

SDG 1 - Mining and Poverty Eradication: Collaborate to optimize resources for poverty alleviation, promote alternative livelihoods beyond mining, and expand anti-poverty strategies. This involves publicly disclosing payment details, ensuring equitable employment access, building local supplier capacity, and initiating early land access planning for projects.

SDG 2 - Mining and Zero Hunger: Manage water resources transparently, minimize land use, share infrastructure benefits with the agricultural community through surveys, and regularly monitor water quality and soil fertility for stronger watershed management. Partner with agriculture and support programs to reduce childhood malnutrition and hunger.

SDG 3 - Mining, Good Health, and Well-being: Establish a healthy workplace, prevent toxic emissions, reduce silica dust, and support mental health. Engage in epidemic response, train community health workers, and recognize traditional medicinal practices.

SDG 4 - Mining and Quality Education: Assess skills regularly, sponsor training, link academic programs with vocational education, collaborate with colleges and universities for curriculum design, and support sustainable livelihoods beyond mining.

SDG 5 - Mining and Gender Equality: Increase women's roles, ensure equal pay, promote women in leadership, offer flexible schedules for childcare, support gender-sensitive career development, include diverse perspectives in community decisions, make social investments gender-inclusive, combat gender-based violence, and monitor women's health.

SDG 6 - Mining, Clean Water, and Sanitation: Recycle metals from waste, reduce water use, align with government policies, integrate diverse water concerns, identify high-value water areas, maintain balance, support portable water planning, delineate watershed responsibilities, and build local water management capacity.

SDG 7 - Mining and Affordable, Clean Energy: Audit energy use, improve maintenance, reduce onsite demand, adopt renewables, diversify power sources, replace diesel generators with local support, integrate into rural electrification, share benefits, and explore co-financing.

SDG 8 - Mining, Decent Work, and Economic Growth: Generate decent jobs, diversify economies, facilitate local bidding, train suppliers through collaboration, build capacity, improve quality, connect to external markets, and collaborate to end child labor.

SDG 9 - Mining, Industry, Innovation, and Infrastructure: Enhance local supplier expertise, improve goods' quality, support suppliers for mine services, explore co-funding with governments, share infrastructure, and utilize business plans to create linkages, clusters, and promote domestic research and development.

SDG 10 - Mining and Reduced Inequalities: Address local wage disparities, establish pre-mining welfare statistics, train and employ marginalized populations, involve excluded groups in local procurement, work with partners for targeted social investments, and promote participatory budgeting in communities, particularly in mining revenues.

SDG 11 - Mining and Sustainable Cities, Communities: Re-mine tailings and urban waste, combine metals recycling with waste energy reclamation. Plan land use considering the life-of-mine, reclaim mines as parks, and collaborate with local authorities for green spaces, including decommissioned mines.

SDG 12 - Mining and Responsible Consumption, Production: Reduce water, energy, land, chemicals, waste, and emissions. Repurpose waste rock, analyze products throughout their lifecycle, extend responsible sourcing to suppliers through industry collaboration, develop and report against materials management codes. Engage consumers about mining and connect them with raw materials.

SDG 13 - Mining and Climate Action: Improve energy efficiency, use renewables, measure and monitor emissions, plan for climate impacts, strengthen response plans, model environmental impacts, adopt climate policies, engage in climate dialogues, and support carbon pricing.

SDG 14 - Mining and Life Below Water: Dispose of tailings responsibly, assess impacts on fishing and marine livelihoods, map breeding grounds and migration routes, minimize habitat disturbance, and collaborate with local authorities to establish conservation areas, marine reserves, and coastal zone management plans.

SDG 15 - Mining and Life on Land: Apply mitigation hierarchy to minimize impact, avoid critical habitat impacts, offset biodiversity impacts, conduct comprehensive environmental assessments. Support projects linking communities and biodiversity, engage in landscape-level planning, restore habitats, participate in reforestation and anti-poaching efforts, and collaborate in research initiatives.

SDG 16 - Mining, Peace, Justice, and Strong Institutions: Address stakeholder concerns, establish accessible grievance mechanisms, participate in conflict-free mineral certification, implement human rights impact assessments, uphold high standards for security contractors, and promote the rule of law in a peaceful working environment.

SDG 17 - Mining and Partnerships for the Goals: Ensure transparent payment data, enhance data and statistical analysis capacity, transfer technologies to host countries, engage in public-private partnerships, and share unused exploration data with national authorities. Foster trust through active dialogue with governments, civil society, and development partners, strengthen coordination between initiatives, and apply SDG indicators.

Rehabilitation plans, which systematically integrate environmental and socioeconomic considerations, are essential for mitigating mine site environmental impacts in alignment with the UN SDGs and fostering sustainable landscapes (Pashkevich et al., 2023). Thoroughly assessing initial environmental conditions, encompassing soil, water, air quality, and biodiversity risks, is imperative for effective strategies (GROM, 2019). Even with modern industrial advancements, but reforestation is not always suitable, better to argue more general using term ecological geotechniques. Mechanical rehabilitation remains essential for effective mining site rehabilitation, as it not only restores ecosystems but also prevents erosion, stabilizes soil, promotes biodiversity, improves water quality, sequesters carbon, and enhances aesthetics with recreational opportunities for communities (Yang et al., 2021). The effectiveness of reforestation depends on the ability of tree species to adapt to the unique challenges posed by newly formed reclaimed mine soils, which exhibit significant spatial variability in habitat conditions and notable fluctuations in both chemical and physical properties (Pietrzykowski, 2019). Additionally, organic amendment, utilizing urban, agricultural, and forestry waste, provides a cost-effective and environmentally beneficial alternative that enhances vegetation establishment, offering potential benefits for the recovery of mining areas in developing countries (Navarro-Ramos et al., 2022).

5 ASSESSMENT OF SOIL LOSS USING RUSLE AROUND MONGOLIAN MINING SITES: A CASE STUDY ON SOIL EROSION AT THE BAGANUUR LIGNITE AND ERDENET COPPER-MOLYBDENUM MINES

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ABSTRACT

Mining constitutes an integral part of Mongolia's national economy and dominates the country's export revenue. At the same time, a wide range of mining impacts on soil, water resources, the atmosphere and the biosphere have been documented across the country. This case study addresses the long-term soil degradation around two mining sites located in the semi-arid steppe zone of Mongolia: the open-cast lignite mine of Baganuur about 140 km east of Ulaanbaatar, and the open-pit copper-molybdenum mine of Erdenet about 240 km northwest of Ulaanbaatar, both of which started commercial extraction in the late 1970s. For the assessment of soil erosion, the RUSLE model was applied in different seasons for the period from 1989 to 2018 at 3-year intervals, considering both climatic variation and the expansion of the mines based on maps and satellite imagery. Rainfall erosivity was identified as the most dominant factor driving soil erosion in the study regions, with mining leading to local increases in soil erodability. The highest soil erosion rates were found in both areas in July 2018, reaching 7.88 t ha^{-1} $month^{-1}$ in the Erdenet area and 9.46 t ha^{-1} $month^{-1}$ in the Baganuur area. The spatial patterns of soil erosion showed higher soil loss rates were in the vicinity of the mines and adjoining industrial sites. Particularly high soil losses were identified in July 1998, July and August in 2013 and July 2018 in both mining areas. The combination of the RUSLE model, remote sensing and ground truth data as and their processing by GIS was found to be a time-saving and cost-effective technique for continuous monitoring of soil erosion and planning of preventive measures in and around mining areas.

5.1 Introduction

Over the past few decades, Mongolia's soils have been affected by a wide range of degradation phenomena including soil erosion, desertification, nutrient depletion and various forms of soil pollution (Batkhishig 2013; Hofmann et al. 2016, Han et al. 2021). Soil degradation in Mongolia is driven by the combined effects of climate change and anthropogenic activities including mining, (over-)grazing, agriculture, urbanization and offroad transportation (Lehmkuhl and Batkhishig 2003; Batkhishig 2013; Chonokhuu et al. 2019). About 72% of the country's land is considered to be degraded (Eckert et al. 2015; Darbalaeva et al. 2020; Liang et al. 2021) and the country has been facing severe desertification (Liang et al. 2021) which according to concerned scientists affects up to 90% of the total pastureland (Darbalaeva et al. 2020). Previously constrained to the regions bordering the Gobi desert, land degradation has in recent years increasingly affected the central part of Mongolia and to a lesser degree also extended to its north (Wang et al. 2020). The combined annual cost of land degradation in the country is estimated at around 2.1 billion USD or 43% of the country's GDP (UNCCD 2018). Batkhishig (2013) therefore noted, that an accurate estimation of soil erosion is crucial in Mongolia, but that there is limited knowledge regarding the spatiotemporal pattern of erosion and the distinction between predominant driving factors.

Over the past few decades, several scientific studies have been conducted on desertification and soil erosion in Mongolia. Climate change and anthropogenic land cover changes resulting from overgrazing, mining activities and deforestration have been documented as reasons for severe soil erosion and land degradation (Batkhishig 2013; Han et al. 2021; Liang et al. 2021). Studies based on remote sensing have recently provided an overview about soil erosion and desertification in Mongolia and identified mining activities as one of the major causes (Eckert et al. 2015). Large areas of land in Mongolia are adversely affected by mining activities, and around 4.6% of the territory of Mongolia currently covered by more than 2700 valid mining licenses (MRPAM 2020). There is well documented knowledge on mining related water, soil and air pollution in Mongolia (Knippertz 2005; Karthe et al. 2014; Timofeev et al. 2016; Karthe et al. 2017; Chonokhuu et al. 2019; Kosheleva et al. 2018), but rather limited and case-specific documentation of mining impacts on soil erosion. Most previous studies have examined sediment transportation and soil erosion in agricultural areas, often combining field measurements and modelling approaches (e.g., Priess et al. 2015). Moreover, several studies have focused on the sources and impacts of sediments in Mongolian river system and identified high livestock densities along the rivers as the core challenge (e.g., Hartwig et al. 2016; Theuring et al. 2015). Onda et al. (2007) and Kato et al. (2010) measured soil erosion and sediment accumulation with radionuclide methods in the two small catchments of the Baganuur stream (0.076 km^2) and the Kherlen Bayan Ulaan stream (0.069 km^2). During the 2003 and 2004 monitoring period, annual soil erosion was estimated to be 0.37 t ha^{-1} yr^{-1} in Baganuur and 0.02 t ha^{-1} yr^{-1} in the Kherlen Bayan Ulaan, with precipitation playing the major role for sediment mobilization and suspended transport. Batkhishig et al. (2019) showed by the cesium-137 radionuclide fallout method that the average soil erosion rate on a mean escarpment of the Ikh Bogd Mountains around Lake Orog was 12.57±1.08 t ha^{-1} yr^{-1} and found a maximum soil erosion rate is 40.87 t ha^{-1} yr^{-1}. This site is not impacted by mining, but its environment is comparable to the Erdenet and Baganuur mining sites but with steeper natural mountain slopes. Research into the causes of soil erosion has identified livestock and overgrazing as a main cause (Lehmkuhl and Batkhishig 2003) but also identified changing rainfall patterns and a trend toward strong convective rainfall events as a problem (Vandandorj et al. 2017).

Mining likely plays a significant but not sufficiently studied role for soil erosion in Mongolia. The country has more than 600 deposits of more than 80 types of minerals and ranks seventh in the world in terms of mineral resources (Davaasambuu 2018). The mining sector has been developing rapidly in recent decades and it is one of the country's most important sources of foreign direct investment (FDI), revenues and exports (Baatarzorig et al. 2018). For instance, in 2014-2016, the country's gross domestic product (GDP) increased by 1.2% due to decline in commodity prices and FDI in the mining sector. In 2017-2018, the GDP growth reached 5.3% due to a recovery of raw material prices and an FDI increase. This growth trend is expected to remain relatively stable in the future (Turmunkh 2020), averaging about 9% annually over the past decade (NSO 2018).

The economy in Mongolia is heavily dependent on the mining sector and revenues from mineral exports including particularly coal, gold and copper (Dagys et al. 2020). Although the rapid development of the mining sector is important for the country's economic development, it has been identified as an important driver of land degradation (Farrington et al, 2005). The effects of mining on water resources have been studied in some detail, including the sector's significant water in water-scarce regions, and the impacts of mining on ground and surface water pollution (Timofeev et al. 2016; Batbayar et al. 2017; Jarsjö et al. 2017; Nottebaum et al. 2020), and the challenges of aligning mining and water policies have recently been addressed (Schoderer et al. 2021). A few studies have investigated land degradation in major mining areas. The total damaged land area in the mining regions of the country was estimated at around 8.1 thousand hectare (ha) (Batmunkh 2021). Mining-related pollution has been linked to bioaccumulation by plants (Kosheleva et al. 2018) and several species of freshwater fish (Kaus et al. 2017), but also to a public health hazard (Nottebaum et al. 2020), thus pointing to a nexus of mineral extraction and the degradation of the abiotic and biotic environment.

In Mongolian mining areas, most previous work on soil degradation has focused on soil pollution, but little work has been done to assess mining-related erosion or to investigate the interlinkages between soil erosion and soil pollution. It has been reported that the generation of barren lands, mine tailings and stored overburdens has led to increased erosion particularly during the rainy season (Kayet et al., 2018). Some authors have described mining as growing concern regarding its role for land degradation (Khishigjargal et al. 2015) and observed a massive expansion of soil erosion due to mining (Batkhishig, 2013). For the Tuul River Basin in Northern Mongolia, Jarsjö et al. (2017) applied the WATEM/SEDEM model to quantify the input of metal-contaminated sediments from Zaamar Goldfield mining area into the river system, and found the mining activities to strongly exacerbate natural soil erosion. The rate of soil loss around the Zaamar Goldfield mining area was reported to be 10 t km^{-2} $month^{-1}$, and the study found that mining-related soil losses contributed to pollutant transport in the mining area. In order to harmonize the development of mining sector in Mongolia with environmental sustainability, it is crucial to study and monitor environmental degradation and develop science-based environmental rehabilitation measures. This particularly includes soil losses due to erosion, which have not been investigated sufficiently in the past.

In this study, we aimed at the quantification and assessment of spatiotemporal pattern of soil erosion in two mining cities of Erdenet and Baganuur, with particular focus on the vicinity of the open-pit mining areas. For the time period from 1989 until 2018, we used a combination of terrestrial data and satellite-based information. The main objectives of this study were (1) to estimate soil erosion rate using the RUSLE method supported by Geographic Information Systems (GIS); (2) to classify spatiotemporal erosion risks and (3) to evaluate the spatial distribution in the two cities of Erdenet and Baganuur with particular focus on identifying the role of open-pit mining areas. The final results of the study can be used by decision-makers at the local, regional and national level to develop science-based soil erosion prevention and rehabilitation plans. This information is relevant both for mining officials and for government agencies responsible for the environmental oversight of mining operations.

5.2 Materials and methods

5.2.1 Study area

The objective of this study is to provide an integrated assessment of soil degradation at Mongolia's two largest open-pit mining sites: the Baganuur lignite mine and the Erdenet copper-molybdenum mining complex, both of which began commercial operation in 1978 (Figure 5.1 and Table 5.1). Baganuur lignite mine is located in Baganuur district of Ulaanbaatar city (N 47°47'10" E108°21'40") and is 140 km east of the city center. The total district covers an area of 622 km^2, of which 416 km^2 is pasture land, 193 km^2 is settlement area, 0.047 km^2 belongs to the road and infrastracture network and 0.14 km^2 is governmental and other land. The city of Baganuur is home to a total population of 29,342 (NSO 2018). Baganuur district is located in a semi-arid steppe regioat the Southern fringe of the Khentii Mountains, and the western bank of the Kherlen River which flows from north to south in the city's vicinity (Kim 2017). The district including mining sites is situated in a wide valley bounded by small hilly mountains in the west and east (Park et al. 2020). The mean annual temperature of Baganuur district is around –2.2°C and the coldest month is January with an average temperature of –20.7°C and the warmest month is July with an average temperature of +18.2°C (Climatedata 2020). The annual mean precipitation is around 250–280 mm and about 70% of the precipitation falls during the summer season from June to August (Kim 2017; Park et al. 2020). The territory of Baganuur area is filled with Cretaceous and Jurassic sediments with Quaternary alluvial, diluvial and aeolian sediments (Park et al. 2020). The Baganuur open lignite mine deposit was estimated at 812 million t in 2014 (Otgochuluu et al. 2015). Baganuur mining site has open pits, mining equipment and offices and the mine uses water through a municipal water supply system. Open-pit mining removes naturally vegetated areas and produces a high amount of waste that leads to an increase in soil pollution and soil erosion surrounding the area. Since the operation of Baganuur mining, 337 Mbcm overburden and 1100m^3/h groundwater usage were estimated (Park et al. 2020). The Erdenet Copper and Molybdenum complex is located in Erdenet city (N 49°03'38" E104°03'31") in Orkhon province, Northern Mongolia. Erdenet city was established in 1976 as a center of mining and industry, and it is the country's second-largest city. Orkhon province, which covers the two districts of Bayan-Undur (where the city of Erdenet is located) and Jargalant, encompasses a total area of 844 km^2, 464 km^2 of this are pasture land, 210 km^2 by settlement area, 9 km^2 by road and infrastructure, 2 km^2 by water bodies, and 140 km^2 by forest. The total population of Bayan-Undur district including Erdenet city is 101,909 (NSO 2018). The city is located in the Orkhon-Selenge volcanic sediment area, which consists of alkali-rich trachyandesite, granite intrusions and Carboniferous deposits (Battogtokh et al. 2013). The climate is continental with an average temperature of 0.7°C and annual mean precipitation of 350 mm, the coldest month is January with an average temperature -22.2°C, and the warmest month is July with +16.5°C (Climatedata 2020) and 90% of total precipitation falls from May to September (Battogtokh et al. 2013). The city of Erdenet is located between two small streams, the Erdenet and the Gavil river, which merge into the Khangal river about 7 km downstream of the city in close proximity to the Cu Mo mine in the South and its large tailing pond in the North (Solongo et al. 2018). The Erdenet mine was established in 1978 and it is one of the largest copper and molybdenum mines in the world with metal deposits estimated as 7.6 Mt of copper (Cu) and 216 600 t of molybdenum (Mo) in 1991 (Munkhtsengel et al. 2006). The Erdenet open-pit mining complex consists of one tailings pond, dams, open-pit mines, a mine waste dump, and an ore processing mill complex. A locally well-known environmental impact of the mine is "white-dust", which is mobilized and transported by wind when parts of the tailings pond dessicate. White-dust affects soil and water quality around the tailings pond, which is problematic as this area is used by animals, herders, and residents to grow crops, and as it affects the Khangal River, which is a source of drinking and irrigation water (Battogtokh et al. 2013).

Table 5.1 Key characteristics of the study area

Study area	Köppen-Geiger climate classification (Köppen 1936)	Average temperature (°C)			Annual mean precipitation (mm)	Elevation (m)	Mine site description (established year)
		Highest	Lowest	Mean			
Baganuur city	Semi-arid (steppe)	+18.2°C (Jul)	-20.7°C (Jan)	-2.2°C	250-280	1150-2200	Baganuur lignite mine (1978)
Erdenet city	Continental and semi-arid (steppe)	+16.5°C (Jul)	-22.2°C (Jan)	0.7°C	350-400	700-2170	Erdenet copper-molybdenum (1978)

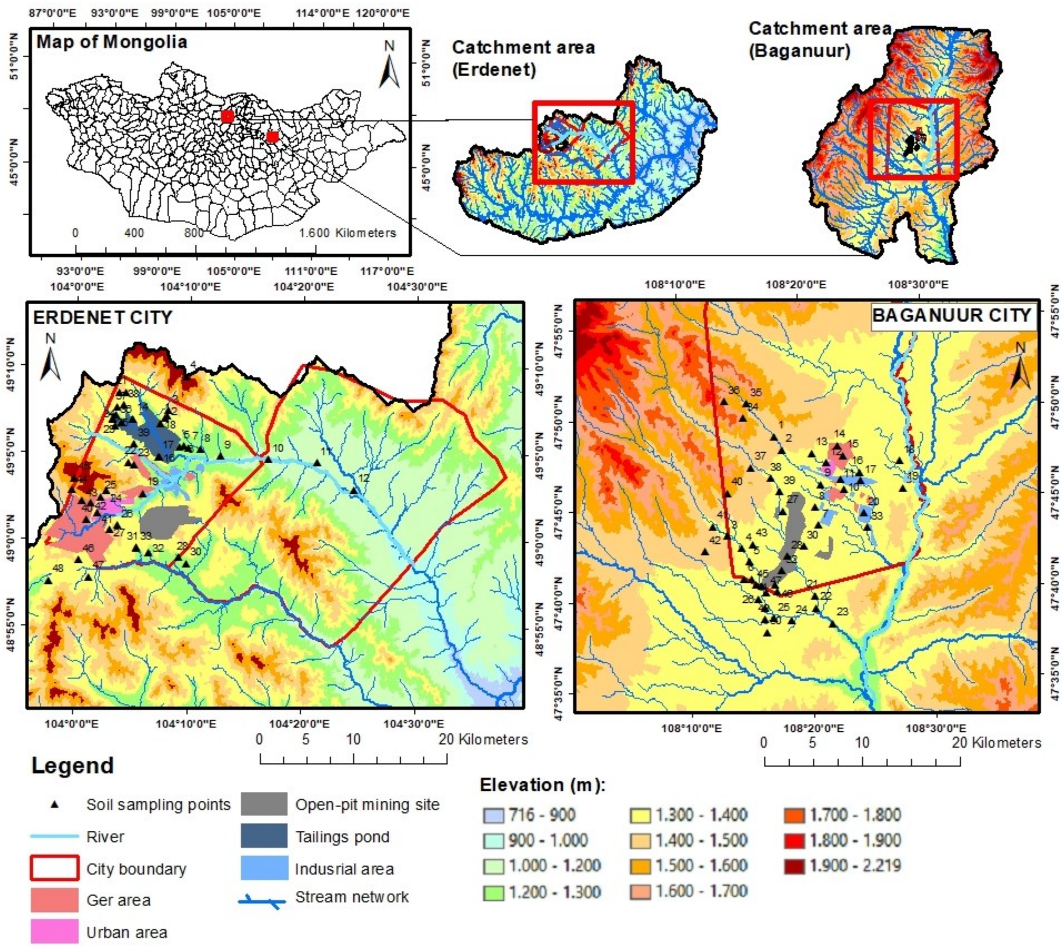

Figure 5.1 Location of the study areas: Erdenet mining area in Erdenet city; Baganuur mining area in Baganuur city

5.3 Data sources

In this study, the following data related to soil characteristics, landcover, topography and precipitation were collected to determine the spatio-temporal pattern of soil erosion.

Table 5.2 Data description and source

In-situ data source, description	Inputs	Outputs
Top layer of the soil (0-10 cm) of the study sites (own data)	Soil data	Soil texture Soil organic matter content Soil erosion –K factor
Remote sensing data source, description	**Inputs**	**Outputs**
The United States Geological Survey: https://earthexplorer.usgs.gov/ Spatial resolution–30 m; Duration: July 1982 to October 2018	Landsat 4–5 data; Landsat 7, 8 data	Normalized Difference Vegetation Index (NDVI); Soil erosion: Land cover management factor – C factor
The United States Geological Survey: https://earthexplorer.usgs.gov/ Spatial resolution–30 m	Digital Elevation Model (DEM)	Soil erosion: Topographic steepness factor – LS
Global climate and weather data: https://www.worldclim.org/ Monthly precipitation, mm Spatial resolution–21 km^2	Precipitation data	Soil erosion: Rainfall intensity factor–R factor

5.4 *Methods*

5.4.1 *Soil erosion estimation*

In this study, the monthly soil erosion for the Baganuur and Erdenet mining areas was estimated using the Revised Universal Soil Loss Equation (RUSLE) model. It is based on the Universal Soil Loss Equation (USLE), which is considered a very practical approach that has been applied in more than 100 countries (Alewell et al., 2019). The USLE was developed in the late 1950s for assisting widespread application including soil conservation and soil management in a wide range of settings such as cropland, urban construction areas, recreational areas, and mine sites (Renard et al., 1991; USDA, 2017). Due to some limitations of the original USLE method, the revised and updated USLE (RUSLE) was developed by Renard (1991). More recently, the application of remote sensing and GIS tools has become a standard practice for mapping soil erosion risks (Bahrawi et al., 2016). The RUSLE can easily combined with GIS and remote sensing approaches which can provide some of the input data (Kulimushi et al., 2021; see Table 5.2). Although the RUSLE model is widely used to estimate soil erosion worldwide, the model has been used in only a very few studies in Mongolia. The equation of the RUSLE model (Figure 5.2) is based on (Schmidt et al., 2016, 2019) :

$$A = R \times K \times LS \times C \times P \tag{5.1}$$

where A is the quantification of soil loss in a month (t ha^{-1} $year^{-1}$), R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} $year^{-1}$), K is the soil erodibility factor (t h MJ^{-1} mm^{-1}), LS is the topographic steepness factor (unitless), C is the cover management factor (unitless), P is the support and conservation practice factor (unitless) (Schmidt et al., 2016, 2019; Kebede et al., 2021). The annual soil loss equation was modified for calculating monthly soil loss using monthly based rainfall and vegetation data (Schmidt et al., 2019).

$$A_{month} = R_{month} \times K \times LS \times C_{month} \times P \tag{5.2}$$

where A is the monthly soil loss in t ha^{-1} $month^{-1}$

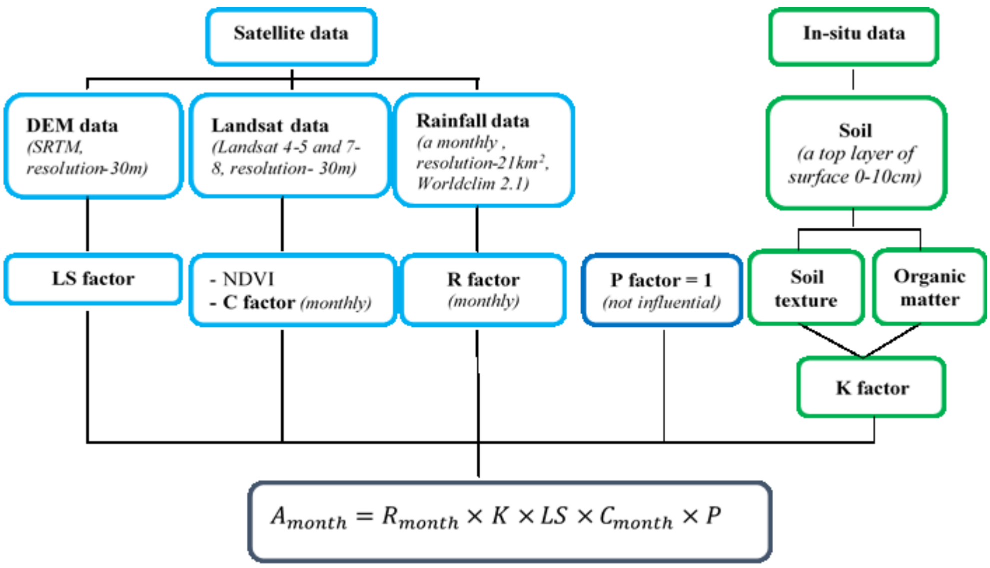

Figure 5.2 The methodological framework of RUSLE model

These input parameters are described in the following.

Rainfall erosivity factor (R);

The rainfall erosivity factor is one of the RUSLE input parameters that calculate precipitation and runoff impact on soil loss (Kayet et al. 2018; Lee et al. 2021). The amount of rainfall and its intensity is considered by this factor (Maqsoom et al. 2020). For calculation of the R factor, satellite-based Worldclim precipitation data (WorldClim) with a spatial resolution of 21 km^2 was used. For regions poorly covered by meteorological data, this database provides moderate spatial resolution data including long-term global monthly precipitation data (Abatzoglou et al. 2018). Average monthly precipitation around the two cities for 1986-2018 is shown (Figure 5.3).

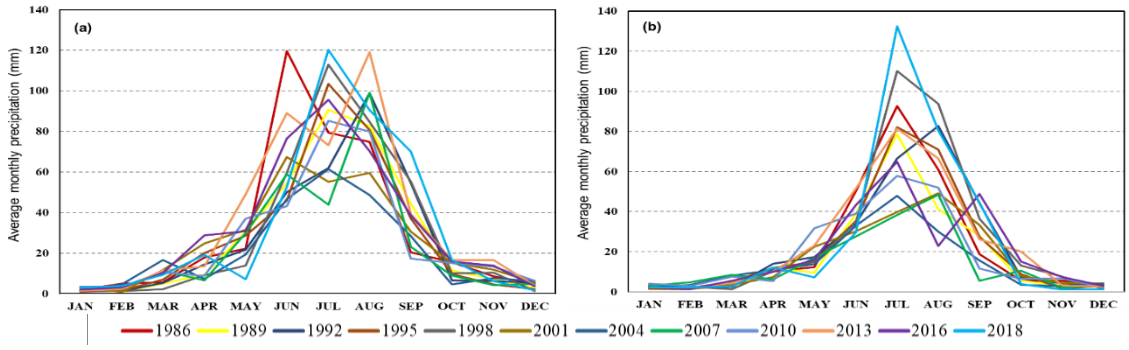

Figure 5.3 Average monthly precipitation (mm) from 1986 to 2018 (Worlclim version 2.1 precipitation data for 1986-2018) (a) Erdenet, (b) Baganuur

In this study, the monthly precipitation data of April to October from 1989 to 2018 were used in the calculation. The rainfall erosivity factor was calculated based on the following equation (Renard and Freimund, 1994; Duulatov et al., 2021) based on monthly precipitation data. Rainfall point data were converted into raster data using the Inverse Distance Weighted (IDW) method in Arcmap software. The IDW method has been used for many studies to estimate R factor and it predicts the values in cells with unknown points (Ouadja et al., 2021).

$$R = 0.0483 + P^{1.61} \tag{5.3}$$

where P is the monthly rainfall (mm). The rainfall data is satellite-based Worldclim precipitation data for 1989-2018.

Soil erodibility factor (K):

The soil erodibility factor (K) factor quantifies the relative susceptibility and transportability of soil from the surface due to rainplash and runoff (Kayet et al., 2018; Hateffard et al., 2021). The K factor is commonly classified based on soil texture and and soil organic matter content (Parveen and Kumar, 2012), and ranges from 0.02 for the least erodible soil to 0.64 for the highest erodible soil (USDA, 2017). A high amount of clay in soils has a high K value due to its easy erodibility, whereas loamy soil has moderate erodibility (Maqsoom et al., 2020). K factor values are negatively correlated with coarse textured soils and positively correlated with fine fractioned soils (Huang et al., 2022). In this study, the K factor was determined according to the soil texture type and soil organic matter content. The point data were converted into raster data using the Inverse distance weighted (IDW) method in Arcmap software. Soil samples were collected from the top layer of the surface (0-10 cm) inside and outside of the fences of the mining sites (Figure 5.1). A total of 48 soil samples were collected from Erdenet mining sites in September 2020 and a total of 50 soil samples were collected from Baganuur mining sites in June 2020. Soil sampling points were georeferenced with a global positioning system (GPS Garmin 64) and are shown in Figure 5.1. A total of 19 soil sampling locations were covered in a previous study by Knippertz (2005). Other sampling locations in Baganuur and Erdenet were selected randomly but represented different land covers including open-pit mining areas, urban and ger settlement areas, and the industrial zone. The simple random method was applied as it provides unbiased estimates of the mean and variance (Worsham et al, 2012). In addition, it time saving and thus allows for a greater number of sampling points to be covered during the same time. All soil samples were air-dried under a normal air condition for 48 hours in a laboratory of German-Mongolian Institute for Resources and Technology (GMIT) and sieved to less than 2 mm. The dry sieve method was used to determine the particle size fractions of the soil. In the process, 100 g of soil of each soil sample was subsequently placed in a sieves of 3 different diameters in order to classify it to fractions from 0.05 to 2.0 mm, 0.002 to 0.05 mm and <0.002 mm according to USDA, 2017. A shaking machine was used for 8 minutes with each sieve. Then the dry sieved results were used to determine soil textures based on a triangular diagram according to USDA standards.

The soil organic matter content of the samples was determined using the Loss on ignition (LOI) method. This method is one of the most commonly used methods for estimating soil organic matter content (Heiri et al., 2001). The soil samples were air dried at 22-25°C for 48 hrs and particle larger than 2 mm were removed. Then, 5.00±0.01 g of soil from each sample was oven dried for 24 hrs at 105°C. After that, the dried samples were cooled in a desiccator, then the samples were heated at 360°C for 2 hrs and then cooled below 105°C (Schulte and Hopkins, 1996).

$$SOM = \frac{(S_{w1} - S_{w2})}{S_{w1}} \times 100 \tag{5.4}$$

where S_{w1} is the soil weight after drying at 105°C, S_{w2} is the soil weight after heating 360°C. The soil erodability factor was then estimated based on texture and soil organic matter content (Table 5.3).

Table 5.3 Soil erodibility factor relationship between Soil Organic Matter Content (SOM) (Schwab et al., 1981)

Soil texture	Amount of organic matter (%)		
	0.5	2.0	4.0
Silty clay	0.25	0.23	0.19
Fine sand	0.16	0.14	0.1
Silt clay loam	0.37	0.32	0.26
Very fine sand	0.42	0.36	0.28
Clay loam	0.28	0.25	0.21
Loamy sand	0.12	0.10	0.08
Silt loam	0.78	0.42	0.33
Loamy very fine sand	0.44	0.38	0.30
Sandy loam	0.27	0.24	0.19

Topographic steepness factor (LS):

Topographic steepness factor (LS) is used to estimate the impact of topography on soil erosion. Soil loss amount per area is directly correlated with the length of the slope (Tessema et al., 2020). The higher and lower slope has high risk of soil erosion (Kayet et al., 2018). It can be estimated by field measurement or a Digital Elevation Model (DEM) with GIS (Maqsoom et al., 2020; Kayet et al., 2018; Hateffard et al., 2021). In this study, satellite-based DEM data (Figure 5.1) from the Shuttle Radar Topography Mission (SRTM) was obtained from the U.S Geological Survey's web site (USGS). The spatial resolution of the SRTM DEM data is 30 m, and its vertical resolution is 16 m or better (Mukul et al., 2017). In this study, the following equation was used to calculate the topographic steepness factor (Parveen and Kumar, 2012; Hateffard et al., 2021).

$$LS = \left(\chi \times \frac{\lambda}{22.13}\right)^{0.5} \times (\text{Sin}\beta/0.0896)^{1.3} \tag{5.5}$$

where χ is the flow accumulation, λ is the raster cell dimension, β is the slope inclination in degrees (◦)

Land cover and management factor (C):

The land cover and management factor (C) is used to estimate soil loss from an area of a particular vegetation cover. Besides soil properties and slope steepness, the C factor is one of the most important drivers of soil erodibility (Panagos et al., 2015). Vegetation cover protects the soil surface from the impact of raindrops, and reduces runoff velocity, and even partial vegetation cover significantly reduces soil erosion (Boussaadi and Mauzai, 2021). In this study, the C factor was calculated based on the Normalized Difference Vegetation Index (NDVI) using the equation (Durigon et al., 2014) below.

$$C = 0.1 \times \left(\frac{-NDVI + 1}{2}\right) \tag{5.6}$$

The NDVI is one of the vegetation indices, that estimates the amount of green vegetation cover in a particular landscape. It ranges from -1.0 for to 1.0, where higher values represent higher vegetation cover and lower values represent low vegetation cover or barren land surface. In this study, NDVIs for the years 1989 to 2018 were presented as seasonal information in the following way: spring (April to May), summer (June to August) and autumn (September to October). This corresponds with the typical definition of these seasons in Mongolia (where the period from November to March can be considered as winter). Only, cloud-free or nearly cloud-free Landsat images were selected (Land cloud cover (LCC) ≤10%) and downloaded (via USGS) calculating the NDVI.

$$NDVI_{L4-7} = \left(\frac{(B4 - B3)}{(B4 + B3)}\right) \tag{5.7}$$

$$NDVI_{L8} = \left(\frac{(B5 - B4)}{(B5 + B4)}\right) \tag{5.8}$$

Conservation factor (P):

The conservation factor (P) represents the effect of precautionary measures for reducing soil erosion rate such as land treatments of countering, compaction, and constructive measures to control runoff and sediment transport (Maqsoom et al., 2020). It ranges from 0 for high-quality preservation practice to 1 for poor protection practices (Kayet et al., 2018). In this study, the P factor for the whole area of both cities was set as 1 (not influential) to calculate the RUSLE model as no prevention practices were applied in the two regions, except for limited drainage systems in the urban area around both mining regions.

Soil erosion risk:

Spatial patterns of soil erosion rates were visualized based on classification steps of 0-0.1, 0.1-0.5, 0.5-1, 1-2, 2-3, 3-5 and >5 t ha^{-1} $month^{-1}$ for showing lower to higher erosion rates regarding to Schmidt et al., 2016.

5.5 Results

5.5.1 R factor estimation

The average monthly value of the R factor from April to October for 1989-2018 ranges from 43.7 to 63.36 MJ mm h^{-1} $month^{-1}$ in Erdenet area and from 34.46 MJ mm h^{-1} $month^{-1}$ to 42.86 MJ mm h^{-1} $month^{-1}$ in the Baganuur area. Generally, the average monthly rainfall erosivity factor was higher in Erdenet area than in the Baganuur area due to higher rainfall in Erdenet.

Moreover, the highest average monthly rainfall erosivity factor was found during the vegetation growing season (June to August) in both study areas, ranging from 112.91 MJ mm h^{-1} $month^{-1}$ to 156.84 MJ mm h^{-1} $month^{-1}$ in Erdenet and from 95.43 MJ mm h^{-1} $month^{-1}$ to 112.41 MJ mm h^{-1} $month^{-1}$ in Baganuur (Table 5.4).

Table 5.4 Average R factor (MJ mm h^{-1} $month^{-1}$) in different months during the study period from 1989 to 2018

Study areas	Average: Apr-May		Average: June-Aug		Average: Sep-Oct		Average: Apr-Oct	
	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest
Erdenet	5.01	12.95	112.91	156.84	10.12	15.96	43.7	63.35
Baganuur	6.41	11.55	95.43	112.41	7.07	10.94	34.45	42.86

5.5.2 C factor estimation

The values of the C factors in the two mining areas differ according to the density of vegetation cover. Average C values range from 0.02-0.073 around Erdenet city and from 0.03-0.068 around Baganuur city during the period from 1989 to 2018 (Table 5.5). The value of the C factor were higher in the vicinity of the tailings pond and open-pit in both mining areas (Figure 5.4) indicating higher vulnerability to erosion. The C factor decreased around both mining area in the growing season, which corresponds to the season of highest precipitation across Mongolia.

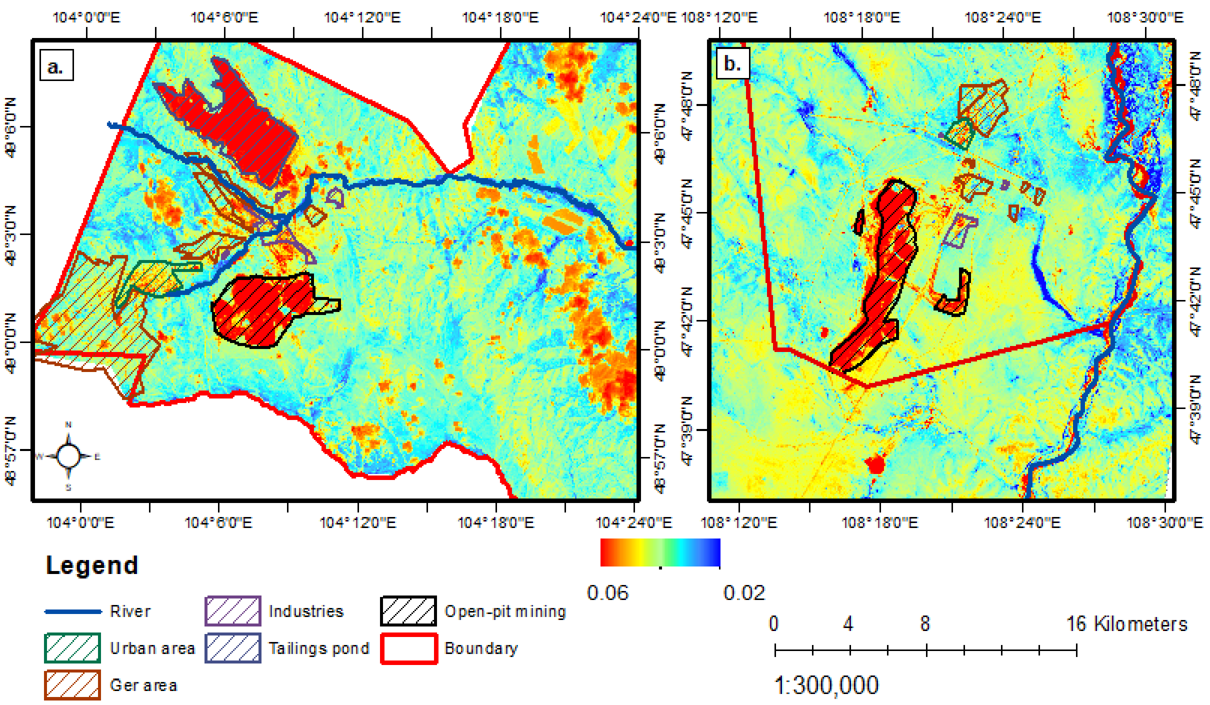

Figure 5.4 Spatial pattern of the C factor around two mining areas: (a) Erdenet, (b) Baganuur

Table 5.5 Average C factor in different months

Study areas	Average: Apr-May		Average: June-Aug		Average: Sep-Oct		Average: Apr-Oct	
	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest
Erdenet	0.036	0.07	0.013	0.067	0.026	0.072	0.025	0.07
Baganuur	0.034	0.06	0.017	0.072	0.035	0.074	0.029	0.071

When rainfall was identified the dominant cause of temporal variations in soil erosion, the C factor based on the vegetation index NDVI was identified as a good predictor of spatial erosion pattern. On the one hand, the C factor reflects the seasonal pattern of vegetation growth. On the other hand, it clearly identifies barren lands that are a consequence of mining operations. The map of spatial distribution of NDVI is shown in Figure 5.5 and Figure 5.6 to show the difference between the highest and lowest precipitation during the peak season of vegetation cover (June to August) during the study period 1989-2018 in both areas

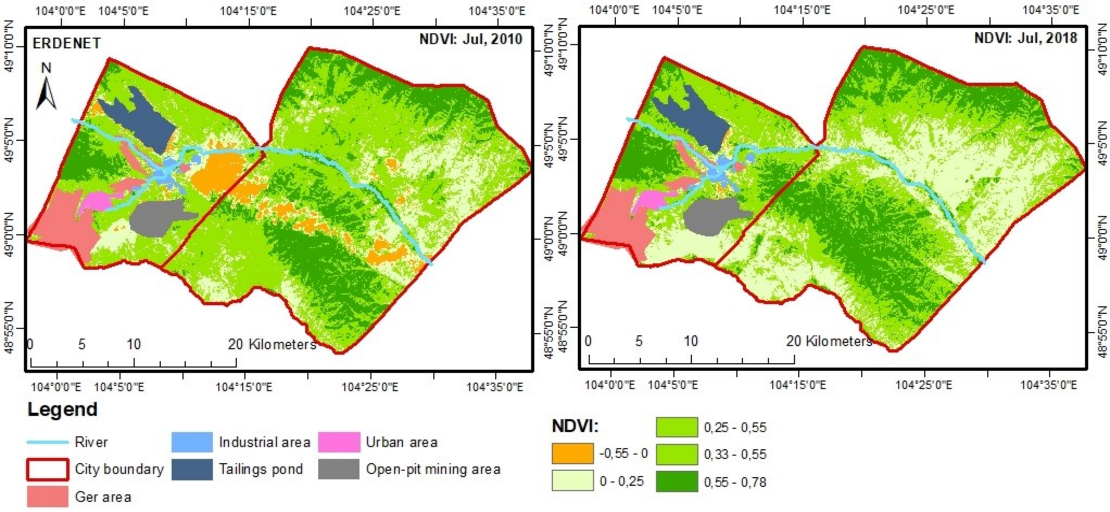

Figure 5.5 Spatial patterns of NDVI regarding the highest and the lowest rainfall months during the study period in higher vegetation cover season in Erdenet area (The lowest: Jul-2010. The highest: Jul-2018)

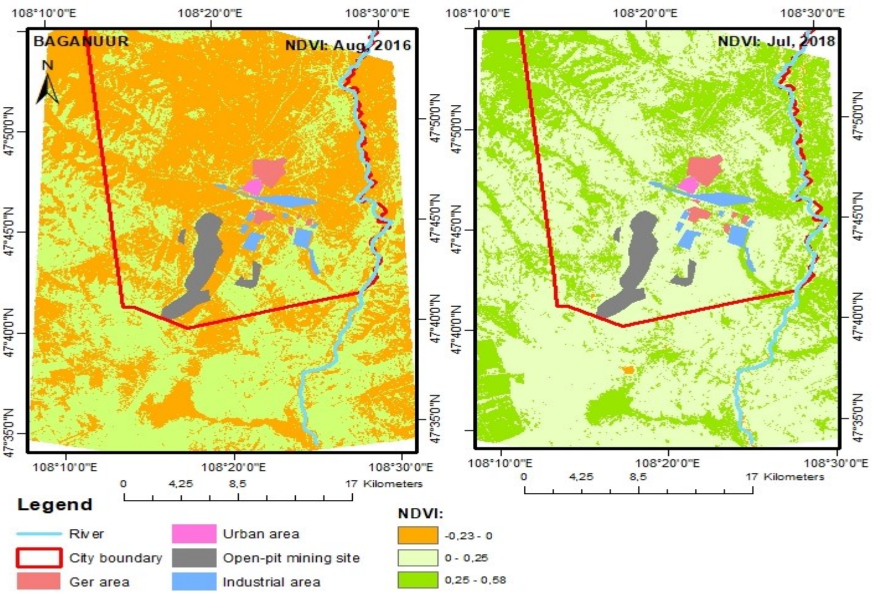

Figure 5.6 Spatial patterns of NDVI regarding the highest and the lowest rainfall months during the study period in higher vegetation cover season in Baganuur area (The lowest: Aug-2016. The highest: Jul-2018)

The spatial patterns of NDVI in wet and dry month and years clearly show that vegetation cover increases when precipitation is higher. However, the results of soil erosion showed that soil erosion rate during the study period was higher in the peak vegetation season from June to August and lower in autumn and spring. Rainfall amount is the most important factor in increasing soil erosion rate. This result is consistent with previous studies (Vandandorj et al., 2017; Schimdt et al., 2019; Shojaei et al., 2020; Duulatov et al., 2021).

5.5.3 *K factor estimation*

The soil erodibilty factor was defined based on SOM content and soil texture. The estimated organic matter content in Erdenet area was 0.16-0.41 % and in Baganuur area 0.05-0.36%. The soil textures of the sampled soils were generally sandy soil (92% of the total samples in Erdenet and 94% in Baganuur), with some loamy and sandy loam textures in the Erdenet area, and loamy sand and sandy loam textures found in Baganuur. These findings agree with literature which describes the soils of Baganuur as sands consisting of quartz, albite and microline (Park et al., 2020), and fine sand and some silt as the predominant soil textures around Erdenet (Battogtokh et al., 2014). Regarding to the SOM content and soil texture, the K values were selected from Table 5.3 as 0.12-loamy sand; 0.25-sandy loam; 0.27-sandy soil. The spatial patterns of the K factor was created in ArcMap software using the IDW technique.

5.5.4 *LS factor estimation*

The LS factor describes the combined effects of slope gradient and slope length (Maqsoom et al. 2020). In this study, the LS factor was calculated using Digital Elevation Model (DEM) data. The results of the LS factor ranged from 0-9.6 around the Erdenet mining area and 0-5.7 around the Baganuur mining area. In both areas, higher values of the LS factor were observed at higher altitudes due to longer and steeper slopes (Duulatov et al., 2021).

5.5.5 *Assessing soil erosion for 1989 to 2018*

The average monthly soil erosion rate was calculated in three different seasons: for spring (April to May), for summer (June to August), and for autumn (September to October) (Table 5.6). The average soil erosion rate was higher in Erdenet area than in Baganuur area due to higher rainfall in Erdenet.

Table 5.6 Average Soil erosion rate (t ha^{-1} $month^{-1}$) in different months (1989-2018)

Study areas	Average: Apr-May		Average: June-Aug		Average: Sep-Oct		Average: Apr-Oct	
	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest
Erdenet	0	0.42	0	4.96	0	0.49	0	2.0
Baganuur	0	0.45	0	4.16	0	0.38	0	1.58

The results of soil erosion modelling from 1989 to 2018 show that both study areas are susceptible to soil erosion, especially during periods of higher precipitation. Previous studies have found that the average soil erosion due to water erosion in summer is higher than soil loss in winter and autumn (Schmidt et al., 2019) and precipitation erosivity is the most important factor influencing soil loss (Schmidt et al., 2016). The highest soil erosion rates in both study region occurred when precipitation peaked between June to August (Table 5.7), which in Mongolia typically for 85-90% of the annual precipitation (Batkhishig, 2013).

5.5.6 *Soil erosion rate in Erdenet area*

Large parts of the total area (90.71%) experienced only few levels of erosion (0 to 0.1 t ha^{-1} $month^{-1}$) when considering the entire 30-year observation period. In general, erosion levels increased during the summer months due to higher precipitation. Erosion rates above 2 t ha^{-1} $month^{-1}$ were calculated only for the summer season, with limited areas even experiencing above 5 t ha^{-1} $month^{-1}$. The highest soil erosion rate (8.31 t ha^{-1} $month^{-1}$) was observed in July 2018 and the lowest soil erosion rate (0.05 t ha^{-1} $month^{-1}$) was calculated for April 2010. These events correlated with the highest rainfall (120.24 mm) in July 2018 and the lowest rainfall (8 mm) in April 2010 of the observation period. The comparison of soil erosion rate in the years with the highest and lowest rainfall in Erdenet is shown in Figure 5.7 to illustrate the spatial distribution. Erosion rates were calculated in July 2018 for the approximate area in the vicinity of different land uses such as open-pit mining area, ger area, urban area, tailing pond and industrial area (Table 9). For instance, the calculation showed that a 20 ha area near the open-pit area experienced erosion rates of 1-2 t ha^{-1} $month^{-1}$. The highest soil erosion rates were found near tailings pond and industrial areas in July 2018.

5.5.7 *Soil erosion rate in Baganuur area*

The results of the average monthly soil erosion rate were quite similar of those of the Erdenet area, with slightly lower values calculated for Baganuur. This can be explained by the higher rainfall in the Erdenet area. In the Baganuur area, higher soil erosion rates were observed during June to August, with 0.21% of the total area experiencing erosion of more than 2 t ha^{-1} $month^{-1}$. The average monthly soil erosion rate was lower in April to May and September to October (Table 5.7) when a threshold of 2 t ha^{-1} $month^{-1}$ was not exceeded. In July 2018, i.e. the wettest month of the observation period, 0.8% of the total area experienced intensive erosion of more than 2 t ha^{-1} $month^{-1}$. The highest soil loss rate (9.46 t ha^{-1} $month^{-1}$) was found in July 2018 and the lowest soil erosion rate (0.056 t ha^{-1} $month^{-1}$) was found in October 2018, corresponding to the highest amount of rainfall (134.65 mm) in July 2018 and the lowest amount of rainfall (4.46 mm) in October 2018. The comparison of the map with the highest and the lowest soil erosion rates is shown in Figure 5.8. In general, a higher erosion rate was found near the open-pit mine and at higher elevations. Erosion rates were calculated in July 2018 for the approximate area considering different land uses (Table 5.9).

Table 5.7 Average Soil loss rates (t ha^{-1} $month^{-1}$) in different months

Study areas	Average months	Eroded areas (%) of each average months according to different soil loss rates (t ha^{-1} $month^{-1}$)						
		0-0.1	0.1-0.5	0.5-1	1-2	2-3	3-5	>5
Erdenet	Apr-May	98.98	0.97	0.04	0.01			
	Jun-Aug	75.61	20.32	2.80	0.90	0.21	0.10	0.06
	Sep-Oct	98.21	1.69	0.06	0.04			
	Apr-Oct	90.71	7.82	0.99	0.32	0.07	0.04	0.05
Baganuur	Apr-May	99.28	0.69	0.02	0.01			
	Jun-Aug	81.26	16.01	1.87	0.65	0.13	0.05	0.03
	Sep-Oct	98.08	0.88	1.03	0.01			
	Apr-Oct	93.41	5.69	0.62	0.21	0.04	0.01	0.02

The estimated highest soil loss rates (>5 t ha^{-1} $month^{-1}$) as well as their area and the amount of eroded soil loss during 1989-2018 in both areas are shown in the Table 5.8. In general, higher soil erosion rates were observed in the Erdenet region than in the Baganuur region. During the study period, the highest erosion in both areas was observed in July 1998, 2013 and July 2018, which is directly related to rainfall.

Table 5.8 Highest soil loss rates (>5 t ha^{-1} $month^{-1}$) and its area

Study area	Soil loss rate (t ha^{-1} $month^{-1}$)	Area (ha)	Soil loss (t $month^{-1}$)	Month-Year
Erdenet	7.88	30	236.4	Jul-2018
	6.65	25	166.25	Aug-2013
	6.23	6	39.738	Jul-1998
	6.12	3	18.36	Jul-1995
Baganuur	9.46	21	198.66	Jul-2018
	8.85	19	168.15	Jul-1998
	5.45	15	81.75	Jul-2013

Table 5.9 Soil loss rates distribution by area (t ha^{-1} month^{-1}) in the vicinity of different area

Study areas	Areas	Eroded areas (ha) according to different soil loss rates (t ha^{-1} month^{-1})						
		0-0.1	0.1-0.5	0.5-1	1-2	2-3	3-5	>5
Erdenet	Open-pit mining	1784	370	66	20			
	Tailing pond	1492	501	37	56	23	8	5
	Industrial	673	400	122	25	23	15	0.5
	Ger settlement	1039	144					
	Urban settlement	390	71	20				
Baganuur	Open-pit mining	1977	872	142	31	3	2	
	Industrial	378	164	24	7	1		
	Ger settlement	485	236	38	9	1		
	Urban settlement	503	235	33	10	1	1	

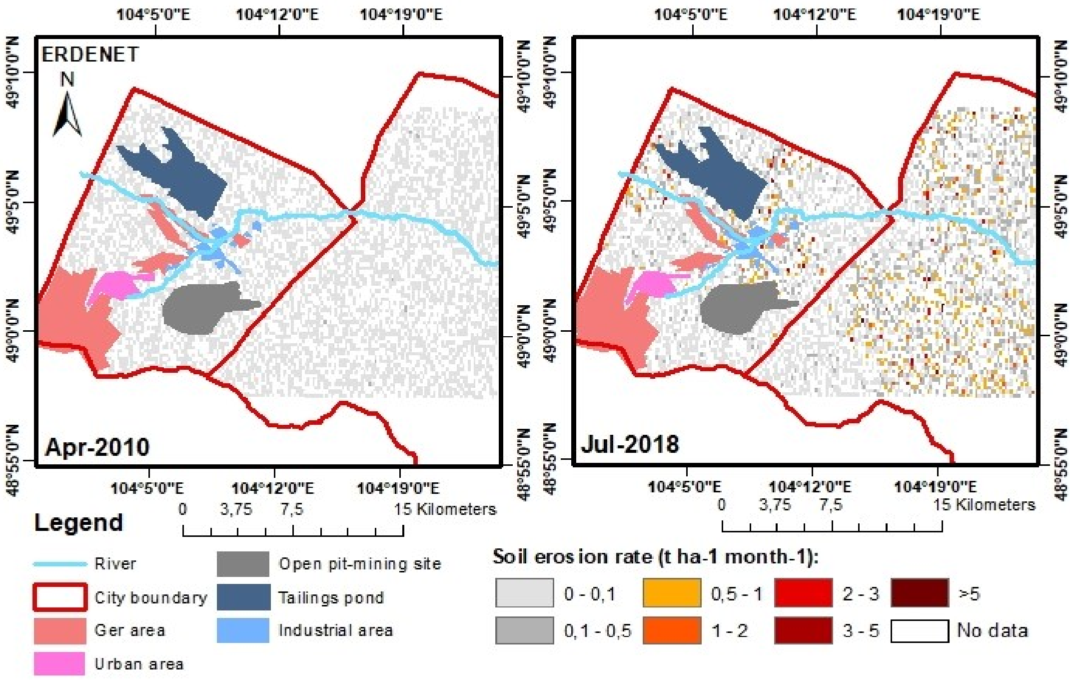

Figure 5.7 Spatial patterns of the highest and the lowest soil erosion rate in Erdenet area (The lowest month and year: Apr-2010. The highest month and year: Jul-2018)

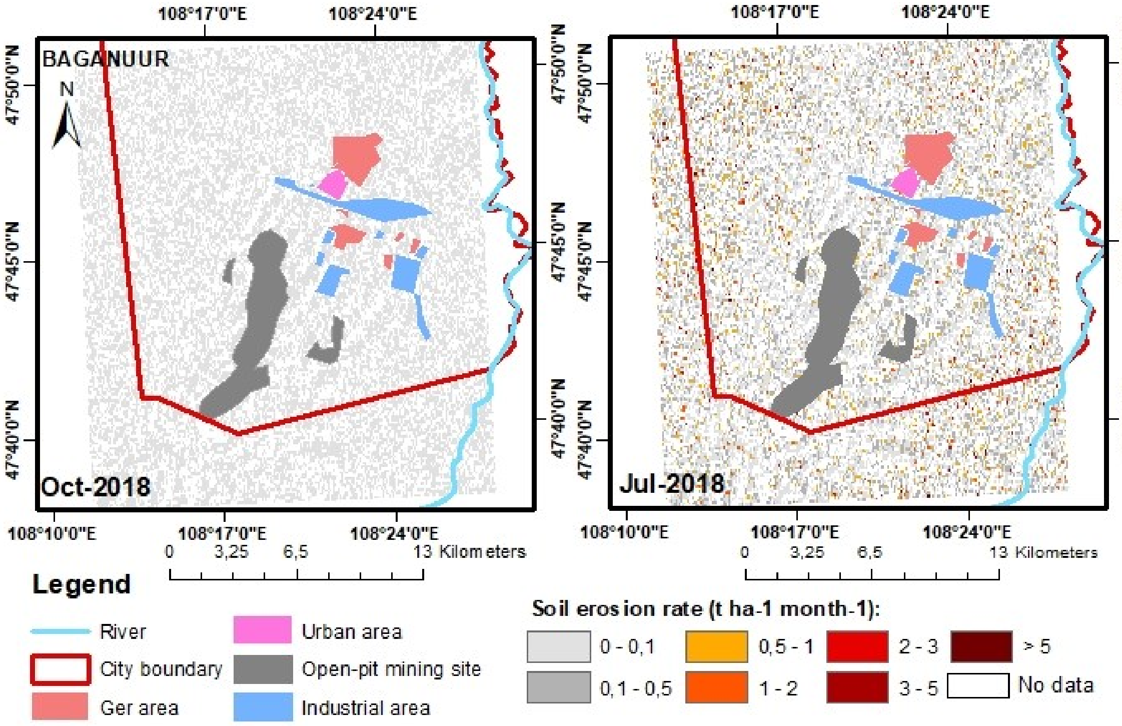

Figure 5.8 Spatial patterns of the highest and the lowest soil erosion rate in Baganuur area (The lowest month and year: Apr-2010. The highest month and year: Jul-2018)

5.6 Discussion and conclusions

This study revealed that in the semi-arid steppe environment of two Mongolia's largest mining sites, the open-cast lignite mine of Baganuur and the open-pit copper-molybdenum mining complex of Erdenet, the spatio-temporal pattern of soil erosion are driven by precipitation pattern and anthropogenic impacts from mining. Some of the highest soil loss rates were found at the extraction sites, but also near mining-related infrastructures such as the tailing pond of Erdenet. The lower soil erosion rates in the vicinity of the open-pit in some respects could be explained by differences in vegetation cover, for instance, a higher vegetation cover found in surrounding areas of the open-pit is explained by lower anthropogenic influences in that area, such as fences. Slightly higher soil loss rates were found in urban and ger settlement areas in Baganuur than in the same settlement areas in Erdenet. This can be attributed to topographic differences between the settlement areas. For example, the urban and ger areas in Baganuur are at a lower elevation and have more opportunities to receive water through precipitation, flooding and snowmelt from the higher elevated areas, and there are several stream channels that run through the settlement (Figure 5.1). Soil erosion rates were higher in the Erdenet area as compared to Baganuur, which is mostly due to higher precipitation. The highest monthly erosion rates were 8.31 t ha^{-1} $month^{-1}$ for Erdenet in July 2018, and 9.46 t ha^{-1} $month^{-1}$ for Baganuur in July 2018, which corresponded to the 30 year monthly rainfall maxima in both areas. The exceptionally high rainfall in 2018 can be attributed to El Niño conditions (UNESCAP, 2019). In Mongolia, intensive flood events were recorded in July 2018 in several parts of the country, particularly central and northern areas (IFRC, 2018). In the light of a trend towards a higher frequency and intensity of extreme precipitation events in the Mongolian steppe zones (Vandandorj et al., 2017), it is likely that such erosion rates will become more frequent in the future. From a soil conservation perspective, it is important to note that apart from steep natural mountain slopes, the highest erosion rates were calculated for the mining sites. Precautionary measures for limiting soil erosion should be considered during mining operation. In the long run, the rehabilitation of abandaned mining sites, and particularly the restoration of surface vegetation, can significantly help in reducing levels. Apart from these specific findings, the results of this study show that a combination of the RUSLE model and a GIS based approach that integrates ground-based data (in our case, soil texture and soil organic matter to calculate the soil erodibility factor K) and remote sensing based information (in our case, NDVI as a proxy for the land cover management factor C, the SRTM-DEM for calculating the topographic steepness factor LS, and a global precipitation dataset for deriving the rainfall intensity factor R) can be useful in operationalizing a soil erosion assessment over relatively large areas and long time periods. It is obvious that results should be interpreted with some caution, as all of the above-mentioned ways for quantinfying the input parameters of the RUSLE model have their limitations; in our case, the soil erodibility factor was based on limited number of samples, and each of the RS based datasets has some limitations (e.g. in terms of spatial or horizontal resolution). Nevertheless, the described approach can be a time-saving and cost effective technique for the operative monitoring and prediction of soil esosion, including the specific situation of mining areas.

6 RESOURCE CONUNDRUM IN MONGOLIA: SOIL CONTAMINATION FROM COAL AND COPPER-MOLYBDENUM MINING

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ABSTRACT

Soil contamination and resulting ecological disturbances are a common phenomenon in mining areas, including the vicinities of the largest and oldest open-pit mining areas in Mongolia. In this work, the potential ecological risk index (RI), Nemerow integrated pollution index (PI_N), and Geoaccumulation index (I_{geo}) were used to estimate the level of soil contamination with Ni, Cu, Zn, As, Cr, and Pb in the top layer of the soils around Baganuur coal mine and Erdenet copper-molybdenum mine. Three different analytical methods were used: portable X-ray fluorescence (pXRF) for the first assessment of samples, and stationary X-ray fluorescence (sXRF), and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) for the confirmation of results in the laboratory. Even though general contamination levels in both study areas were relatively low, some potentially toxic elements were found at contents several times higher than the maximum permissible level (MPL) according to the national standard of Mongolia. In the Baganuur area, Zn was up to 2.8 and As was up to 3.00 times higher, while in the Erdenet area, As was up to 2.4, Cr was up to 1.7, Cu was up to 8.1, and Zn was up to 1.2 times higher than MPL of the national standard in the vicinity to the mining and industrial area. The estimation of the pXRF measurement had generally similar results to the other two laboratory methods based on spatial distributions of heavy metal content. Among the different geochemical indices, the PI_N showed a more accurately distinguished spatial distribution of contamination. For example, highly contaminated areas were found in the vicinity of the open pit, the tailings pond, and the industrial area based on PI_N results: 3.6-4.9% of the total area in Baganuur and 3.1-4.9% of the total area in Erdenet. The identified pollution levels emphasize the essential need for soil rehabilitation in mining areas, a key factor in Mongolia's economic development and environmental stability. In addition, the lack of documented soil rehabilitation initiatives underscores the pressing need for enhanced environmental responsibility in the country's expanding mining sector.

6.1 Introduction

Soil resources are crucial for ensuring food security, biodiversity preservation, climate resilience, and other planet-scale aims. Sustainable management and protection of these resources are essential for achieving long-term development goals on regional levels. Soil contamination by heavy metals and metalloids (HMM) is a significant environmental issue worldwide that is relevant for soil health but for other environmental compartments as pollutant fluxes to water, the biosphere, or the atmosphere are possible (Ángel et al., 2023). Soil pollution with heavy metals, therefore, constitutes a complex health risk to humans and wildlife. For instance, some chemical elements, such as Hg, Cd, Cu, and As cause harmful consequences of a severe variety of disorders for human health even in low contents (Qi et al., 2020). Furthermore, contaminated soils with HMMs can lead to decreased soil fertility and become one of the main causes of increased soil degradation (Lehmkuhl and Batkhishig, 2003; Knippertz, 2005). Accumulation of heavy metal substances in the soils is mainly caused by anthropogenic activities such as mining and agricultural industrial processes, traffic dust, domestic emission, heavy industry, and chemical manufacturing (Knippertz, 2005; Hu et al., 2013; Pusz et al., 2021; Rasulov et al., 2013; Wang et al., 2020). In addition, mining activities are among the main causes of increased heavy metals in river loading (Karthe et al., 2017; Jarsjö et al., 2017).

At the regional and local levels, the extraction of metals, notably copper and molybdenum, can significantly impact freshwater reserves (Meißner, 2021), particularly in places like Mongolia, when water usage surpasses established limits, accounting for environmental needs and carrying capacities.

In the early 21st century, Mongolia faces a resource conundrum: On the one hand, the country depends economically on the extractive sector, but on the other hand, mining threatens the country's unique environment in multiple ways. In the last few decades, mining and other heavy industries have been rapidly developing in Mongolia and the mining industry is the major contributor to the country's economy (Batbayar et al., 2017). However, mining-related environmental degradation became a huge issue for regional ecosystems in general and soils in particular (Knippertz, 2005; Kosheleva et al., 2010; Pecina et al., 2023). Soil resources in Mongolia are integral to its economy, culture, environment, and overall well-being. So far, several studies have investigated heavy metals in the soils of Mongolia's biggest cities, particularly in the vicinity of mining areas (Knippertz, 2005; Kosheleva et al., 2010; Timofeev et al., 2016; Jarsjö et al., 2017; Karthe et al., 2017; Park et al., 2020; Pecina et al., 2023).

Baganuur coal and Erdenet copper-molybdenum mining and processing complexes are the pillars of the Mongolian economy. The Baganuur open-pit lignite mine produces 57% of Mongolia's domestic energy coal (Shagdaryn, 2016). The total area of the mine is 3169 ha (Dash, 2014). Davaasuren et al. (2015) reported a high content of radioactive isotopes of K, U, And Th in the ash of Baganuur coal. The authors also found that the radiation background of the Baganuur district was 1.6-1.7 times higher than the world's mean. So, the increased radiation levels are first of all caused by the natural rock composition, while coal extraction and incineration are the secondary sources. Mercury contents in Baganuur coal allow an assumption that its combustion is the main source of Hg emission in Ulaanbaatar (Chung and Chon, 2014). Nevertheless, Hg emissions occur at the power plant, and cannot be related to the mining process *per se*. The Erdenet open-pit mine extracts 32 million tons of ore and produces ca. 530,000 tons of copper concentrate and ca. 4500 tons of molybdenum concentrate annually (Mongolian Copper Corporation, 2016), accounting for more than 10% of Mongolia's GDP. The recent years saw constant growth in the volume of rock mass processing, extraction of copper-molybdenum ore, and accumulation of tailings at the Erdenet mine (Danilov et al., 2019). During each explosion in a quarry, 200-500 tons of fine dust and 6000-10000 m^3 of gases are released into the atmosphere; the resulting dust and gas cloud with a volume of 15-20 million m^3 is ejected to a height of 150-300 m and in its development can reach a height of 16 km and spread in the direction of the wind to a distance of 10-14 km. Dust content varies from 680 to 4250 mg/m^3 depending on the specific consumption and type of explosive, type of rocks, and other factors (Nosyrev et al., 2015). The volume of tailings in Erdenet reaches 600 million m^3, and their area is more than 1300 hectares (Zhargalsaikhan, 2022). The tailings consist of non-magnetic minerals: quartz, albite, and muscovite (95-98%). The rest 2-5% are magnetite, hematite, and iron which are probably the crusher material of the processing plant (Batbaatar, 2016). These tailings are the secondary raw materials that can be used to ensure the stable functioning of a mining enterprise upon mine closure after the exhaustion of the deposit (Davaahuu, 2015). However, the potential secondary resources are lost due to the aeolian deflation. Under the dry and windy climate during spring and autumn, the exposed sediments of mine tailings become an additional source of anthropogenic windblown dust and pose potential threats to the surrounding environment and human health. The combination of ground-based in-situ measurements and spatiotemporal satellite data analysis done by Batbold et al. (2022) showed the dust dispersion from the Erdenet tailings over an area of over 2,000 km^2.

Additionally to the air quality deterioration, the company affects the water resources. The wastewater seeps into the small tributaries of the Orkhon River through the dam of the tailing dump, bringing 1550 tons of suspended sediments annually (Mekhanobr Engineering, 2001) and the vast geochemical association of Cu, Mo, Ag, Se, Re, U, Th, Mg, Pb, Zn, Sb, Mo, Se, As, and Bi in the contents above background values (Byamba, 2007). Solongo et al. (2018) analyzed the waters and sediments from two shallow ponds and three rivers flowing through Erdenet city, downstream from the tailings storage facilities. The results suggest that the surface sediments from urban ponds and rivers play a role as secondary contamination sources of Mo rather than as sinks of Mo in the area. Similarly, Munemoto et al. (2020) investigated rare earth element contents in river water and sediments collected from the Erdenet, Gavil, and Khangal rivers. Their findings imply that these water bodies can be a potential source of contamination with rare earth elements and yttrium in the terrestrial water systems.

Evaluating the overall environmental conditions and contamination of mining sites depends on soil evaluations, which are essential for collecting materials and facilitating the movement of pollutants across the biosphere, hydrosphere, and atmosphere, and are particularly crucial in vulnerable ecosystems with changing climatic conditions (Buslaev et al. 2021). Even though a number of studies about mining-related environmental degradation and contamination in Mongolia have been done in recent years (Pecina et al., 2023), a comprehensive overview of the mining impacts on heavy metal soil pollution is still missing. This deficit makes it difficult to prioritize, at the national level, mitigation measures which depend on reliable knowledge of pollution and the associated ecological risks (Rong et al., 2022) that may result from exposure to contaminants in soil, water, air, and sediments (Saha et al., 2022). In Mongolia, such an ecological risk assessment was recently conducted in the former coal mining areas of Nalaikh district in Ulaanbaatar city. Investigations revealed moderate ecological risks due to pollution with Zn and very high ecological risks for pollution with Cr and As (Battsengel et al., 2020). To assess soil contamination, pollution indices are essential methods that facilitate the complex data to inform decision-makers and technicians, as well as raise public awareness. Among the group of indices, the Geoaccumulation index (Igeo) is the most useful index to define soil pollution in any region of the world (Kowalski et al., 2018). Igeo reflects the risk of single heavy metal in soil, and the Nemerow integrated pollution index (PI_N) reflect a risk of various heavy metals (Su et al., 2023).

Accurate estimation of heavy metals in soil is crucial and challenging (Shahbazi et al., 2019). During the last few decades, different X-ray fluorescence methods, Inductively Coupled Plasma mass spectrometry multielemental and isotope detection and portable X-ray fluorescence became effective analyzers and are widely used for measuring heavy metals in soil worldwide (Marguí et al., 2022). In Mongolia, previous studies on soil contamination by heavy metals and metalloids used conventional laboratory methods. So far, only a few studies have investigated soil pollution with pXRF analyzers. Even though the laboratory determination of heavy metals is more accurate and allows for lower detection limits, the use of pXRF instruments can be less expensive and time-consuming, and allows for a first in-situ screening that can help in identifying both pollution hotspots as well as non-contaminated areas (Hu et al., 2017; Jang, 2009; Shuttleworth et al., 2013; Chen et al., 2021). This has led to an increasing popularity of pXRF methods (Chen et al., 2021) but for certain elements including Ag, Cd, Co, Ni, V, Au, Bi, Cs, Hf, Pd, Sc, Ta, Te, and W accuracy issues have been documented (Hall et al., 2014). In Mongolia, a recent study compared heavy metal pollution of soils in a tannery region of Ulaanbaatar city to laboratory-based methods. The measurement results between the field-based pXRF device and laboratory-based analytical tool were highly correlated, the only exception was Cr content (Naidansuren et al., 2017).

In this study, the spatial distribution of heavy metals in the soils of mining areas was analyzed and used as the basis for potential ecological risk assessments. This included the Baganuur lignite mine in Baganuur city and the Erdenet copper and molybdenum mine in Erdenet city. The study aims to (1) investigate HMM content (Ni, Cu, Zn, As, Cr, and Pb) in top soils using portable X-ray fluorescence (pXRF), a stationary X-ray fluorescence (sXRF) and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), (2) delineate contamination zones based on spatial distributions of HMM, Potential ecological risk index (RI), Nemerow integrated pollution index (PI_N) and Geoaccumulation index (I_{geo}), and (3) define the correlation between distance and HMM content based on linear correlation analysis. The results of the research could serve as a document to develop appropriate mitigation measures for ecosystem and human health risks.

6.2 Materials and methods

6.2.1 Study area

The two biggest open-pit mining sites in Mongolia, the Erdenet copper and molybdenum mine in Erdenet city and the Baganuur lignite mine in Baganuur city, are the study areas of this research (Figure 6.1). The basic geographical information about the study areas is shown in Table 6.1.

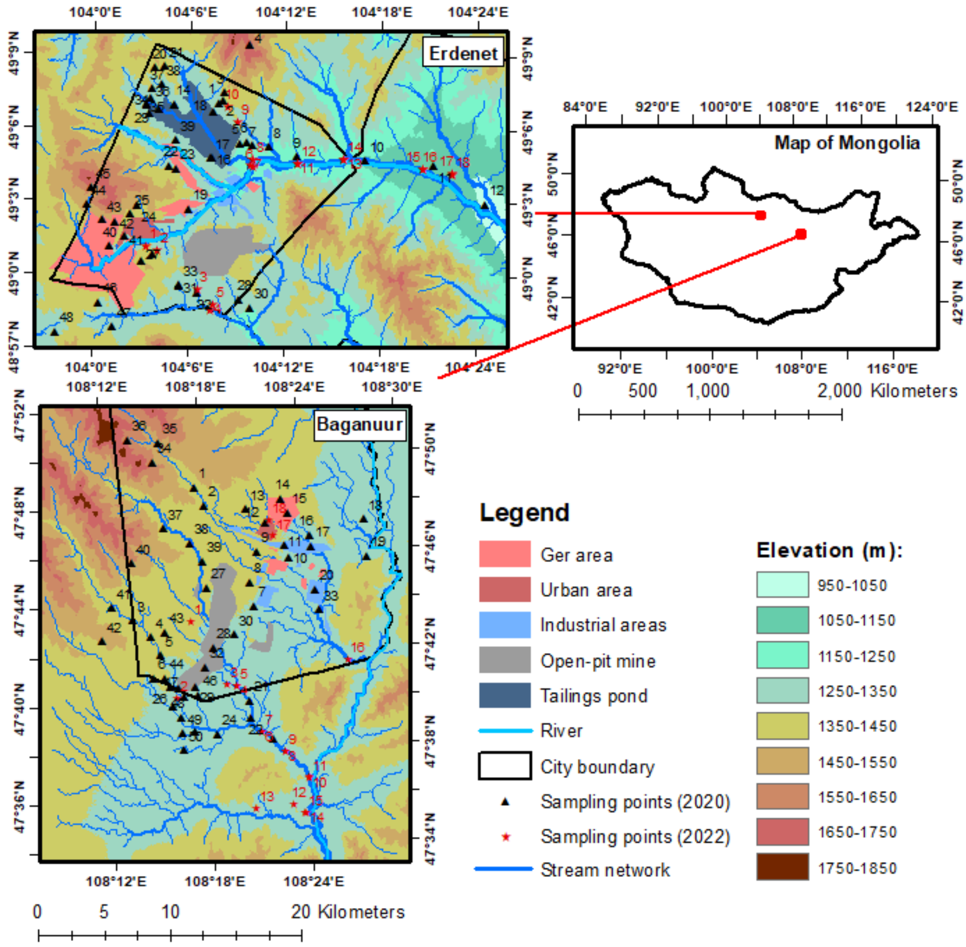

Figure 6.1 Elevation and locations of soil sampling points of the study area

Table 6.1 Study area information

Study area	Mine site information	Established year	Location (distance from Ulaanbaatar city)	Soil type (Khadbaatar 2021)	Köppen-Geiger climate classification (Köppen 1936)	Average temperature, °C Sodnomdarjaa et al. 2023)		
						Highest (month)	Lowest (month)	Mean
Erdenet city	Erdenet copper-molybdenum mine	1978	N 49°03'38" E104°03'31" (240 km northwest)	Chernozem and dark Kastanozem	Continental and semi-arid	+16.5°C (Jul)	-22.2°C (Jan)	0.7°C
Baganuur city	Baganuur lignite mine	1978	N 47°47'10" E108°21'40" (140 km east)	Kastanozem	Semi-arid	+18.2°C (Jul)	-20.7°C (Jan)	-2.2°C

A thorough examination of scientific literature highlights a diverse range of soil contamination challenges in the Erdenet and Baganuur mining areas. This includes notable instances of elevated heavy metal and metalloid content and variations in soil contamination levels, as documented in Tables 6.2 and 6.3. The comprehensive analysis underscores the significance of addressing these specific concerns in formulating effective remediation strategies and environmental management plans for the affected regions.

Table 6.2 Soil pollution issues in the Erdenet mining area as documented in the scientific literature

Element	Documented soil pollution issues	References
Cd	Some samples exceed Mongolian soil standard	Pecina et al., 2023 (n=48)
Co	All samples exceed Mongolian soil standard	Park et al., 2020 (n=5)
Cu	All samples well below Mongolian soil standard, only one outlier above	Pecina et al., 2023 (n=48)
Ni	All samples well below Mongolian soil standard	Park et al., 2020 (n=5)
Pb	All samples well below Mongolian soil standard	Pecina et al., 2023 (n=48)
Zn	All samples well below Mongolian soil standard	Pecina et al., 2023 (n=48)
	All samples well below Mongolian soil standard	Park et al., 2020 (n=5)
^{226}Ra	Specific radioactivity levels in soil samples from the Baganuur coal deposit are up to 2.4 times higher than the world mean	Erkhembayar et al., 2013 (n=4)
^{232}Th	Specific radioactivity levels in soil samples from the Baganuur coal deposit are up to 1.3 times higher than the world mean	Erkhembayar et al., 2013 (n=4)
^{40}K	Specific radioactivity levels in soil samples from the Baganuur coal deposit are up to 3.1 times higher than the world mean	Erkhembayar et al., 2013 (n=4)

Table 6.3 Soil pollution issues in the Erdenet mining area as documented in the scientific literature

Element	Documented soil pollution issues	References
As	Mean content in urban soils about four times the natural background	Chonokhuu et al., 2019 (n=29)
	Content elevated up to 1.6 times versus natural background	Timofeev et al., 2016 (n=225)
	Content in the mining area exceed the Mongolian soil standard, while levels in the tailings dam, residential, and background areas are far below the reference level	Yondonjamts et al., 2019 (n=60)
	The average value in the industrial zone and the tailings dump exceeds the Mongolian soil standard	Jargalsaihan et al., 2023 (n=29)

	Content of a single urban soil sample above natural background	Battogtokh et al., 2014 (n=27)
Cd	Content elevated up to 2.3 times versus natural background	Timofeev et al., 2016 (n=225)
Cr	Mean content in urban soils slightly above natural background	Chonokhuu et al., 2019 (n=29)
	Content elevated up to 2.6 times in stream sediment, only slightly elevated in urban soils	Battogtokh et al., 2014 (n=27)
Cu	Higher pollution rates found near tailing ponds	Knippertz, 2005
	Elevated levels in almost all land use classes	Kosheleva et al., 2010 (n=50)
	Content elevated up to 10.6 times versus natural background	Timofeev et al., 2016 (n=225)
	Content significantly elevated in almost all samples, up to 30.6 times versus natural background in urban soils and up to 48.6 times in stream sediments	Battogtokh et al., 2014 (n=27)
	Content in the mining area exceed the Mongolian soil standard, while levels in the tailings dam, residential, and background areas are far below the reference level	Yondonjamts et al., 2019 (n=60)
	Contents in the industrial, transport, and residential areas, exceed the Mongolian soil standard	Jargalsaihan et al., 2023 (n=29)
	Content in the mining area exceeds the Mongolian soil standard	Suyundukov et al., 2021 (n=2)
Mo	Elevated levels in almost all land use classes	Kosheleva et al., 2010 (n=50)
	Content elevated up to 10.7 times versus natural background	Timofeev et al., 2016 (n=225)
	Elevated contents in almost all urban soil (up to 19 times versus natural background) and stream sediment samples (up to 15.6 times)	Battogtokh et al., 2014 (n=27)
	Content in the mining area exceed the Mongolian soil standard, while levels in the tailings dam, residential, and background areas are far below the reference level	Yondonjamts et al., 2019 (n=60)
	Contents in the industrial and transport areas exceed the Mongolian soil standard	Jargalsaihan et al., 2023 (n=29)
Ni	Mean content in urban soils more than 50% above natural background	Chonokhuu et al., 2019 (n=29)
	Content only slightly above natural background	Timofeev et al., 2016 (n=225)
	Contents below Mongolian soil standard, close to natural background	Kosheleva et al., 2010 (n=50)
Pb	Higher pollution rates found near tailing ponds	Knippertz, 2005
	Mean content in urban soils slightly above natural background	Chonokhuu et al., 2019 (n=29)
	Content slighly elevated in urban soil samples (up to 3 times the natural background), but typically not in stream sediments	Battogtokh et al., 2014 (n=27)
	Contents below Mongolian soil standard, slightly above natural background	Kosheleva et al., 2010 (n=50)
Se	Content elevated up to 1.4 times versus natural background	Timofeev et al., 2016 (n=225)
Zn	Mean content in urban soils about twice the natural background	Chonokhuu et al., 2019 (n=29)
	Content only slightly above natural background, about 40% above background in industrial areas	Timofeev et al., 2016 (n=225)
	Contents in episodic samples in the transport area exceed the Mongolian soil standard	Jargalsaihan et al., 2023 (n=29)
	Content slightly elevated in some urban soil samples, and more significantly elevated in stream sediments (up to 2.8 times versus natural background)	Battogtokh et al., 2014 (n=27)

6.2.2 Soil sampling and laboratory analysis

Soil sampling: Soil samples were collected from a top layer (0-10 cm) of the fields in the vicinity of the open-pit mining, industrial, and human settlement areas (ger area and urban area). Urban areas are supplied by central heating, water supply and sewerage systems. Contrastingly, ger areas are not connected to those systems. Local combustion of coal (for heating and cooking purposes) and dumpling of ashes in the ger districts may be a local source of pollution that does not exist in the same way in other urban areas.

The field study of soil sampling work was done in 2020 and 2022. In the year 2020, a total of 48 surface soil samples were collected from Erdenet city and a total of 50 surface soil samples were collected from Baganuur city (Figure 6.1). Among the soil samples in Erdenet, 19 soil samples' locations were identical to the locations sampled by Knippertz et al. (2005) close to the tailings pond of the Erdenet mine. In the year 2022, a total of 18 soil samples were taken from each study area through the stream network from the open-pit and tailings pond (Figure 6.1). These samples were taken from the top layer (0-10 cm) of the soils and some samples from sediments of Kheren river in Baganuur city and Gavil river in Erdenet city. The coordinates of the soil sampling points were recorded with a global positioning system (GPS Garmin 64). Before the soil samples were analyzed, all samples were air-dried for around 48-72 hours at normal air temperature (26±2°C) in a laboratory of the German-Mongolian Institute for Resources and Technology (GMIT). After that, rock particles with more than 2 mm and plant roots were removed by sieving.

Texture analysis: Soil texture was determined by the dry sieve method based on particle size classification by the U.S. Department of Agriculture (USDA). A certain amount of soil samples (50 – 150 g) was placed in the three different diameters of sieves such as 0.05-2.0 mm (sand), 0.002-0.05 mm (silt), and <0.002 mm (clay) by USDA (2017) and approximately 8-10 minutes of shaking to separate material. After that, all soil samples were sieve-measured using the analytical balance, and USDA soil texture triangular diagram was used to determine soil texture.

Soil pH analysis: The procedure of the methods in this study was as follows: the air-dried soil sample and distilled water are mixed in a ratio of 5:1, respectively, for 1 hour in the shaker, and the pH is determined using a pH meter (Hanna HI2002 pH meter).

Assessment of HMM contamination: Contents of heavy metals and metalloids in the soil samples in 2020 were estimated using a pXRF in a laboratory of the German-Mongolian Institute for Resources and Technology in Mongolia (GMIT) and sXRF analysis in a laboratory of Department of Physical Geography and Geoecology of RWTH Aachen University in Germany. Heavy metal contents of the soil samples in 2022 were measured by ICP-OES in a laboratory (SGS Mongolia) in Mongolia. The contents of the elements were finalized by averaging pXRF measurements of two parallel samples for each soil sample. A total of 16 elements were detected by pXRF, and more than 30 elements were determined by sXRF analysis and ICP-OES. The main difficulty in measuring element content using pXRF is its limit of detection (LOD). When the desired element content is out of the range, the device likely sends the wrong values on the screen, specifically 0. Regarding the results of the three different analyses, the Mongolian standard of Soil quality, maximum approvable levels of contaminants in the soil (MNS 5850:2019) and previous studies (Knippertz 2005; Kosheleva et al. 2010; Timofeev et al. 2016; Chonokhuu et al. 2019; Park et al. 2020; Pecina et al. 2023), the most overlapped crucial elements were selected for further analysis, and those elements are potentially toxic heavy metals such as Ni, Cu, Zn, As, Cr, and Pb.

6.2.3 Contamination assessment

The analysis of the soil contamination level was calculated based on estimated contents of HMM in each soil sample (average, maximum, and minimum contents are shown in Table 6.5) and using the following geochemical indices.

Potential ecological risk index (RI): The index was developed by Hakanson in 1980, and it assesses the environmental risk degree due to heavy metals in water, air and soil (Zhou et al., 2022). The potential ecological risk index is calculated using the following equation given by Hakanson (1980):

$$RI = \sum_i^n E_r^i \tag{6.1}$$

$$E_r^i = T_r^i \times C_f^i \tag{6.2}$$

$$C_f^i = \frac{C_{HM}}{C_{ref}} \tag{6.3}$$

where E_r^i is the ecological risk factor of the substances, E_r value classified as no pollution (<2), moderate pollution (2-5), moderate to severe pollution (5-20), severe pollution (20-40) and extreme severe pollution (>40); T_r is the toxic-response factor of the each substances (Ni=5; Cu=5; Zn=1; As=10; Cr=2; Pb=5); C_f^i is the contamination factor, C_{HM} is the measured content of HMM in each soil sample, C_{ref} is the reference content of the HMM. The classification criteria of the RI index are given in Table 6.4.

Geoaccumulation index (Igeo): the Geoaccumulation index was proposed by Müller (1969) and provides a qualitative assessment of heavy metal contamination on soil pollution (Panghal et al., 2021). This index is one of the widely used indexes to determine soil pollution and represents soil contamination in the top layer of the soil.

$$I_{geo} = log_2 \left[\frac{C_n}{1.5B_n}\right] \tag{6.4}$$

where C_n is the measured content of the examined metal n in the soil, B_n is the geochemical background content or reference value of the heavy metal n and 1.5 is a constant by Müller (1969) to minimize the effect of possible variations in the background values which may be attributed to lithology and it is classified by Müller (1981) as shown in Table 6.4.

Table 6.4 Soil contamination categories by Igeo and RI

Igeo	Categories of contamination	RI index classes	Categories of contamination risk
I<0	Unpolluted	<150	Low ecological risk
0 – 1	Unpolluted to moderately polluted	150-300	Moderate ecological risk
1 – 2	Moderately polluted	300-600	Considerable ecological risk
2 – 3	Moderately to highly polluted	>600	Very high ecological risk
3 – 4	Highly polluted		
4 – 5	Highly to extremely polluted		
5<	Extremely polluted		

Nemerow integrated pollution index (PI_N): The Nemerow integrated pollution index was introduced by Nemerow in 1974 to assess the combined contamination level (Nemerow, 1974).

$$PI_N = \sqrt{\frac{PI_{max}^2 + PI_{ave}^2}{2}} \tag{6.5}$$

$$PI_i = \frac{C_i}{T_i} \tag{6.6}$$

where PI_i is the pollution index of HMM in each sample, C_i is the measured content of HMM in each soil sample, T_i is the permissible content of the HMM (soil reference values of each HMM in this study, shown in Table 6.4), PI_{max} is the maximum value and PI_{ave} is the mean value of PI_i of all heavy metals in each sample. PI_N values are classified as no pollution (≤0.7), precautionary pollution (0.7-1), slight pollution (1-2), moderate pollution (2-3), and severe pollution (≥3) (Pecina et al., 2023).

6.3 Statistical analyses

The descriptive statistical analysis of Ni, Cu, Zn, As, Cr, and Pb contents in both study areas was performed by Microsoft Excel 2010. Pearson correlation and linear model analyses were performed to assess correlations among the three analytical methods. Linear model analysis was performed to estimate the correlation between distance and heavy metal content. The original dataset contains 48 pXRF measurements in Erdenet, 50 pXRF measurements in Baganuur, and 26 sXRF measurements at both sites. In order to compare the contents of the HMM such as Ni, Cu, Zn, As, Cr, and Pb, 26 pXRF data have been selected which were taken at the same locations as the sXRF samples. In addition, the same HMM were measured using ICP-OES in 2022. The total number of samples was 18 at both sites, although the sampling points did not exactly coincide with those obtained by pXRF and sXRF. The HMM data from ICP-OES were used to calculate the relationship between the distance from the source area and heavy metal content with respect to the stream network (Figure 6.1). The analysis was undertaken to test the hypothesis that HMM content diminishes significantly with distance from the source areas. In order to test the distribution of the HMM displayed in the maps (Figure S6.1 and Figure S6.2) for pXRF, sXRF, and ICP-OES, the data were gridded using ArcMap 10.8 software. The gridded dataset of the HMM contains content at the same locations. The grid dataset included 225 data points in Erdenet and 220 in Baganuur.

6.4 Results

6.4.1 Basic soil characteristics

In both study sites, the dominant soil particles were silt and fine sand, and the soil textures were predominantly sandy soil (92-94%), and loam or sandy loam (6-8%). The soil pH of the soils in Erdenet and Baganuur mining areas ranged from 3.5 to 8.5 and 4 to 8 respectively. The soil pH values are presented in Figure 6.2 based on an interpolated result. The spatial distributions of the soil pH show acid conditions (3.0-5.0) in the vicinity of the tailings pond, open-pit and industrial area of Erdenet, and the higher hills, ger area and the area below the open-pit mine in Baganuur. A previous study in Erdenet by Kosheleva et al., 2017 found that more acid soils were found in areas closer to the mining sites and anthropogenic areas. Recent literature describes soil pH ranges of 5.6-7.1 for Baganuur (Park et al., 2020) and 5.2-6.3 for Erdenet (Kosheleva et al., 2017), but it is important to note that these studies covered different areas as compared to the investigation presented here.

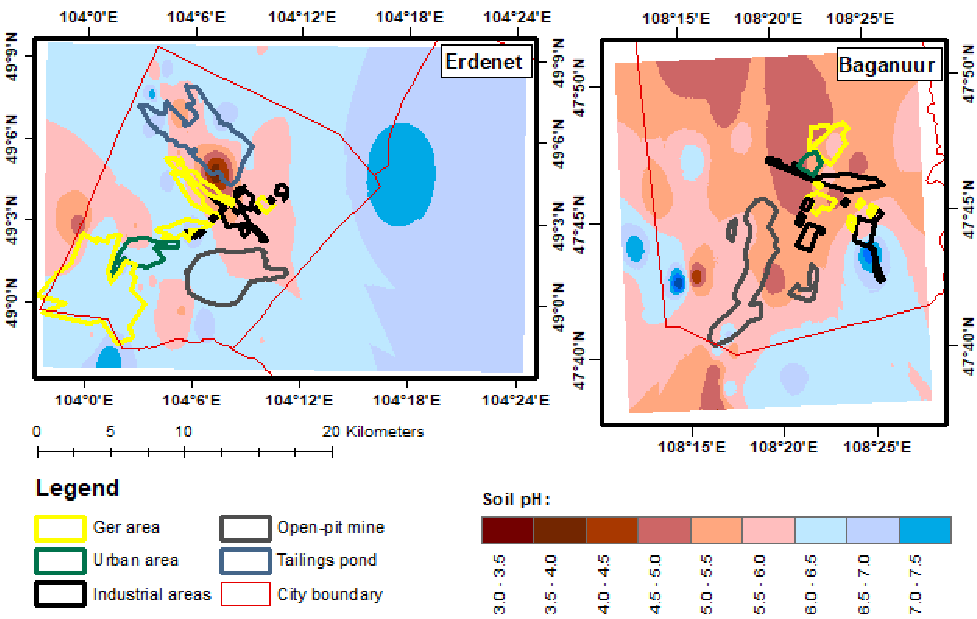

Figure 6.2 Spatial distribution of soil pH results

6.4.2 *Heavy metals content in soils*

Descriptive statistics for heavy metals in the soil samples are provided in Table 6.5. In this study, average contents of HMM were determined by sXRF, ICP-OES and pXRF for locations without discernable anthropogenic impact were considered as reference values and used for the calculation of geochemical indices. Additionally, reference values of previous studies, Mongolain national thresholds, and the global average chemical composition of 13,925 soil samples from 55 mined coal fields are documented in Table 6.6. The average content of all HMM (except some points of Cr and As) is significantly higher in the soils of the Erdenet area than in the Baganuur area. The content of Ni, Cu, Zn, As, Sr, and Pb in the soils of Erdenet and Baganuur area were interpolated from point data to raster map for showing spatial distributions using the Inverse distance weighted (IDW) method in ArcMap 10.8 software.

According to the spatial distributions of the HMM, Ni, Zn, Pb, As, and Cr contents were higher in low areas in Erdenet based on all methods (pXRF, sXRF and ICP-OES) and Cu content is higher in areas in the vicinity of an open-pit mine, tailings pond, industrial and aer area in Erdenet city. In the Baganuur area, higher values of HMM contents were found in areas of higher elevation. In general, 1.78-2.02 times higher content of Cr, 2.5-2.66 times higher content of Ni, 2-6.66 times higher content of Cu, 1.38-1.64 times higher content of Zn, 0.65-1.12 times higher content of As and 0.75-0.93 times higher content of Pb were found in the soils in Erdenet area than Baganuur based on the contents of the HMM. The median contents of individual HMM in soils in descending order are Cu>Zn>Cr>Ni>Pb>As in Erdenet, and Zn>Cr>Pb>Cu>Ni>As in Baganuur. The relatively high levels of Cu and Cr in Erdenet are a matter of concern due to the element translocation from soils to biota. Baljinnyam et al. (2009) analyzed the lungs, spleens, livers, kidneys, and hearts of grazing animals in Erdenet and found them to be a suitable biological indicator to determine the level of contamination of surface soil and vegetation: higher contents of Cr and Cu in soils were reflected by higher levels in inner organs of goats and sheep.

Table 6.5 The descriptive characteristics of the HMM in the soils (mg kg^{-1})

HMM	Method	HMM content (mg kg^{-1}) Erdenet area					Baganuur area				
		Mean	Mdn	Min	Max	SD	Mean	Mdn	Min	Max	SD
Cr	pXRF	56.47	45.0	35.0	105.0	22.2	23.33	22.5	10.0	45.0	13.29
	sXRF	58.75	57.52	33.0	104.95	16.05	31.77	32.17	14.4	51.35	8.21
	ICP	38.61	39.5	12.0	60.0	14.1	19.5	19.5	11.0	30.0	4.82
Ni	pXRF	40.44	45.0	15.0	75.0	13.76	26.47	25.0	10.0	50.0	11.84
	sXRF	32.06	33.15	19.15	49.95	7.22	12.92	12.42	7.45	22.4	3.53
	ICP	20.16	20.0	9.0	33.0	6.53	8.83	8.0	5.0	14.0	2.5
Cu	pXRF	74.79	60.0	20.0	290.0	49.92	11.86	30.0	10.0	60.0	11.86
	sXRF	58.21	45.05	27.35	271.85	48.47	16.54	14.8	8.75	36.3	6.12
	ICP	186.28	103.0	37.0	484.0	168.31	17.0	15.45	8.8	28.6	6.6
Zn	pXRF	91.04	90.0	65.0	115.0	13.20	72.1	65.0	40.0	275.0	39.6
	sXRF	86.46	84.3	63.3	123.2	13.01	58.64	54.62	27.7	114.85	21.09
	ICP	74.66	76.5	41.0	115.0	21.31	54.72	46.5	29.0	164.0	29.48
As	pXRF	10.32	10.0	5.0	20.0	3.56	10.56	10.0	5.0	30.0	5.19
	sXRF	5.86	5.27	1.55	11.15	2.64	7.56	8.02	2.7	14.55	2.62
	ICP	10.94	9.0	4.0	24.0	5.65	9.0	8.0	6.0	17.0	3.16
Pb	pXRF	14.37	15.0	5.0	30.0	4.79	20.9	20.0	10.0	50.0	6.11
	sXRF	20.58	20.4	14.05	29.35	3.37	22.14	21.75	19.1	26.1	1.90
	ICP	16.5	17.0	12.0	25.0	3.18	22.22	22.0	18.0	29.0	2.94

Table 6.6 Mean reference (background) contents of HMM in the soils, found in this and previous studies, the global reference levels in coal mine soils, and the Mongolian standard (mg kg^{-1})

Study area	HMM value description (sample number in Figure 6.1)		Cr	Ni	Cu	Zn	As	Pb
Erdenet	Reference values /this study/	pXRF, n=1 (46)	45	50	55	95	10	15
		sXRF, n=1 (46)	59.3	37.35	36.9	92.7	3.85 (*10*)	22.1
		ICP, n=2 (ave.17, 18)	60	32	64.55(*60*)	103 (*100*)	4 (*10*)	18.5
	Reference values /previous studies/	Knippertz 2005			112	67.8		71
		Kosheleva et al. 2010	81.7	34.2	24.3	65		22.5
		Timofeev et al. 2016	51	26.7	46.6	89.2	9.7	22.4
		Chonokhuu et al. 2019		18.6		77.8	4	15
Baganuur	Reference values /this study/	pXRF, n=1 (34)	20	30	35	85 *(60)*	10	25
		sXRF, n=1 (34)	29	11.05	10.4	36.95	8.4	19.1
		ICP, n=2 (ave.17, 18)	22	10	13.6	57	8.5	25.5
	Reference values /previous studies/	Park et al. 2020	36.86	13.66	35.77	70.38	14.17	8.2
		Pecina et al. 2023			13.6	51.7		29.6
Global average levels in the soils of coal mines		n=13,925	150	78.2	63.9	138	15.9	39.3
Maximum permissible level (MPL) of the heavy metals		Mongolian standard MNS5850:2019	60	60	60	100	10	50

(number) – value used to calculate the pollution indices
n – a total number of samples

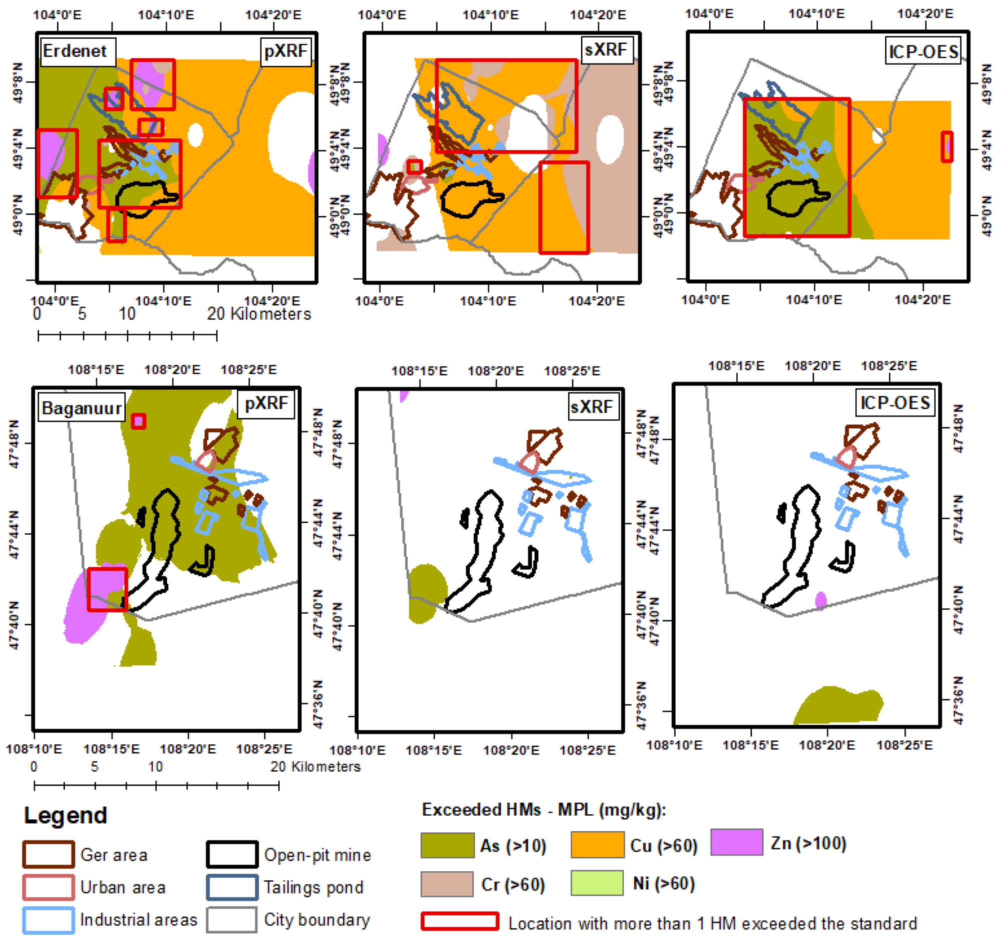

Figure 6.3 Spatial distributions of exceeded HMM than the maximum permissible level of MNS5850:2019

Table 6.7 HMM contents exceeding Maximum permissible level of MNS 5850:2019 (exceedance factors)

Study area	HMM	Method					
		pXRF		sXRF		ICP-OES	
		Min *(ID)*	Max *(ID)*	Min *(ID)*	Max *(ID)*	Min *(ID*)*	Max *(ID*)*
Erdenet	Cr	0.05	1.75 *(3)*	0.55 *(19)*	1.74 *(3)*	0.2 *(11)*	1.0 *(17)*
	Cu	0.33 *(22)*	4.83 *(16)*	0.45 *(8)*	4.53 *(5)*	0.39 *(4)*	8.06 *(6)*
	Zn	0.65 *(30)*	1.15 *(45)*	0.63 *(8)*	1.23 *(22)*	0.41 *(10)*	1.15 *(5)*
	As	0.01	2.0 *(24)*	0.15 *(8)*	1.11 *(15)*	0.2 *(17)*	2.4 *(3)*
Baganuur	Zn	0.4 *(23)*	2.75 *(6)*	0.27 *(1)*	1.14 *(18)*	0.41 *(11)*	1.15 *(6)*
	As	0.01	2 *(43)*	0.27 *(8)*	1.45 *(19)*	0.2 *(17)*	2.4 *(3)*

(ID) – Soil sampling point IDs in 2020 (Figure 6.1)
(ID) – Soil sampling point IDs in 2022 (Figure 6.1)*

Spatial patterns of HMM contents exceeding the MPL of the Mongolian standard (MNS5850:2019) are shown in Figure 6.3 and Table 6.7. In the Baganuur area, Zn exceeded the MPL by up to 2.84 times and As by up to 3.0 times both in the vicinity of the open-pit mine area. Whereas in the Erdenet area, Cr exceeded the MPL by up to 1.75 times, Cu up to 8.06, Zn up to 1.23 times, and As up to 2.4 times (Table 6.7). The significantly higher number of exceedances were found near tailings ponds, and in river sediments downstream of Erdenet. In Baganuur, most exceedances were found in proximity to the open-pit mine and downstream of it (Figure 6.1). The pattern confirms the hypothesis of a pollutant dispersal by wind and through the tailing impoundment by flowing water in Erdenet (Battogtokh et al., 2020). Apart from a spread downstream from pollution sources, it is obvious that HMM contents are higher near anthropogenically impacted areas, especially industrial and mining areas (Huang et al., 2019; Li et al., 2020). In most cases, individual and mean contents of HMM are below the MNS5850:2019 standard values and agree with values from the previous studies. In general, the results of the HMM of this study confirm the main findings of earlier studies: (1) HM reference values in Erdenet were higher for Cr, Ni, Cu, and Zn as compared to Baganuur, with similar values for As and Pb (Knippertz, 2005; Kosheleva et al., 2010; Timofeev et al., 2016; Chonokhuu et al., 2019; Park et al., 2020; Pecina et al., 2023).

The case of Pb is more specific to Mongolia. The study of Erdenebayar et al. (2019) shows that lead exposure remains common, especially in peri-urban areas of Erdenet where nearly 30% of the children aged 4–7 years have blood lead levels above the current reference value of 5 μg/dL established by the United States Centers for Disease Control and Prevention. The authors suggest that this can be attributed to the effect of lead pollution from large mining operations. However, we consider this effect as an indirect one because the legacy Pb pollution is more probably related to leaded gasoline formerly used in Mongolia by mining fleets, and by private vehicles as well. Nevertheless, the urban transportation system can be a source of higher ecological risk. Dorjhand et al. (2010) found that both aqueous and organic extracts of Erdenet soils have mutagenic effects on *E.coli* and *S.typhimurium* strains, and the highest effect was registered in samples taken near the city highway.

6.4.3 Geochemical assessment of soils

In this study, the most commonly used geochemical indices were applied for assessing the level of heavy metal contamination in the soils, such as Potential ecological risk index (RI), Ecological risk factor (Er), Nemerow integrated pollution index (PI_N) and Geoaccumulation index (I_{geo}) based on the HMM (Ni, Cu, Zn, As, Cr and Pb) in Erdenet city and Baganuur city.

Potential ecological risk (RI): In general, RI results indicated relatively low ecological risk in both study areas. Only at sampling point number 6 (2022) (Figure 6.1) which is the area at the downward (south east) stream network from the tailings pond in the Erdenet area, a higher Er result was found based on a Cu value of 40.3 mg kg^{-1}, indicating a moderate potential ecological risk. Battogtokh et al., 2014 found that stream sediments had a higher contamination than soils and it had much coarser particles of ore stock materials. In the Baganuur area, As contents (5.57-14.17 mg kg^{-1}) were found in the flying dust in the mining area and around 80% of the measured particle size around the mining site was around less than 150 µm (Park et al., 2020). Regarding the Er results, a relatively significant difference of the mean and median was calculated for Cu and a significantly higher standard deviation was found in Cu and As in the Erdenet area. Contrastingly, in the Baganuur area, the difference between the median and mean was relatively low for all HMM, and a higher standard deviation was found for As, Ni, and Cu.

Geoaccumulation index (I_{geo}): Generally, mostly unpolluted to moderately polluted soils were found in both areas. When considering the Igeo for different HMM, higher values were found for Cu in the Erdenet area and Zn in the Baganuur area (Figure 6.4 and Figure 6.5). A higher difference was found for Cu between mean and median values in Erdenet and Zn in Baganuur. A relatively higher standard deviation was found in Erdenet for Cu and Cr and in Baganuur for Zn, Cu and As (Table 6.8). Yondonjamts et al. (2019) also reported significantly high enrichment factor and I_{geo} values in the Erdenet mining area, confirming that Cu and As in the soil from the mine industrial area reach serious levels and their sources may be related to anthropogenic activities such as mining.

Nemerow integrated pollution index (PI_N): The index showed that both studied sites have slight to moderate pollution (Figure 6.6). Analysis of the PI_N classifications percent compared to the total area showed that around 2.3-5.8% area was not polluted, 9.6-12.8% of the area falling into the category of precautionary pollution, 62-77.1% area into slight pollution, 7.6-9.8% area into moderate pollution and 3.9-4.6% area into severe pollution in Baganuur. For the Erdenet area, around 3.5-5.3% area is not polluted, 3.6-6.8% area showing precautionary pollution levels, 65.4-78.9% slight pollution, 9.1-22.6% area moderate pollution, and 3.1-4.9% area severe pollution. Soils with moderately to severely polluted areas were found in the vicinity of the open pit in the Baganuur area and in Erdenet; soils with the highest pollution were found in areas near the tailings pond, open pit, and urban-industrial agglomeration based on both analytical methods (Figure 6.6).

For the Baganuur mining area, we additionally used enrichment factors to establish the extent to which contents of specific elements in the impacted soils surpass *the global average levels of coal mine soils* (Table 6.6). The positive finding is that the mean levels of all six considered elements (Table 6.5) are below the worldwide reference levels for polluted soils of coal extraction sites. Nevertheless, attention is drawn to the accumulation of As and Zn. Specifically, the maximum contents in certain samples exceed the typical pollution levels of coal mines: 1.1 or 1.9 times for As and 1.2 or 2.1 times for Zn (measured using ICP or pXRF). The contents of these two elements determined through sXRF are nearly equivalent to worldwide levels. In order to gain insights into the origins and routes of contamination, further exploration into the presence and distribution of these elements within the host rocks and original uncontaminated soils is necessary. This requirement constitutes a distinct subject for independent case studies. However, an illustrative concept worth noting is the "coal affinity index" which gauges the efficiency of coal in acting as a geochemical barrier for trace elements (Ketris and Yudovich, 2009). This index is computed by dividing the worldwide abundance of a particular element in coal by its global abundance in sedimentary rocks. A heightened coal affinity index signifies that coal has absorbed more chemical elements from the surroundings compared to sedimentary rocks. Following this classification, As and Zn are classified as highly coalphile and coalphile elements, respectively.

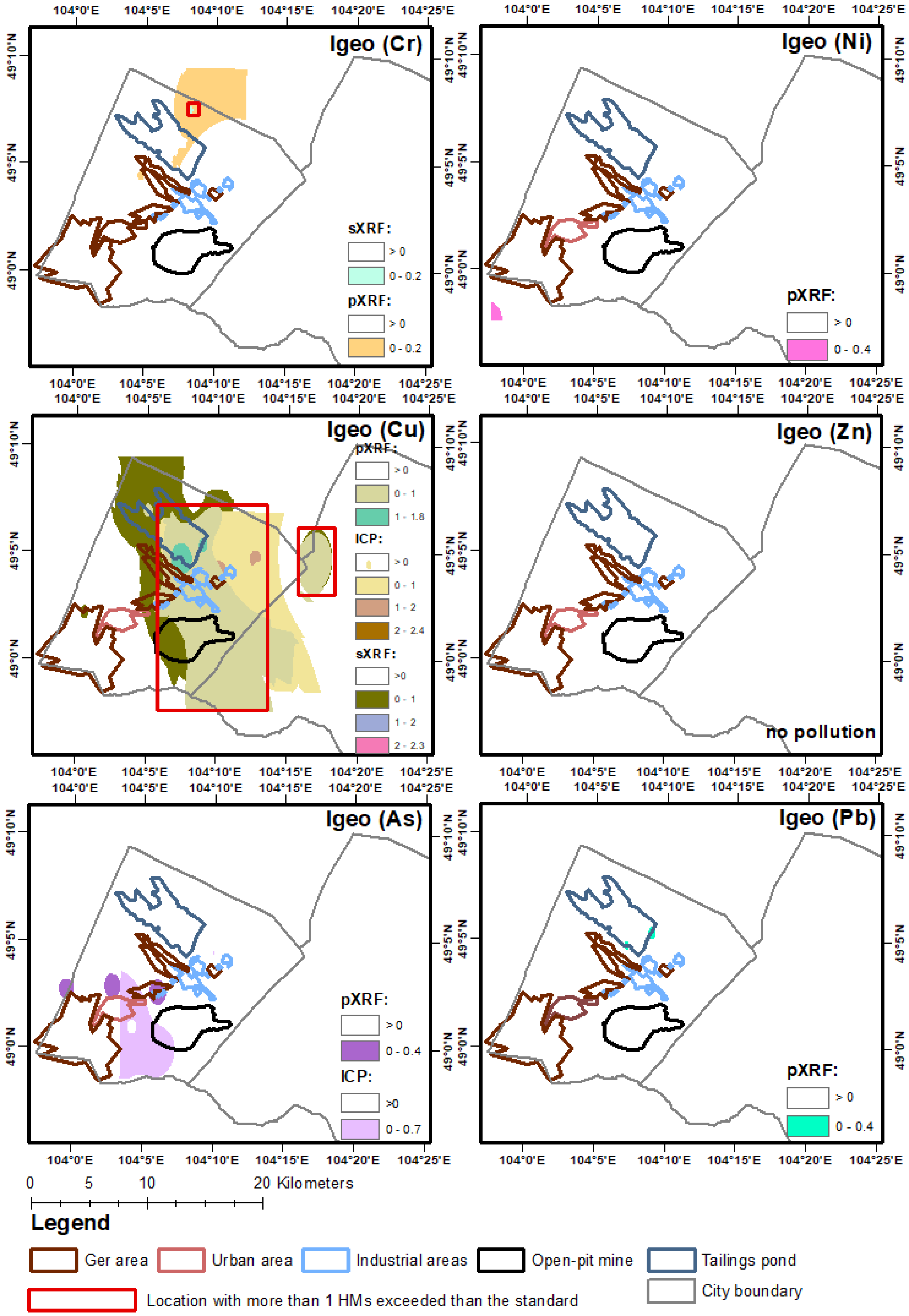

Figure 6.4 Spatial distributions of Geoaccumulation index (Igeo) results in Erdenet area. Unpolluted (<0); unpolluted to moderately polluted (0-1); moderately polluted (1-2); moderately to highly polluted (2-3); highly polluted (3-4); highly to extremely highly polluted (4-5); extremely polluted (>5)

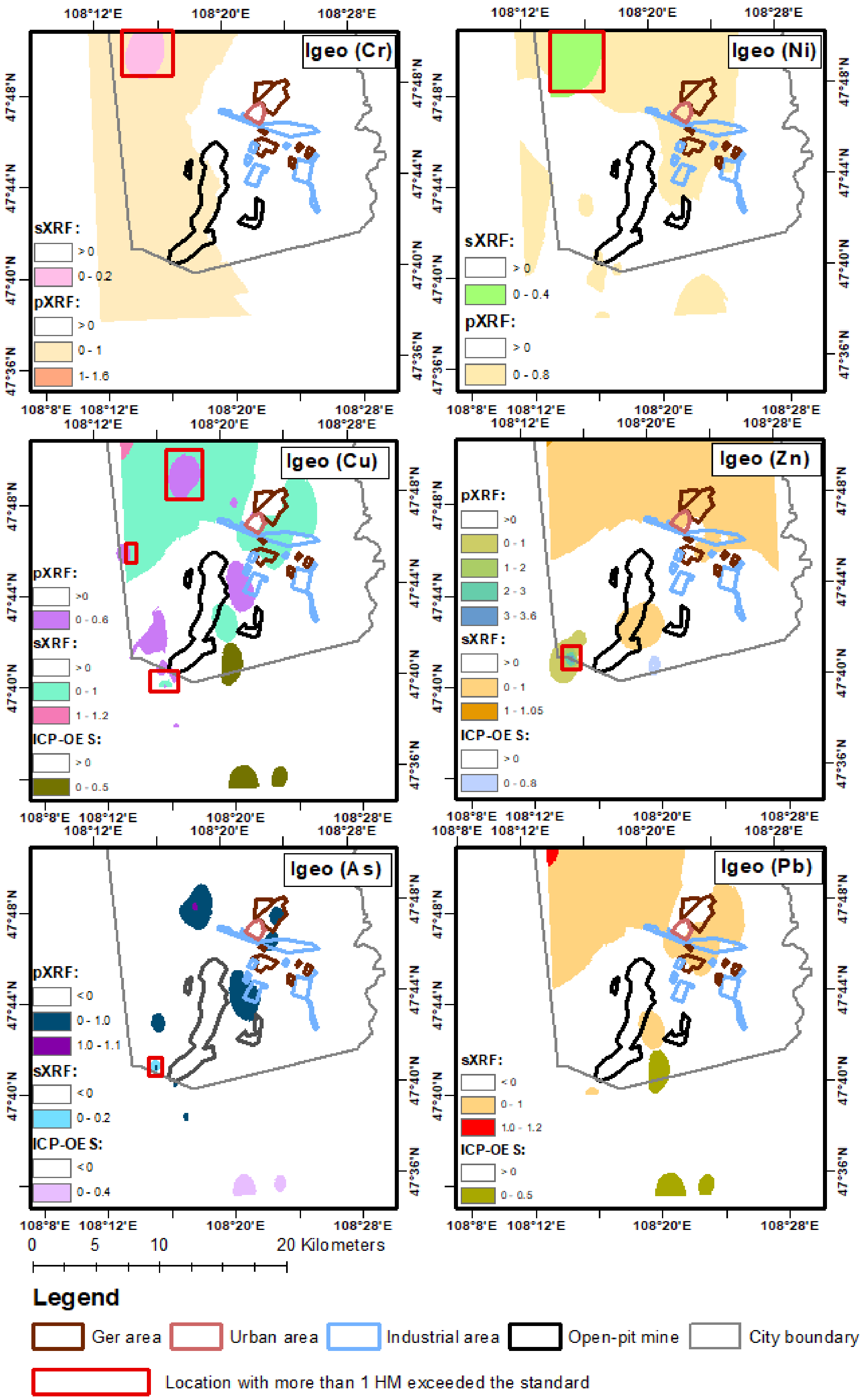

Figure 6.5 Spatial distributions of Geoaccumulation index (Igeo) in Baganuur area. Unpolluted (<0); unpolluted to moderately polluted (0-1); moderately polluted (1-2); moderately to highly polluted (2-3); highly polluted (3-4); highly to extremely highly polluted (4-5); extremely polluted (>5)

6.4.4 *Statistical analysis results*

Table 6.8 Basic statistical results of Geochemical indices based on HMM

Index	pXRF					sXRF					ICP-OES				
	Mean	Mdn	Min	Max	SD	Mean	Mdn	Min	Max	SD	Mean	Mdn	Min	Max	SD
I. ERDENET AREA															
1.1 Igeo															
Cr	-0.3	-0.5	-0.9	0.6	0.5	-0.6	-0.6	-1.4	0.2	0.4	-1.3	-1.1	-2.9	-0.5	0.6
Ni	-0.9	-0.7	-2.3	0.4	0.6	-0.8	-0.7	-1.5	-1.1	0.3	-1.3	-1.2	-2.4	-0.5	0.5
Cu	-0.3	-0.4	-2.0	1.8	0.7	-0.1	-0.3	-1.0	2.3	0.7	-0.2	-0.3	-1.9	2.4	1.1
Zn	-0.6	-0.6	-1.1	-0.3	0.2	-0.7	-0.7	-1.1	-0.2	0.2	-1.1	-0.9	-1.8	-0.3	0.4
As	-0.5	-0.5	-1.5	0.4	0.5	-1.5	-1.5	-3.3	-0.4	0.7	-0.7	-0.7	-2.9	0.6	0.8
Pb	-0.7	-0.5	-2.1	0.4	0.5	-0.7	-0.7	-1.2	-0.3	0.2	-0.8	-0.7	-1.2	-0.1	0.3
1.2 RI															
	27.1	26.3	17.4	51.1	6.7	25.6	24.6	13.8	57.6	7.9	29.3	25.5	18.5	68.9	12.5
1.3 PI_N															
	1.3	1.1	0.8	3.8	0.6	1.5	1.2	0.9	5.4	0.8	1.6	1.2	0.7	5.9	1.34
II. BAGANUUR AREA															
2.1 Igeo															
Cr	0.4	0.5	-0.5	1.5	0.8	-0.5	-0.4	-1.5	0.2	0.4	-0.8	-0.7	-1.6	-0.1	0.4
Ni	-0.9	-0.8	-1.4	0.1	0.6	-0.4	-0.4	-1.1	0.4	0.3	-0.8	-0.8	-1.6	-0.1	0.4
Cu	-0.3	-0.2	-1.9	0.6	0.6	0.01	-0.1	-0.8	1.2	0.4	-0.4	-0.4	-1.2	0.5	0.5
Zn	-0.4	-1.2	-1.6	1.6	0.5	0.001	-0.02	-1.0	1.1	0.5	-0.7	-0.8	-1.5	0.9	0.5
As	-0.5	-0.5	-1.4	1.1	0.6	-0.8	-0.6	-2.2	0.2	0.5	-0.6	-0.6	-1.1	0.4	0.4
Pb	-0.6	-0.6	-1.6	0.7	0.4	-0.4	-0.4	-0.5	-0.1	0.1	-0.8	-0.7	-1.1	-0.3	0.2
2.2 RI															
	23.0	21.4	8.0	45.5	8.4	32.4	32.3	21.8	43.8	5.2	28.3	27.1	18.3	43.0	6.8
2.3 PI_N															
	1.1	1.1	0.7	3.4	0.5	2.2	2.1	1.7	2.9	0.3	1.2	1.1	0.7	3.4	0.4

Figure 6.6 and 6.7 illustrate the correlation between the contents of heavy metals and metalloids and their relationship with the distance from the tailings pond in the Erdenet area and the open-pit mine site in the Baganuur area. Overall, the HMM content generally decreased with increasing distance from the tailings pond and open-pit mine sites in both areas. In the Erdenet area, correlations for Ni, Zn, and Pb are not significant at the level α=0.05 while significant correlations were found for Cu, As, and Cr. In the Baganuur area, no significant correlations were observed for Cu, Zn, and Cr, while significant correlations were observed for Ni, As, and Pb. The lack of significant correlations for the elements Ni, Zn, and Pb in Erdenet and Cu, Zn, and Cr in Baganuur probably due to the low contents of these elements at the source areas.

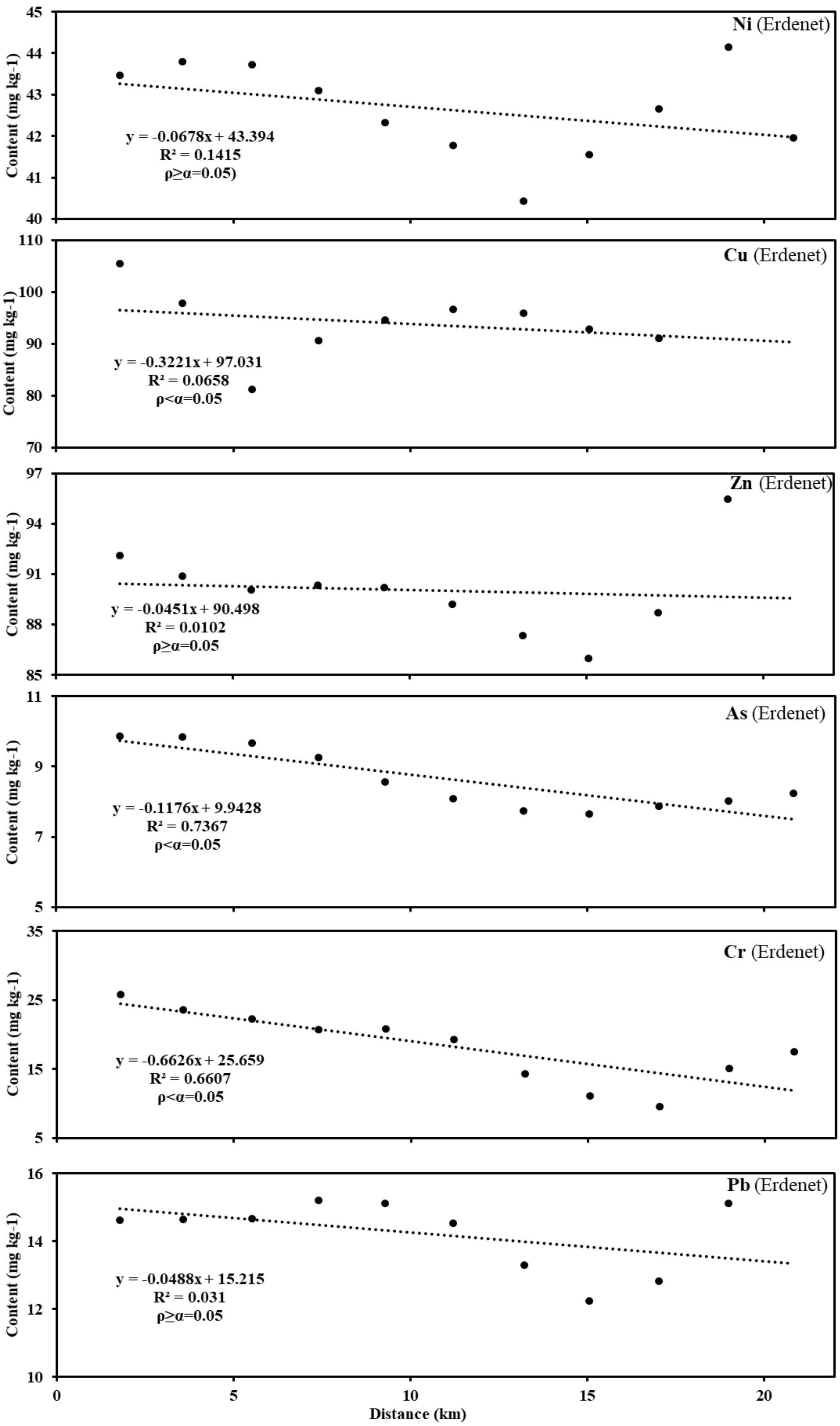

Figure 6.6 The correlation dependence of the HMM contents on the distance from the tailings pond in the Erdenet area

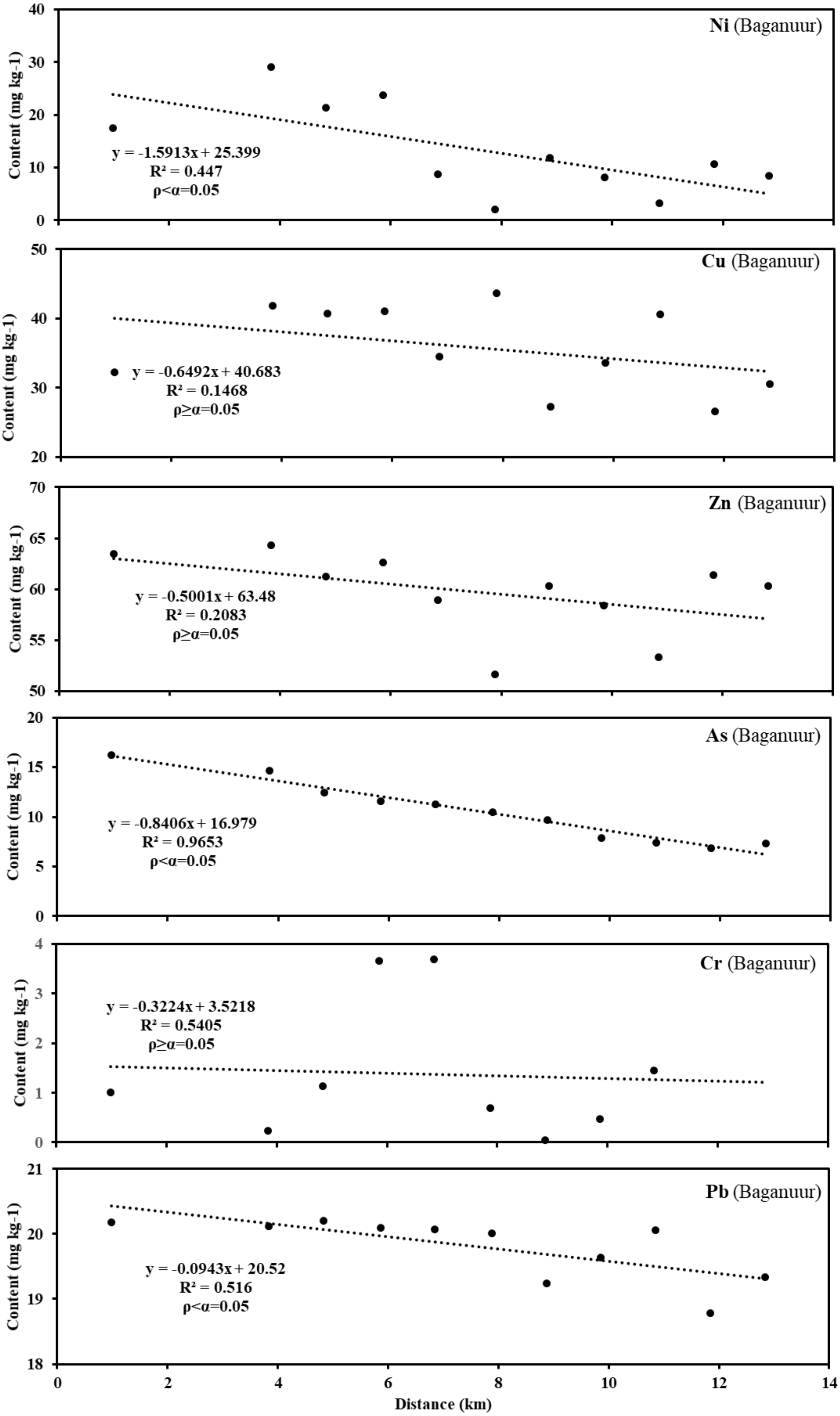

Figure 6.7 The correlation dependence of the HMM contents on the distance from the open-pit in the Baganuur area

Linear correlation analyses were performed among the three different analytical methods, pXRF, sXRF, and ICP-OES, to quantify the HMM contents. The purpose of these analyses was to comprehensively examine the interrelationships and dependencies among the results of the HMM obtained using these methods. In the Erdenet area, higher correlations were observed among all methods for Cr, Cu, As and Pb. The higher correlations between some methods were pXRF and ICP-OES, and ICP-OES and sXRF for Ni and Zn, as well as pXRF and sXRF for Zn. Weaker correlations were found for some methods, such as ICP-OES and sXRF for Cr, pXRF and sXRF for Ni, and pXRF and ICP-OES for Zn. In the Baganuur area, higher correlations were observed among all methods for Pb, and higher correlations were observed in some methods such as pXRF and sXRF for Cr, Cu, and As and pXRF and ICP-OES for Ni, Cu, and Zn. However, weaker correlations are exhibited between pXRF and sXRF for Ni, ICP-OES and sXRF for Cr, Ni, Cu, and Zn, and pXRF and ICP-OES for Cr and As. As far as the comparability of the different analytical methods is concerned, the correlation analyses indicate that reliable estimates are provided particularly for Cr, Cu, As, and Pb in Erdenet, and for Pb in Baganuur. Weaker estimates of the content of HMM are indicated for pXRF and sXRF for Ni, ICP-OES and sXRF for Cr, and pXRF and ICP-OES for Zn in Erdenet, while in Baganuur ICP-OES and sXRF, ICP-OES for Cr, pXRF and sXRF, ICP-OES for Ni, ICP-OES and sXRF for Zn, and pXRF and ICP-OES for As.

Table 6.9 Linear correlation analyses among pXRF, sXRF, and ICP-OES based on HMM contents (n=225 in Erdenet, n=220 in Baganuur)

HMM (mg kg^{-1})	Erdenet area				Baganuur area			
	R	Significance level	R	Significance level	R	Significance level	R	Significance level
1. Cr	*sXRF*		*ICP-OES*		*sXRF*		*ICP-OES*	
pXRF	0.5	++	0.14	++	0.18	++	0.107	-
ICP-OES	0.19	-			0.05	-		
2. Ni	*sXRF*		*ICP-OES*		*sXRF*		*ICP-OES*	
pXRF	0.016	-	0.25	++	0.11	-	0.21	++
ICP-OES	0.69	++			0.05	-		
3. Cu	*sXRF*		*ICP-OES*		*sXRF*		*ICP-OES*	
pXRF	0.83	++	0.38	++	0.36	++	0.16	++
ICP-OES	0.26	++			0.106	-		
4. Zn	*sXRF*		*ICP-OES*		*sXRF*		*ICP-OES*	
pXRF	0.25	++	0.017	-	0.23	++	0.18	++
ICP-OES	0.45	++			0.04	-		
5. As	*sXRF*		*ICP-OES*		*sXRF*		*ICP-OES*	
pXRF	0.57	++	**0.72**	++	0.19	++	0.09	-
ICP-OES	0.78	++			0.44	++		
6. Pb	*sXRF*		*ICP-OES*		*sXRF*		*ICP-OES*	
pXRF	0.14	++	0.15	++	0.41	++	0.2	++
ICP-OES	0.68	++			0.24	++		

++ correlation is statistically significant at level α=0.05
- correlation is not statistically significant at level α=0.05
R – Pearson correlation coefficient

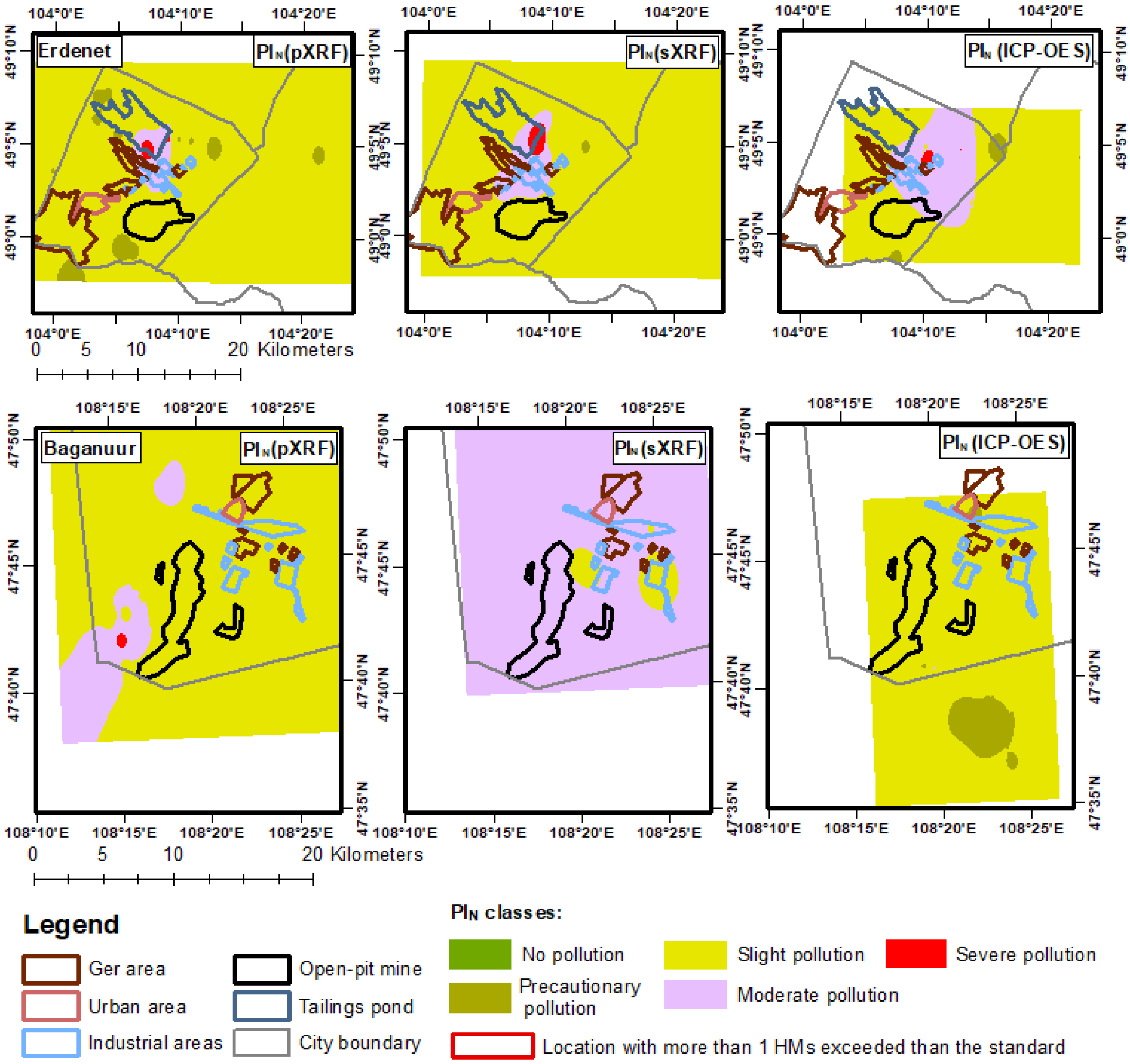

Figure 6.8 Spatial distributions of Nemerow integrated pollution index

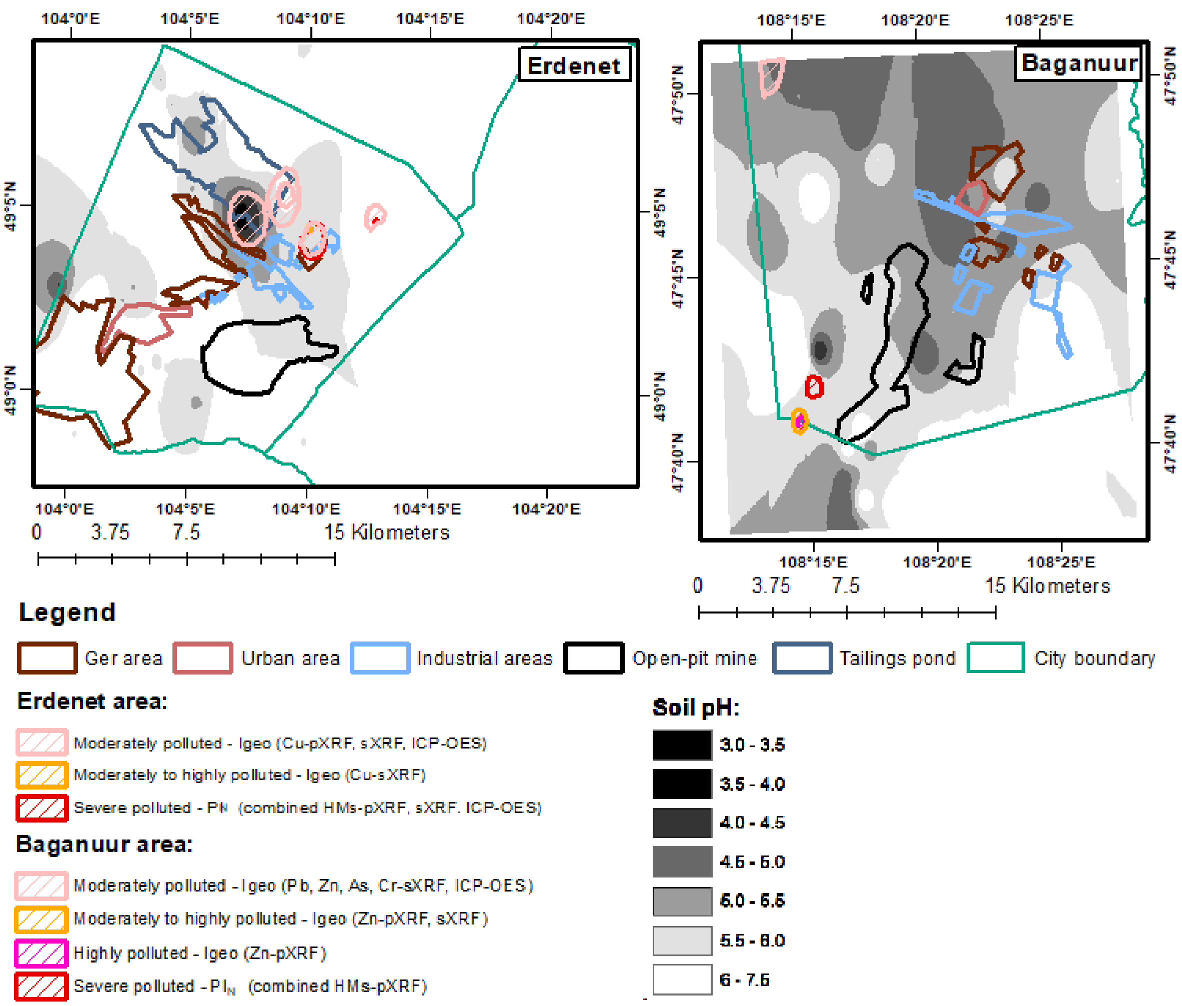

Figure 6.9 Moderately to severe polluted soils distributions comparing with acidic soil distributions

Soils were moderately to highly polluted by Cu near the tailings pond in Erdenet area and moderately to highly polluted by Zn the near open-pit mining area in Baganuur area. Additionally, higher polluted soils were overlapped by acidic conditions based on the spatial distributions (Figure 6.9).

6.5 Discussion and conclusions

6.5.1 Analytical methods and pollution indices

Assessing soil contamination status and the associated ecological risks is essential for evaluating the environmental impacts of mining and planning mitigation and rehabilitation measures. This study analyzed two of the largest and oldest mining operations in Mongolia, the Erdenet copper-molybdenum and the Baganuur lignite mine, regarding their impacts on soil pollution. Both mines were established in 1978 and are among the most crucial mining enterprises for the country's economic and infrastructural development and stability. Based on different analytical methods and pollution indices, this study documented elevated pollution levels in the vicinity of the mining site, tailings pond and industrial areas of both cities. Contents of Zn, As exceeded the MPL of the Mongolian soil standard in Baganuur, whereas the MPL was exceeded for As, Cr, Cu, and Zn in the Erdenet area. Soil pH is considered to be one of the most important soil characteristics for plant growth and contamination. Soil pH is measured using pH scale, in which the alkalinity or acidity of the soil is determined and varied under the influence of weathering, climate, parent rock features, and anthropogenic activities. In terms of soil heavy metal contamination, an acidic pH increases the heavy metal mobility in the soil (Olalekan et al., 2016). The polluted soils with higher HMM content were found to be consistent with acidic conditions in both mining areas. Geochemical pollution indices showed relatively low to moderate contamination risks, but Nemerow integrated pollution index showed severe pollution levels on 3.6-4.9% of the total area in Baganuur and 3.1-4.9% of the total area in Erdenet, mostly in the vicinity of the mine site, tailings pond, and industrial area. In many cases, this was due to simultaneous pollution by several HMM.

6.5.2 Pollution pathways

Contents of Zn and As exceeded the MPL of the Mongolian soil standard in Baganuur, and the maximum contents of these two elements in certain samples were also found to exceed the global reference levels of coal mine soils. In the Erdenet area, the MPL was exceeded for As, Cr, Cu, and Zn. Yondonjamts et al. (2019) studied the geochemical source and dispersion of these elements in the topsoil near the Erdenet mine: Cu is largely associated with the organic and sulfide fraction, while As and Zn are associated mainly with the residual and Fe/Mn oxide fractions. Mineralogically, Cu contamination in these soils is associated with the soil mineral chalcopyrite ($CuFeS_2$), and residual fractions of As and Zn may be adsorbed by quartz (SiO_2).

Soil contamination with As in the vicinity of the Erdenet and Baganuur open-pit mines can arise from a multitude of factors. Deposits frequently encompass trace quantities of As, which may be liberated into the surroundings during the excavation of overburden rocks and sediments containing the metalloid. These materials can subsequently undergo weathering, leading to the leaching of As into the nearby soil. During the conveyance and storage of coal and ore, there exists a potential for the dispersion of dust into the immediate environment. In addition, it could be demonstrated that for some HMM, there is a significant relationship between the content and distance from the source area. This applies in particular to Cu, Zn, and Cr in Erdenet, and Ni, As, and Pb in Baganuur.

6.5.3 Soil remediation

The pollution levels identified in this research, along with those reported in the previous studies, should serve as the foundational information for devising strategies for soil remediation. The initiatives aimed at revitalizing the land disturbed by mining in both areas focused on several tasks. In Baganuur, an attempt to restore the degraded soils of the coal mine was made in 2003 by planting legumes such as *Bromus imernus* L., *Medicago sativa* L., and *Elymus* L. The monitoring results advise that nitrogen and carbon cycle, as well as the microorganism activity, are still inferior to the background levels: the humus content, invertase activity, and catalase activity were lower by 17.1%, 20.0%, 78.6% than in the control soil, respectively (Jambalsurenet al. 2021). Schwarz et al. (2016) report that the project “Sustainable Site Development of the Mining Region Erdenet, Mongolia” targeted reforestation of the nearby Bayan Undur mountain, optimization of water and waste management, and several educational and civil society improvements. So far, despite the many set goals, no soil clean-up attempts are known in both mining areas.

6.5.4 Future outlook

Both mines were established in 1978 and are among the most crucial mining enterprises for the country’s economic and infrastructural development and stability. In a mining-intensive nation like Mongolia, the implications of their situations extend far beyond their borders. In fact, for many other major mining sites in the country, such as the vast coal and copper-molybdenum mines of the Gobi region, the cluster of gold mines of the Selenga river basin, and a multitude of smaller mines, relatively little information on soil pollution is documented, making it difficult for government bodies to enforce environment regulations and plan rehabilitation measures. In the future, a detailed meta study on environmental pollution in Mongolian mining regions is needed in order to better understand the environmental impacts of a growing mining sector, but also the benefits of increasing environmental awareness and responsibility among mining companies.

7 ALIGNING ERDENET COPPER-MOLYBDENUM MINE REHABILITATION WITH SDGS BY MITIGATING SOIL EROSION AND CONTAMINATION

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ABSTRACT

Mining operations in Mongolia have contributed significantly to national economic growth. However, the lack of adequate mine land rehabilitation practices has resulted in various forms of land degradation, including land cover change, soil erosion, and sites contaminated with heavy metals and metalloids (HMM), with significant negative effects on ecosystems and potential risks to human health. At the example of the copper-molybdenum mining site of Erdenet (the oldest and one of the largest copper mines in Mongolia), this study addresses the key drivers and impacts of soil degradation in Erdenet and comparable mining sites in Mongolia, and assesses rehabilitation potentials that focus on environmental protection combined with economic progress. This case study particularly provides insights and potential solutions for dealing with soil erosion and soil contamination as two commonly experienced phenomena in mining region. Key priorities for the next 10-15 years are continued environmental assessments and monitoring, the development and implementation of science-based mitigation plans including tailings storage facility rehabilitation and measures for erosion control and soil pollution remediation. In addition to site-specific measures, this also includes the advancement and better implementation of laws and regulations. As Mongolia is committed to make significant progress on the SDGs, rehabilitation measures are also discussed in this context.

7.1 Introduction

The mining sector in Mongolia is one of the most important components of the country's economy, accounting for 25% of the Gross Domestic Product (GDP), 87% of exports, 72% of industrial production, and 75% of foreign direct investment (Krusekopf 2023). However, it has contributed to a wide range of environmental degradations over the years, including soil erosion and contamination, significant water abstractions and pollution, land degradation, and loss of habitat and biodiversity. Therefore, sustainable management of mining operations aimed at mitigating and reversing environmental impacts is essential to ensure sustainable development of the mining sector in Mongolia (Mongolia VNR 2019).

Stockpiles, sludges, gullies, and tailings storage facilities affect not only soil quality and soil stability, but also soil biodiversity and ecosystem functions (Worlanyo and Jiangfeng 2021). In dry seasons, fine and dusty tailings easily drift into the surroundings of mines, posing a threat to human health and causing pollution in the air, soil, and water (Sun et al. 2018). Therefore, the sustainable management of soils around mine tailings is a global concern, with specific concerns affecting dryland regions. As sustainable mining and mining site rehabilitation needs to consider both environmental sustainablity and human well-being, it aligns with the Sustainable Development Goals (SDGs) introduced in 2015, particularly SDG 6 (clean water and sanitation), SDG 12 (responsible consumption and production), and SDG 15 (life on land). Successful implementation of SDGs requires active engagement and collaborative participation of both public and private parties to achieve meaningful progress toward the proposed goals (Yakovleva et al. 2017).

Tailings can be considered as a resource in at least three ways: firstly, for reprocessing to concentrate and extract valuable metals or minerals; secondly, using them as a filler to backfill mined-out areas, and thirdly, use as raw material for construction. However, these methods incur additional costs such as transportation and treatment (Sun et al. 2018). Therefore, a common practice to deal with mine tailings is the creration of a vegetation cover with tolerant species. However, natural successions in this process typically require a minimum of 50-10 years (Daily 1995). Elevated trace metal concentrations may limit or even inhibit plant growth in polluted mining sites. Some studies have shown that endophytic bacteria such as *Pseudomonas koreensis AGB-1*, can simultaneously enhance plant growth and heavy metal extraction from soils (Babu et al. 2015; Chu et al. 2018), and that adding coal spoil amendments to soils can help reducing the metal uptake by less tolerant plants in copper mine tailings (Bandyopadhyay 2021). Grass is a widely studied plant for phytomanagement due to its high biomass productivity, rapid growth, strong resistance, and effectiveness in soil remediation (Elekes 2014).

The objectives of environmental rehabilitation in mining sites should be carefully prioritized, considering environmental sustainability, the requirements of local populations, and the issue of affordable and reasonable expenses (Worlanyo and Jiangfeng 2021). In addition, targets must align with local environmental conditions and the selection. In phytomanagement, the use of indigenous plants is therefore highly recommended. In arid regions, the most simple and effective species selection involves choosing local, well-adapted native plants. Selecting a minimum of 4-5 plant varieties for replanting helps mitigate the risk of failure in mine rehabilitation (Xu et al. 2023). In recent years, resource management approaches from tailings, have shown the potential to bring innovative solutions in mineral and solid waste processing. However, some gaps still need to be addressed, particularly in the transfer of technology from academia to practice and in enhancing the efficiency of recovering and using valuable compounds (Araujo et al. 2022).

In recent years, several studies have assessed the state of the environment at mining sites across Mongolia, especially in major cities and industrial areas with mining activity, and have demonstrated a significant link between mining operations and overall environmental degradation (Lehmkuhl and Batkhishig 2003; Knippertz 2005; Kosheleva et al. 2010; Timofeev et al. 2016; Karthe et al. 2017; Jarsjö et al. 2017; Batbayar et al. 2017; Chonokhuu et al. 2019; Pecina et al. 2023; and Sodnomdarjaa et al. 2023). However, the rehabilitation of mining sites and mining waste management have not received sufficient attention in Mongolia (Frauenstein et al. 2021).

This study examines mining impacts and rehabilitation potentials at the example of the Erdenet copper-molybdenum mine. This mining operation has significantly contributed to the country's economy since its inception in 1978, and has served as a model for many other extractive sector developments in Mongolia. The Erdenet Cu-Mo mine contributed the country's GDP in 2006, accounting for a surplus of 3.9% (ADB 2007), but its relative importance has recently declined due to other major mines such as th Oyu Tolgoi copper and gold mine starting their operation. Nevertheless, the mine remains the most important company in this region in terms of revenue and employment. On the negative side, however, Erdenet city faces severe environmental issues due to over four decades of intensive mining and a population increase to around 102,000 residents (NSO 2022). Environmental problems include substantial air, water, soil pollution, and land degradation (e.g. Batbayar et al. 2017; Pfeiffer et al. 2015; Munkhsuld et al. 2024; Sodnomdarjaa et al. 2023 and 2024). Much of the waste from the ore processing is pumped to a tailings storage facility about 3 to 4 km north of the plant, which is a notable source of airborne particulate matter (PM), commonly known as "white dust" (Lkhagvajargal et al. 2018), leading to environmental and health issues, along with contamination of ground and surface water in the downstream areas near the tailings storage facility. In the soils, higher concentrations of copper and molybdenum were detected, although the soils appeared to be less contaminated than the stream sediments. Elevated levels of sulfate, calcium, magnesium, and arsenic were found in the Khangal River, and a lesser impact on groundwater quality due to the recharge process (Battogtokh et al. 2014; Karthe et al. 2017). Approximately 10 km downstream of the Erdenet mining area, molybdenum concentrations still exceed WHO health-based guidelines during the summer (Solongo et al. 2021). Moreover, the rate of soil loss was greater near the TSF and the mining areas of the Erdenet mining operation, primarily due to rainfall intensity, transportation, and other mining activities, as determined by field observations, scientific literature, and erosion modeling based on RUSLE (Sodnomdarjaa et al. 2023). Therefore, to ensure a sustainable future for the Erdenet mining operation, it is crucial to address these issues, with a particular focus on rehabilitating the TSF (Schwarz et al. 2016). The current TSF operates at around 60% capacity therefore, it is essential to build a new TSF with a focus on efficient post-closure monitoring, minimizing costs, managing ongoing liabilities, and advancing environmental sustainability in the next decade (Dagva et al. 2016). In addition, to improve the current situation, promoting modern technologies and research for developing construction materials from the TSF is crucial (Jargalsaikhan et al. 2023).

This research paper aims to delineate a rehabilitation plan focused on mitigating soil erosion and contamination at the Erdenet copper-molybdenum mine, aligning with SDGs 6, 12, and 15. The plan was outlined for the Erdenet area, with specific emphasis on studies by Sodnomdarjaa et al. (2023) on soil contamination and erosion. It also takes into account previous studies on the environmental impacts of the Erdenet mine and the laws and regulations governing the mining sector in Mongolia. The objectives of this study are as follows: (1) to conduct a literature review on soil contamination, soil erosion, and rehabilitation in the Erdenet mining area from its inception to the present; (2) to prepare a spatial map delineating areas with elevated soil loss rate and soil contamination levels, based on previous studies and own study findings from 2020 to 2023 conducted in Erdenet city, to facilitate the prioritization of rehabilitation recommendations; and (3) to make recommendations for a rehabilitation plan in the Erdenet mining area using the findings and suggestions of previous relevant research and laws and regulations.

7.2 Study area

The Erdenet mining area is situated in the Erdenet city of Orkhon province, which is located approximately 360 kilometers to the northwest of Mongolia's capital city (Figure 7.1). Founded in 1975 to exploit the country's copper ore reserves, it is now the country's third-largest city with a population of 102,000 (NSO 2022) and plays an important role in the national economy. The city of Erdenet is located in the valley between the Selenge and Orkhon River catchment areas and has three rivers passing through its territory: Erdenet, Gavil, and Khangal. The Gavil and Erdenet Rivers originate in mountain valleys and flow into the Khangal River, which later joins the Orkhon River (Solongo et al. 2021). The climate condition of the city can be described as a dry winter subarctic climate (Dwc) according to the Köppen climate classification. The average temperature is 0.8°C, the lowest temperature was recorded in January with an average temperature of -17°C, and the warmest month is July with an average temperature of 17°C. The annual precipitation fluctuates substantially ranging from 260 to 598 mm during the past 30 years. Most of the annual precipitation falls between late May and September, and July is the month with the highest precipitation with an average rainfall of 100 mm (Figure 7.2).

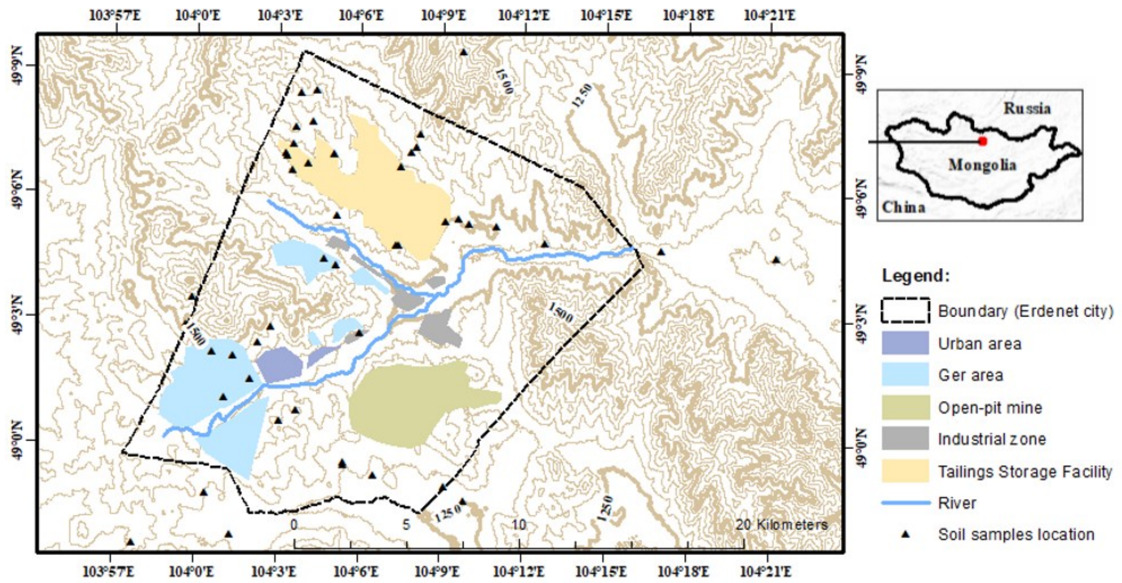

Figure 7.1 Erdenet city with land-use regions and contour lines

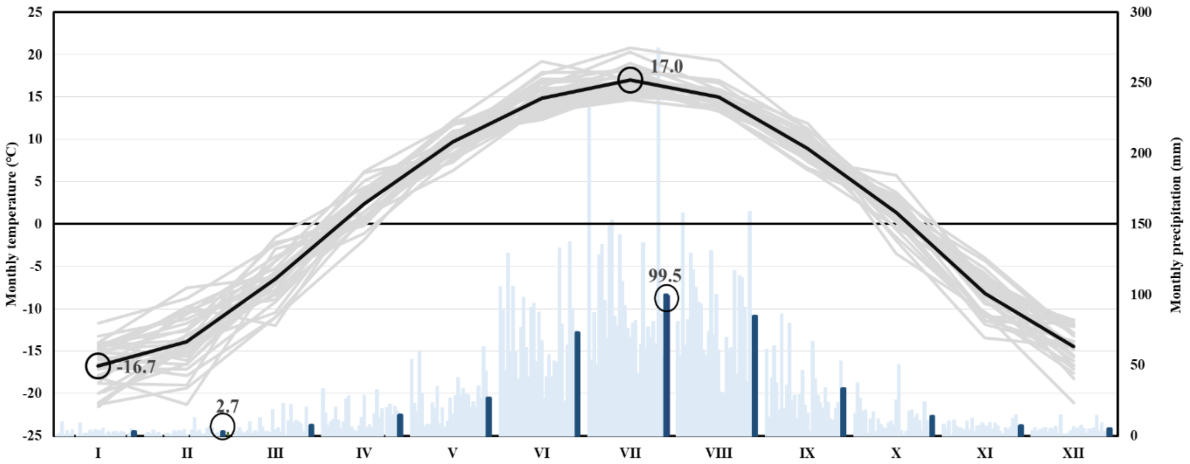

Figure 7.2 The climograph of Erdenet city: Average, maximum, and minimum temperatures and precipitation (1985-2014). Data source: Meteorological station in Erdenet city of Orkhon province, National Meteorological Agency Meteorology and Environmental Monitoring in Mongolia (NAMEM)

7.3 Data and methods

7.3.1 Literature search

To conduct a comprehensive literature review on soil contamination, soil erosion, and rehabilitation in the city of Erdenet and Orkhon province, with a special focus on the Erdenet copper-molybdenum open-pit mining area, Scopus, Web of Science and Google scholar database searches were conducted to retrieve all published studies from 1975 to 2023. In addition, a search for local studies in the area during the specified period was conducted using the National Library of Mongolia in Ulaanbaatar's resources, including locally available books and journals. For the online searches, the following search terms were used: (TITLE-ABS-KEY ("soil erosion" OR "soil contamination" OR "rehabilitation")) AND (TITLE-ABS-KEY ("Erdenet city" OR "Erdenet copper-molybdenum mining area" OR "Erdenet")).

7.3.2 Regulatory framework review

In this context, a comprehensive assessment of the laws and regulations related to environmental sustainability in Mongolia's mining sector has been carried out, with a particular emphasis on their implications for ensuring responsible mining practices and environmental rehabilitation in mining areas. This assessment includes a systematic analysis of policies and measures at the national and local levels to measure their effectiveness in advancing environmental sustainability and reducing environmental impact. A search process was conducted using the library's resources, which included books, journals, articles, and web-based search engines, including the official legal and regulatory website of Mongolia (Legalinfo.mn), the official website of the Erdenet mining operation (erdenetmc.mn), and other online search engines such as Google, Google Scholar, ScienceDirect, and Web of Science. The following keywords were used in a web-based search to identify the main outline for a comprehensive assessment of laws and regulations regarding environmental sustainability in Mongolia's mining sector. The focus of the search was particularly on responsible mining practices and environmental rehabilitation, and the keywords included "Environmental sustainability laws in Mongolia", "Mining sector regulations in Mongolia", "Responsible mining practices in Mongolia", and others related to mining policx and environmental impacts.

7.3.3 Current status SDGs in Mongolia (Erdenet mining operation)

Mongolia has actively pursued the achievement of the Sustainable Development Goals (SDGs), making significant steps since the inception of the Sustainable Development Vision 2030 (SDV 2030) approved by the Mongolian government in 2016. The government further strengthened its commitment to sustainable development by approving Vision 2050, a comprehensive policy framework that includes the Five-Year Development Guidelines for 2021-2025. In addition, the Government Action Programme for 2020-2023, along with its implementation plan, was approved, serving as a new long-term strategic policy document. This replaces the SDV 2030 and its implementation plan, aligning with the revised law enacted in May 2020 on the country's development policy, planning, and management. These national strategies, summarized in Vision 2050 and related development guidelines, collectively address approximately 80% of the SDGs, reflecting Mongolia's commitment to integrated sustainable development. However, despite commendable progress, the country faces challenges related to SDG indicators. These challenges include data gaps, the lack of government-approved indicators and baselines, and insufficient alignment of SDG indicators to the Mongolian context. A critical issue relates to the coordination and responsibilities of relevant institutions for the development and reporting of national indicators. In 2021, the United Nations Development Programme (UNDP) highlighted the need to strengthen coordination and establish clear responsibilities of stakeholders. This step is essential to overcome the challenges related to data quality, availability, and alignment, and to ensure a more robust and accurate monitoring and evaluation framework for Mongolia's sustainable development efforts. As Mongolia align its commitment to the SDGs, its focus must extend beyond policy adoption to effective implementation and monitoring. Strengthening institutional coordination and addressing data-related challenges are essential steps to ensure that national strategies align are effortlessly aligned with the global goals of the SDGs, namely sustainable development across economic, social, and environmental dimensions.

7.3.4 Spatial mapping of soil erosion and contamination

Creating a spatial map to delineate areas with higher soil loss rates and soil contamination levels was made based on the findings of our previous studies (Sodnomdarjaa et al., 2023) conducted in the Erdenet mining area from 1989 to 2023. This spatial map helps to identify areas in need of immediate rehabilitation and facilities, prioritizing recommendations, and preventing further soil erosion and contamination. As part of this study, a total of 48 surface soil samples were collected from various locations (Figure 7.1), including mining areas, urban and ger settlements, and industrial zones. These samples were analyzed to assess soil contamination and erosion by considering factors such as soil texture, organic matter content, and presence of heavy metals and metalloids. Heavy metals and metalloids in soils were analyzed using portable X-ray fluorescence (pXRF), and stationary X-ray fluorescence (sXRF). Soil erosion rates were calculated using the Revised Universal Soil Loss Equation (RUSLE), and the calculation was modified to monthly soil erosion (Schmidt et al. 2019).

$$A = R \times K \times LS \times C \times P \quad (7.1)$$

where A is the quantification of soil loss in a month (t ha^{-1} $month^{-1}$), R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} $month^{-1}$), K is the soil erodibility factor (t h MJ^{-1} mm^{-1}), LS is the topographic steepness factor (unitless), C is the cover management factor (unitless), and P is the support and conservation practice factor (unitless) (Schmidt et al., 2016, 2019). This study fouces on the elevated soil erosion rate and higher soil contamination that Sodnomdarjaa et al. found in this area in 2023. Specifically, areas with higher soil erosion rates (>3-5 t ha^{-1} $month^{-1}$), and soil-contaminated areas where soil heavy metals and metalloids exceed the maximum permissible limit (MPL) of the Mongolian soil quality standard (MNS 5850:2019) were identified, such as chromium (Cr >60 mg kg^{-1}), nickel (Ni>60 mg kg^{-1}), copper (Cu>60 mg kg^{-1}), zinc (Zn >100 mg kg^{-1}), arsenic (As >10 mg kg^{-1}), and lead (Pb >50 mg kg^{-1}). The point data of the heavy metals and metalloids concentrations were converted into raster data using the inverse distance weighted (IDW) method with ArcMap 10.7.1 software.

7.3.5 Rehabilitation planning

There are only a limited number of studies, particularly guidelines and concepts for mine rehabilitation planning in open-pit mining areas in Mongolia. Technical guidelines for the rehabilitation planning of open-pit coal mine areas in Mongolia were introduced by GROM (2019) and Frauenstein et al. (2021). According to the guidelines, the mine rehabilitation planning includes land restoration, public engagement in projects, ongoing environmental impact assessments during mining operations, landscape re-use based on the rehabilitation of abandoned mine areas, and biodiversity conservation to identify pollution-sensitive areas. In the context of the Erdenet mining area, the Rehabilitation pyramid was introduced by Knippertz 2005 (Figure S7.1). This concept can serve as a basic guide for the development of the rehabilitation plan and the extension of monitoring activities, ensuring that it is consistent with the specific environmental conditions and socioeconomic requirements of the Erdenet mining area. In developed countries, an interdisciplinary approach is suitable for validating the effectiveness of measures related to ongoing structural change in creating sustainable and multifunctional post-mining landscapes. There are cultural services such as aesthetics, spiritual value, educational opportunities, and recreational amenities that ecosystems provide for the well-being of humans and other species (Gerwin et al. 2023). The concept of ecosystem services encompasses multiple functions, such as supporting nutrient cycling, maintaining soil health, supporting primary production, and preserving biodiversity. It also includes the provision of essential resources such as food, fresh water, and biomass energy. In addition, ecosystem services include climate regulation and flood prevention.

Furthermore, the incorporation of the Resource Nexus approach (Pashkevich et al. 2023; Brouwer et al. 2024), is relevant in the context of global former coal mines and in line with the principles of the Sustainable Development Goals (SDGs). This approach highlights the formulation of rehabilitation strategies, initially focusing on the elimination of hazards in surface and groundwater resulting from mine dumps. Simultaneously, it aligns with the Sustainable Development Goals (SDGs), specifically SDG 6 for clean water and sanitation, SDG 7 on affordable and clean energy and SDG 12 for responsible consumption and production. This ensures an understanding of societal needs in line with SDG 1 for no poverty, SDG 2 for zero hunger, and SDG 8 for decent work and economic growth. In addition, the approach extends to delineating land-use guidance based on SDG 9 for industry, innovation, and infrastructure, and SDG 15 for life on land. The phases of post-mining rehabilitation planning shown in Figure 3 are based on the concepts and frameworks of the UN SDGs. By considering both these two overarching perspectives, rehabilitation strategies can effectively address not only environmental concerns but also socioeconomic aspects. This contributes to the establishment of sustainable landscapes and land use. For a more detailed explanation, it is essential to assess the initial conditions of environmental degradation and pollution before outlining rehabilitation plans. This includes comprehensive analyses of soil quality, surface and groundwater quality, air quality, potential risks to biodiversity, and environmental degradation.

7.4 Results and discussions

7.4.1 Research Findings: Web and Library Sources

Table 7.1 presents key challenges and potential recommendations from the studies and other findings in 31 articles, seven reports, and a summary of 18 laws and regulations. This study focuses on understanding the environment and socio-economic impacts of the tailings pond and the Erdenet open-pit mine.

Table 7.1 A summary of research findings from the web and library sources

Criteria	Challenges	Recommendations	Source
Environmental status	Soils near industrial, tailings storage facility, and mine areas showed the highest Cu and Mo concentrations, primarily due to water and wind-driven dispersion.	Continuous environmental assessments and monitoring are essential in the Erdenet mining area.	Knippertz, 2005; Kosheleva et al., 2010 and 2017; Battogtokh et al., 2014; Timofeev et al., 2016; Yondonjamts et al., 2019; Chonokhuu et al., 2019; Jargalsaikhan et al., 2023
	The absence of a protective lining under the tailing pond directly affects the Khangal River by increasing levels of SO_4, Ca, Mg, Mo, and As.	Urgent source control measures are essential to mitigate these impacts.	Battogtokh et al., 2014
	Increased accumulation of Cu and Mo in stream sediments due to leaks in the tailing pond and temporary storage of subgrade ore materials from rock piles during rainfall runoff and the lack of containment.		
	Wind-driven dust from the tailing pond has evenly spread with heavy metals and metalloids contamination in soils in the area.		
	The current tailings pond operates at around 60% capacity.	Develop a mining closure plan for this reservoir. Build a new tailings pond within the next 10-14 years.	Dagva et al., 2016
	The tailings pond in the area is estimated to contain 700 million m^3 of residue material, covering 18 km^2, with a rock-fill dam approximately 100 m high. It ranks one of the largest in the world and is associated with considerable negative environmental impacts.	Urgent rehabilitation of the tailings pond is necessary, requiring collaboration between the mining industry and the public sector.	Schwarz et al., 2016
	Mining operations in the Erdenet area consume a high amount of water and release pollutants, high concentrations of Cu, As, and Mo found downstream of the Khangal River.	In this area, a science-based environmental management concept is essential.	Karthe et al., 2017
	Dry white dust from the tailings pond spreads over a long distance, up to 14-68 km, carried by winds. This airborne dust is linked to an increase in health problems, including heart attacks, respiratory issues, allergies, and other severe diseases.	White dust dispersion significantly decreased during rainy days. It is recommended to first stabilize the areas by maintaining constant humidity through irrigation and then rehabilitate tailings dumps by planting leguminous trees.	Lkhagvadorj et al., 2017
	The current negative trend of forest regeneration inhibition due to overgrazing will further continue depending on the Cu-Mo mining in Erdenet.	The presently most effective measure is to protect the impacted forest stands from additional grazing, primarily through methods like fencing.	Juřička et al., 2019

	The most significant contamination of HMM was identified in surface and groundwater near the tailings ponds.	It is crucial to encourage and support businesses in developing construction materials from tailings ponds based on modern technologies and studies.	Jargalsaikhan et al., 2023 Potravny et al., 2023
	Soil erosion is significant near the tailings pond, mining area, and industrial zone.	Planting trees and constructing drainage around the tailings and mine site to prevent water erosion.	Sodnomdarjaa et al., 2023
Law enforcement	Despite the abundance of laws and regulations in the mining sector in Mongolia, the implementation and enforcement of laws and regulations are weak.	Enhance the monitoring of law and regulation implementation.	UNDP, 2018; Sternberg and Ahearn, 2023
	The total number of violations of the Environmental protection law in Mongolia, the mining sector, ranges from 15-25%.	Engaging both local citizens to governmental levels is crucial for enhancing environmental management plans.	UNDP, 2018
	There are overlaps and gaps in laws and regulations related to environmental protection and assessments, land pollution caused by chemicals, toxic substances, and the utilization of natural resources.	Improving an information system for professional organizations to share the update on legal changes and relevant research.	
		Continuously update standards and rehabilitation plans to align with evolving laws and regulations, meeting the dynamic needs of modern development.	
SGSs performance	Mongolia ranks 157th in the Environmental, Social, and Governance Index (ESG), despite its engagements with numerous donor institutions and its commitment as a signatory to UN SDGs and other related environmental protection initiatives.	Innovative collaboration among the government, civil society, and academics provides a pathway to developing Social Impact Assessment (SIA) legislation.	Jiang et al., 2022; Sternberg and Ahearn, 2023;
	It stresses the lack of relevant research and national debate on current global initiatives.		Sternberg and Ahearn, 2023;
	Mongolia faces mining challenges, including influential companies, state strategies contributing to corruption, ongoing protests, and a lack of effective guidance, regulation, and experience.		
	Mining and other human activities have degraded around 48 ha of land, deforested 20 ha, and 37 ha need both physical and biological rehabilitation. Nitrite levels in the Khangal River have increased to 1.8 times the national standard.	Develop and approve a "Climate Change Adaptation and Mitigation Plan" to enhance soil, water, forest, biodiversity, and waste management in Orkhon province.	Bayarjargal et al., 2016
		Establish a collaborative effort for environmental management from local to government levels, including workshops, training, and green procurement promotion.	
		Monitoring the progress of SDGs and their implementation status by the monitoring team	

ESG-Environmental, Social and Governance

7.4.2 Erdenet mining company and the SDGs

In the following analysis, we consider the compliance of the Erdenet mining company's with the sustainable development agenda (UN SDGs). The data used for this analysis was provided by the company (erdenetmc.mn).

1 No poverty: The Erdenet mine employs more than 7,000 people, over 90 % of whom local residents. The monthly salary is around 40% above the national average (NSO 2022).

2 Zero hunger: The Erdenet mining operation engages in annual collaborations with local administration as part of its social responsibility initiatives, with a focus on supporting local citizens and small businesses, including agriculture.

However, there is a lack of publicly available information on specific actions, outcomes, and inprovements in food production attributed to Erdenet mining's support.

3 Good health and well-being: The Erdenet mining operation prioritizes the safety of its all staff, aligning with the national safety standard (MNS ISO 45001:2018). It ensures ongoing internal and external safety monitoring at the mining sites. In addition, the mining operation continually provides safety training, safety equipment, and clothing for all employees, and consistently addresses necessary improvements in compliance with evolving safety environment requirements and developments.

4 Quality education: Since 1978, the Erdenet mining company has supported the "Erdenet Complex" University". This university combines theoretical education, research, and industry in the mining sector and has trained over 100,000 skilled workers, 1800 bachelor's degree engineers, and 300 master's degree engineers since its establishment in 1975. The students gain practical experience through internships at the Erdenet mine operation and other local industries. Successful students benefit from tuition fee waivers provided by the mining operation, and upon graduation, many continue to contribute their expertise to the Erdenet mining operation.

5 Gender equality: The mining operation promotes for gender balance, with more than 30% of its total employees being female. It is committed to further increasing the representation of women among its employees and strive to achieve gender equality.

6 Clean water and sanitation: The mine operation has invested in improving the water supply and wastewater treatment systems in the town of Erdenet. In 1999, monitoring systems and water meters were installed in households and industries. In addition, in 2005, 14 new pumping stations were renewed to improve the efficiency and reliability of the main water source for consumers. Furthermore, the mining process incorporates a sustainable approach by using 66% recycled water and 34% fresh water sourced from the Selenge River (Pestriak et al. 2019).

7 Affordable clean energy: The mine operation initiated a partnership with "Erdenet Complex" university, establishing a solar panel research laboratory in 2019 to explore green energy solutions for both the mine and local energy needs. As part of this initiative, an on-grid system using solar panels was installed to provide power for the student dormitory at "Erdenet Complex" University.

8 Decent work and economic growth: This mining operation plays a crucial role in Mongolia's economy, accounting for approximately 10% of the country's total income in 2023. Additionally, it ensures equitable labor practices and workers' rights and continually improves the working environment and safety conditions in alignment with Mongolia's labor laws.

9 Industry, innovation, and infrastructure: Currently, there is insufficient publicly available information and evidence regarding the implementation of innovative and sustainable mining technologies by the Erdenet mining operation.

10 Reduced inequalities: With the exception of the 2019 meeting with representatives of the local citizens of Govil, Bayantsagaan, and Jargalant soums in Orkhon province to address the "white-dust" issue around the mining area, there is a noticeable lack of active participation of local residents in decision-making and implementation processes within the mining operation, especially on environmental issues.

11 Sustainable cities and communities: As part of the mining operation's commitment to social responsibility, a major project called "Miner 1, 2, 3" was initiated, which involved the construction of apartments for 1300 households. In 2021, the first phase, "Miner-1", comprising 400 households' apartments, will be operational with affordable costs and waived fees for both mining employees and local residents.

12 Responsible consumption and production: Since 2014, the mining operation has leased a secondary tailings dump to Achit-Ikht Co., Ltd. The company processes mixed ore derivative deposits that are unsuitable for flotation. Therefore, through hydrometallurgical methods, these deposits are transformed into economically valuable materials, specifically

A-grade copper cathodes. This initiative has resulted in the production and export of copper, contributing over 250 billion MNT (Mongolian tugrug) to the national economy since 2014 (achit-ikht).

13 Climate action: In 2019, the Erdenet mining operation established an internal environmental monitoring department. They launched a reforestation project covering approximately 38 hectare in an abandoned tailing area. The primary objective of this initiative is ecological restoration and land rehabilitation, in line with the “One billion trees” National Campaign initiated by the President of Mongolia.

14 Life below water: The Erdenet mining operation conducts monthly analyses and monitoring of soil, water, and air quality in the surrounding area through its environmental laboratory. The laboratory has accredited four times by the Mongolian Accreditation Center.

15 Life on land: Since 2008, an ongoing initiative has resulted in the planting of over 50,000 trees on a 38 hectar area in collaboration with professional institutions focused on rehabilitating obsolete areas around the mining site and addressing deforested regions in Orkhon Province.

16 Peace, justice, and strong institutions: The mine promotes transparency through its website and local news, and complies with both local and national laws. Annual contracts with the local government contribute to social stability, and their progress is audited at year-end. This process guides continuous improvement in accordance with local government requirements.

17 Partnerships for the goals: The Erdenet mining operation has collaborated with both local and international organizations, focusing on production technologies, safety, and transportation. However, there is a notable gap exists in collaboration with research institutions concerning matters related to environmental impact, as evidenced by the limited availability of data and research, particularly in the context of rehabilitation.

Leaning on a multitude of examples around the world, we should be aware of the possible distinction between the current Erdenet mining company’s commitment to SDGs and the ongoing stewardship of the land once mining concludes. While the company demonstrates a commendable dedication to sustainable development during its operational phase, it is imperative to underscore the importance of transitioning this commitment seamlessly into post-mining practices.

Securing the persistence of environmental and socio-economic responsibilities beyond the active mining phase is crucial for achieving sustained objectives in erosion prevention, soil decontamination, and the formulation of future pathways for land use. To develop proactive suggestions and foster a resilient and sustainable environment for the long term, we performed a spatial analysis of the area affected by mining and processing operations.

7.4.3 Finding most eroded and contaminated terrain

The spatial map illustrating soil erosion and contamination was created on the basis of our own previous studies conducted in the Erdenet mining area (Sodnomdarjaa et al. 2023), with the purpose of the map being to delineate regions exhibiting higher rates of soil loss and increased heavy metals and metalloids contamination. One of the main objectives of the map is to provide a detailed representation of the increased soil erosion rates observed in the Erdenet mining area during the study period, which runs from 1989 to 2018. Specifically, the map aims to delineate and highlight areas where the soil loss rate exceeds a range of >3-5 t ha^{-1} $month^{-1}$ based on the average monthly soil erosion rate. Another key objective of the map is to identify regions with increased concentrations of heavy metals and metalloids such as Cr, Ni, Cu, Zn, As, and Pb in soils. These concentrations serve as thresholds for designating areas as soil-contaminated, with the criteria of surpassing the MPL as outlined in the Mongolian soil quality standard (MNS 5850:2019). Three different methods, including sXRF, pXRF, and ICP-OES, were used to assess heavy metals and metalloids pollution. The area was considered to exceed the permissible limits for heavy metals and metalloids if it contained two or more overlapping elements, each exceeding the specified threshold at a single location point.

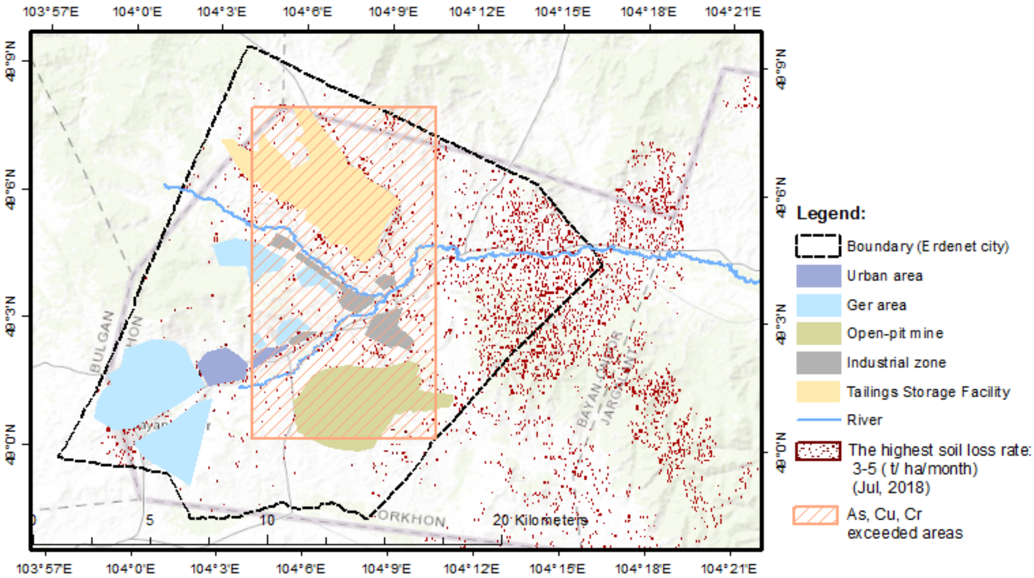

Figure 7.3 Spatial distribution of the highest soil erosion rate and contamination (more than two types of HMM presented area)

Figure 7.3 shows the results of the spatial map illustrating the distribution of elevated soil erosion rates and heavy metals and metalloids concentrations. Regarding results of monthly soil erosion rates from 1989 to 2018, elevated soil erosion rates were mainly found during the peak vegetation growing season and the peak precipitation period. The highest soil erosion rates were found in July 2018, reaching a value of 8.31 t ha^{-1} month^{-1} in the vicinity of TSF, industrial zones, and higher elevated areas. In the spatial distribution analysis of heavy metals and metalloids and their exceedances, the concentrations of Cu, As, and Cr exceeded the MPL defined in the Mongolian soil quality standard (Sodnomdarjaa et al. 2024). These elements overlapped in the same locations when analyzed by at least two different analytical methods. Cr concentrations were found to be as high as 104 mg kg^{-1} when analyzed by both sXRF and pXRF methods. The Cu concentrations were significantly higher, ranging from 271 to 475 mg kg^{-1}, which were determined using all three analytical methods. As concentrations ranged from 11 to 29 mg kg^{-1} when assessed using sXRF and pXRF. The spatial distribution of the heavy metals and metalloids contamination exceedance was found in the vicinity of mining areas, TSF, and some parts of the residential areas.

7.4.4 Rehabilitation potentials

Land reclamation:

The study of soil erosion caused by mining in the Erdenet area between 1989 and 2018 shows that the main factors contributing to the increased rate of soil erosion are not only related to human activities. Natural factors, particularly the intensity of rainfall, have also contributed significantly to this phenomenon over the years. Precipitation significantly increases soil erosion. (Zhao et al. 2021), and its higher amount in a shorter time triggers the intensification of soil erosion (Dunkerley et al. 2019; Zhao et al. 2021). Erdenet is located in the northern part of Mongolia, and differs from other regions of the country with higher annual precipitation patterns, ranging from 260 to 590 mm (Figure 7.2). Erdenet is located in soil regions identified as mountain forest steppe, forest gray, and mountain steppe kastanozem. This area is considered one of the most important agricultural regions in Mongolia, which is due to the higher levels of nutrients and humus present in the soils compared to other regions of the country (Khadbaatar 2020). The results of estimation the monthly soil erosion rate from 1989 to 2018 revealed that the erosion rate is significantly higher during periods of increased rainfall variability, although this coincides with the peak of the vegetation growing season in the country (Table 7.2).

Table 7.2 The highest rate of monthly soil erosion (t ha^{-1} $month^{-1}$) considering the average across various months from 1989 to 2018

Study area	Apr-May	June-Aug	Sep-Oct	Apr-Oct
Erdenet	0.42	4.96	0.49	1.96

Furthermore, elevated monthly soil erosion rates have been identified in the vicinity of the mine site, industrial areas, and tailings pond. Therefore, measures to address the ecological conditions of the rainy season, including the development of hydro construction and water management plans for water retention, drainage, and pipelines based on stream networks, especially near the tailings pond and mining areas, are essential for effective soil erosion control (Sodnomdarjaa et al. 2023). Increasing vegetation and forest cover is also one of the most effective approaches to preventing soil erosion (Liu et al. 2020). The local government of Erdenet City needs to integrate water management and forestation plans into its strategic planning to mitigate soil erosion, in line with short- and long-term environmental management strategies. Implementation of the environmental management plan to mitigate and prevent soil erosion requires the incorporation of elements such as afforestation, drainage systems, and protective barriers (Figure 7.7).

Soil remediation:

This study documented elevated levels of contamination in the vicinity of the mining site, tailings pond, and industrial areas in Erdenet, using various analytical methods for evaluation. The MPL in Mongolian soil quality standards was exceeded for As, Cr, Cu, and Zn. In the topsoil near the Erdenet mine, Cu is mainly associated with the organic and sulfide fractions, while As and Zn are mainly associated with the residual and Fe/Mn oxide fractions (Yondonjamts et al. 2019). Mineralogically, Cu contamination in these soils is related to the presence of the mineral chalcopyrite ($CuFeS_2$), while residual fractions of As and Zn may be adsorbed by quartz (SiO_2). Contamination of soil with As in the vicinity of the Erdenet mine may be due to several factors. Deposits often contain trace amounts of As, and the excavation of overburden rock and sediments containing the metalloid can release it into the surrounding environment, where these materials can subsequently undergo weathering processes, resulting in leaching of As into the nearby soil. During the transportation and storage of ore, there is a potential for dust to spread into the immediate environment.

The pollution levels identified in this study, along with those reported in previous studies, should serve as the basis for deriving strategies for soil remediation. Liu et al. (2018) suggested the integrated use of multiple soil remediation techniques, such as chemical stabilization and phytoremediation at different project stages and locations, to effectively address soil contamination. Kumpiene et al. (2008) pointed out that it is difficult to deal with contaminated sites with elevated concentrations of several heavy metals and metalloids and that the mobility of the elements is mainly influenced by organic matter due to the soil pH. For example, the leaching of Cu, Zn, Pb, As, and Cr is strongly pH dependent with the lowest mobility being around neutral to slightly alkaline conditions. Kumpiene et al. (2008) found that the soil pH has the most significant influence and shows a robust effect on element mobility. A successful soil remediation project includes key steps such as technology pre-screening, remedial investigation, feasibility study, selection of best remediation techniques, design and implementation of remediation practices, and evaluation of performance (Liu et al. 2018). For As-contaminated soils, primary technologies include phytoextraction and chemical immobilization, with additional technologies serving as supportive measures. Future research should prioritize environmentally friendly bioremediation measures and the integration of potential supportive measures (Wan et al. 2020). Several approaches are available to mitigate excess Cu concentrations, including the use of organic fertilizers, applying poly (amidoamine) dendrimers and potassium lignosulfonate, rice straw biochar and specific plants such as *Leersia hexandra, Elsholtzia splendens, Sedum plumbizincicola, Ipomea alpine, Eleocharis acicularis, Aeolanthus biformifolius, Commelina* *communis, Haumaniastrum katangense*, and *Rumex acetosa* (Mir et al. 2021). Recent studies (Bao et al. 2022; Ao et al. 2022; Wani et al. 2022) highlighted the promising potential of bioremediation for heavy metals and metalloids contaminated soil. This natural approach, utilizing endophytic fungi, plants, bacteria, mycorrhiza, and algae, proves to be a safer and more innovative method compared to traditional physical and chemical remediation, effectively accelerating the removal of chromium, for example, from contaminated soil.

The mitigation of contamination with multiple metals poses challenges since element mobility is primarily influenced by soil pH and organic matter, but factors such as mechanical erosion, particle size distribution, etc., also affect the process. The most effective technologies for the removal and/or control of contamination with As, Cr, Cu, and Zn include phytoextraction and chemical immobilization, with a special emphasis on the importance of environmentally sound and nature-based remediation. To effectively address the contamination of kastanozems in the arid subarctic climate, we recommend an integrated approach that includes techniques such as chemical stabilization and phytoremediation.

Future pathways for land use:

In 2016, the United Nations Development Programme (UNDP) in Mongolia conducted research regarding the long-term sustainability goals set for the year 2025 for the city of Erdenet in the Orkhon Province, in line with the United Nations' Green and sustainable development goals. Based on the results of previous studies and project reports in the Erdenet mining area, as well as the legal framework governing the mining industry in Mongolia, the key challenges that need to be prioritized over the next 10-15 years to achieve sustainable operation of the Erdenet mine in line with the UN SDGs is summarized in Figure 7.4.

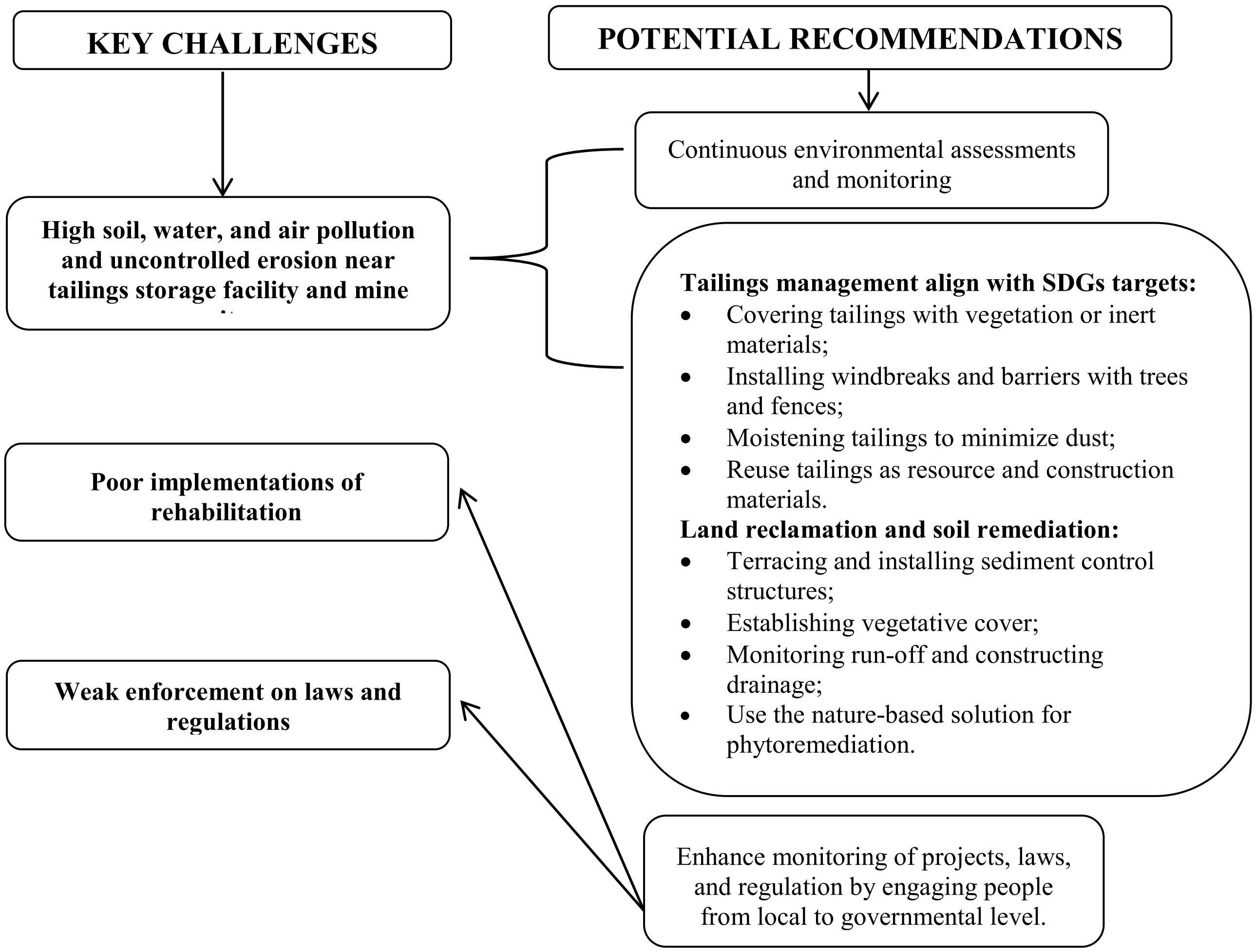

Figure 7.4 Summary of key challenges and recommendations for the next 10-15 years in the Erdenet area

Long-term successful rehabilitation needs to be linked to the definition of rehabilitation goals, the establishment of achievable success criteria, and the comparison of performance indicators (Grant et al. 2016). There is also a need to enhance collaboration between the government, mine enterprises, and research institutions to promote environmental protection and strengthen governance in the mining sector (Xu et al. 2023). Rehabilitation plans can serve as a comprehensive strategy to mitigate environmental impacts at the copper mine sites while aligning with broader sustainability goals such as the UN SDGs. It also requires ongoing environmental assessments, reporting and progress based monitoring, and continuous improvement of the rehabilitation plan. A fundamental goal of the rehabilitation is to establish optimal land capabilities that can support a wide range of future land uses (Pavloudakis et al. 2020). A graphical representation (Figure 7.5) was developed as a plan and recommendations for potential rehabilitation measures in the Erdenet area. The developed plan is consistant with the findings of previous studies, the environmental management and mine closure plan of the Erdenet mining operation, and follows legal and regulatory standards.

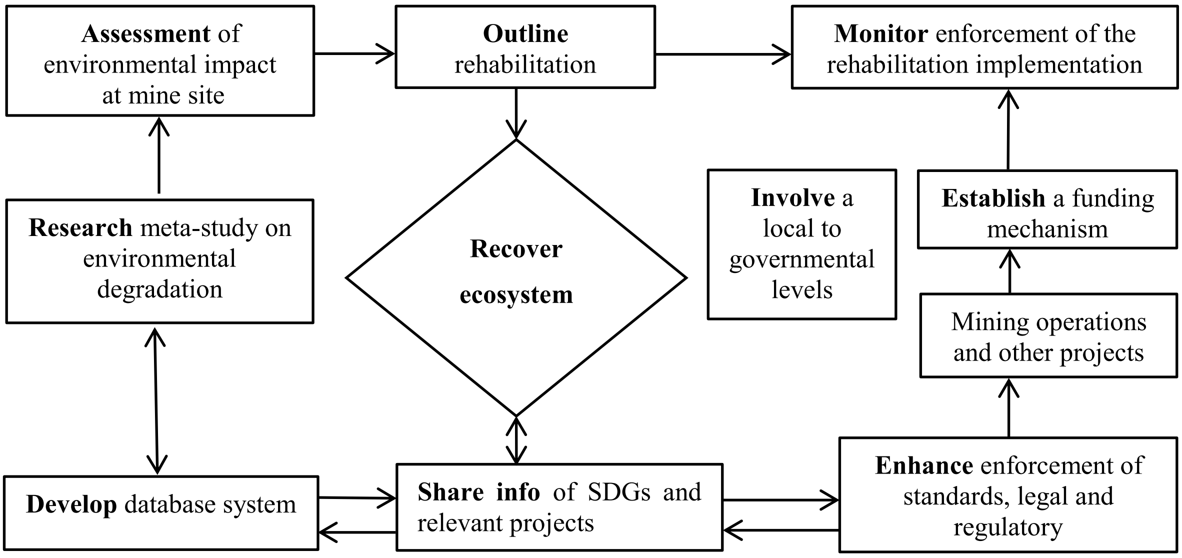

Figure 7.5 Rehabilitation pathways to recover the ecosystem in Mongolia, especially in the case of the Erdenet mining area

The primary rehabilitation recommendation derived from this study is visually represented by a general rehabilitation map, as shown in Figure 7.6. The plan includes the construction of approximately 7 km of concrete road from the open-pit to the city's main road, the provision of approximately 500 hectar for soil quality improvement, 1000 ha for reforestation (new tree planting), and 30 ha for new drainage systems around the tailings pond and the open-pit mining area in the town of Erdenet. Reforestation initiatives are being undertaken in the areas surrounding of the open-pit mine site and the tailings storage facility. Despite the degraded and infertile soils in these areas, there is an urgent need to plant suitable trees adapted to the climate and environment in the Erdenet area, after improving the soil quality through biological and mechanical soil improvement processes. The afforestation initiative should be undertaken with a long-term plan to ensure sustainable maintenance and growth of the planted trees. A comprehensive and detailed assessment is required to redefine the afforestation, recultivation, drainage area, and road length determinations. Terrer et al. (2021) summarized the results of 108 experiments on the absorption of CO_2 by natural ecosystems. They found that the faster trees grow, the more soil organic carbon will be taken from the ground. Roots and microorganisms work more actively in symbiosis with trees, and soil carbon turns into carbon dioxide and is released into the atmosphere. This is most evident manifested in forested steppes. So, if trees are thoughtlessly planted in steppe regions, erosion will be mitigated, but CO_2 emissions can intensify. This contradicts SDG 13 on climate action, which demands to reduce global CO_2 emissions by 45 percent by 2030 compared to 2010 and reach net-zero emissions by 2050.

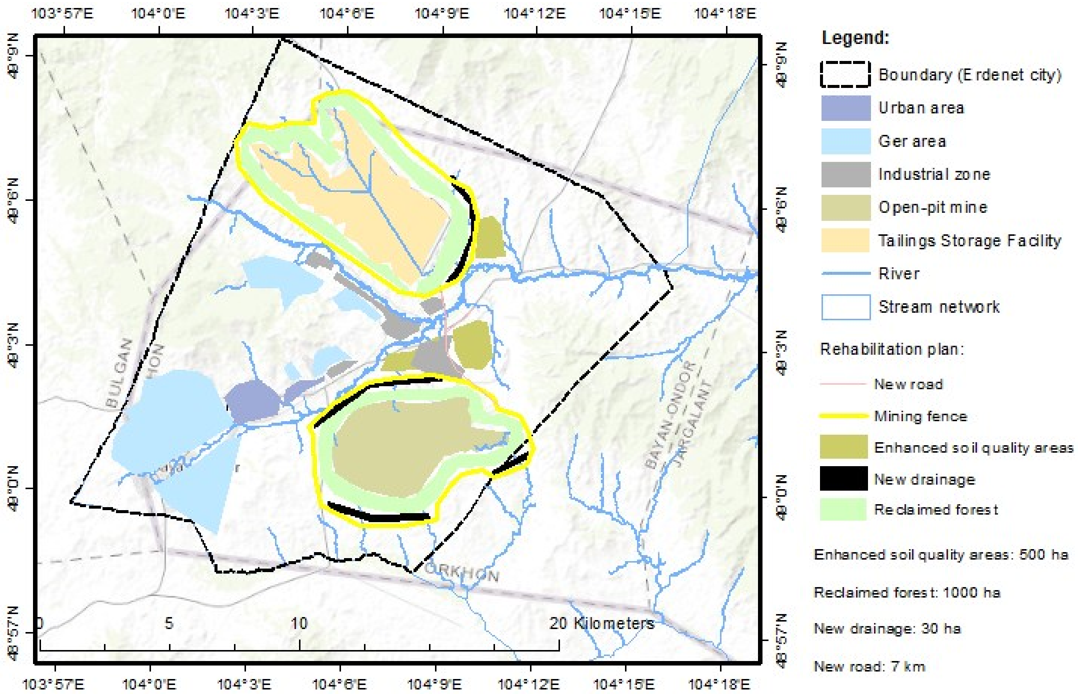

Figure 7.6 The rehabilitation plan map in the Erdenet area

7.5 Conclusion

This study assessed the rehabilitation needs and developed a rehabilitation plan for the Erdenet mining area based on previous surveys, relevant laws and regulations on the one hand and the current state of knowledge regarding rehabilitation strategies for mining sites in alignment with the UN SDGs. Investigations preceding this study include an assessment of soil erosion from 1989 to 2018 (Sodnomdarjaa et al. 2023) and the assessment of soil contamination by heavy metals and metalloids, particularly Cr, Ni, Cu, Zn, As, and Pb (Sodnomdarjaa et al. 2024). An integrated assessment of the results revealed that areas with higher levels of soil contamination often overllapped with elevated soil erosion rates. Elevated soil erosion rates were mainly observed during the period of highest precipitation. The highest soil erosion rates were recorded in July 2018, peaking at 8.31 t ha^{-1} $month^{-1}$, especially in the vicinity of the TSF, industrial zones, and higher elevated areas. An analysis of heavy metals and metalloids showed that the Mongolian standards (MPL) for the elements Cu, As, and Cr were exceeded. Cr concentrations reached 104 mg kg^{-1}, Cu concentrations were significantly higher and ranged from 271 to 475 mg kg^{-1}, and As concentrations ranged from 11 to 29 mg kg^{-1}. Exceedances of heavy metals and metalloids contamination were mainly observed in areas close to the mining sites, the TSF, and some residential areas.

The rehabilitation pyramid was used to highlight how rehabilitation measures through land reclamation and soil remediation can help to address the core aspects of environmental degradation, contributing to an amelioration of water pollution, soil contamination, the distribution of white dust, accumulation of mining waste, forest degradation, soil erosion, and resulting health impacts for both the local people and wildlife. Based on the findings of our own research, independent studies and reports, and the existing legal framework for mining in Mongolia, it is clear that addressing these challenges is an important goal for mining areas like Erdenet over the next 10-15 years. For the TSF in Erdenet, the following rehabilitation measures can be recommended: irrigating the surface, building new a TSF, planting of trees and construction of drainage around the TSF, and producing construction materials from the tailings. To effectively tackle the contamination of kastanozems with As, Cr, Cu, and Zn, an integrated approach may include chemical stabilization and phytoremediation techniques. Continuous environmental assessments and monitoring are basic prerequisites for the successful implementation of rehabilitation actions. The measures should be derived based on the currently applicable laws and regulations and the UN SDGs. Further studies are needed to assess the effectiveness of rehabilitation efforts under the local conditions, including an ongoing monitoring of soil pollution and erosion and its environmental implications.

8 SYNTHESIS

The doctoral dissertation summarizes the results of the investigations of soil erosion, contamination, and potential rehabilitation strategies within Mongolia's largest open-pit mining sites, including the Erdenet copper-molybdenum mine and the Baganuur coal mine. These mining operations play crucial roles in Mongolia's economic and infrastructural development. The study aims to understand how mining activities impact soil quality and the surrounding environment. It analyzes erosion patterns over a long-term period from 1989 to 2018, with observations made at three-year intervals. Additionally, it investigates the dispersion of contaminants in the surrounding ecosystems, particularly within the top layer of soils in and around the vicinity of the mining sites. Furthermore, the research explores into potential methods for restoring impacted areas, aiming to encourage sustainable land use practices guided by the principles of the United Nations Sustainable Development Goals (SDGs) and insights from previous studies, particularly those focused on the study area. This study not only contributes to academic knowledge but it also provides practical insights essential for guiding policy decisions and promoting responsible resource management in Mongolia's mining sector. Throughout the dissertation, essential data were gathered through a combination of field observations, remote sensing data capturing methods, and laboratory techniques, all aimed at addressing the research questions outlined in Chapter 1.2. These findings are summarized to directly address the questions listed below:

1. *What is the primar source contributing to the increases of soil erosion and contamination around the mining sites in the cities of Erdenet and Baganuur?*

The study identified that increased soil erosion and contamination near the Erdenet copper and molybdenum mine and the Baganuur coal mine sites are primarily influenced by increased rainfall intensity and human activities such as mining regions and industrial operations. In the semi-arid steppe environment of mining sites, the heightened soil erosion pattern is influenced by both precipitation variations and anthropogenic effects from mining activities (Batkhishig, 2013), with Vandandorj et al. (2017) underscoring that mining-induced soil erosion increases due to changes in rainfall distribution and rise in intense rainfall events associated with mining operations. Therefore, it is crucial to monitor soil erosion rates regularly and enforce suitable mitigation measures, particularly in mining regions in Mongolia. Previous research in the country predominantly focused on soil contamination in major cities affected by mining and industrialization (Lehmkuhl and Batkhishig, 2003; Knippertz, 2005; Karthe et al., 2014, 2017; Timofeev et al., 2016; Kosheleva et al., 2018; Han et al., 2021; Pecina et al., 2023). Elevated levels of SO_4^{2-}, Ca, Mg, and As were found in the river of Khangal in Erdenet city (Battogtokh et al., 2014; Karthe et al., 2017), the river located 2.5 km from the Erdenet copper and molybdenum mining and tailings dump (Solongo et al., 2021). In particular, the white dust from the tailings storage facility can be dispersed throughout the surrounding area during the dry seasons in spring, summer, and fall season (Lkhagvajargal et al., 2018) and enter the river system and further into the groundwater sources through wind and water erosion. Approximately 10 km downstream of the Erdenet mining area, increased levels of molybdenum concentraions still exceed WHO health-based guideliness during the summer (Battogtokh et al., 2014; Solongo et al., 2018). Park et al. (2020) found that As is higher than the national standard (MNS 5850:2008) in the soils and soil contamination is primarly visibile in the city center by dust in the Baganuur mining area. Zn was found around 2.8 and As was found 3 times higher than MPL in Baganuur area, while in the Erdenet area As was found 2.4 times higher and Cu was up to 8 times higher in the vicinity of the mining areas, industrial regions in both areas and tailings storage facility in Erdenet mining site. Regarding to the Nemerow Integrated pollutiona index, contamination hotspots are in the vicinity to mining sites and other industrial areas in both mining sites (Sodnomdarjaa et al., 2023). However, there is a notable scarcity of studies that have assessed soil erosion in Mongolia, with Onda et al. (2007), Kato et al. (2010), and Batkhishig et al. (2019) employing cesium-137 radionuclide, while Jarsjö et al. (2017) utilized WATEM/SEDEM. Batkhishig et al. (2019) found the average soil erosion rate in the non-mining impacted mountainous area to be approximately 12.5 t ha^{-1} $year^{-1}$, with a maximum soil erosion rate of 40.8 t ha^{-1} $year^{-1}$; Jarsjö et al. (2017) reported a soil loss rate of 10 t km^{-2} $month^{-1}$ around a gold mining area. Monthly soil erosion rates tend to be higher near mining and other anthropogenic activities; for example in case of July 2018, in the Erdenet mining area, soil loss rates exceeded 5 t ha^{-1} $month^{-1}$ in a 5 ha area within the tailing storage facility, while open-pit mining sites covering 20 ha experienced rates ranging from 1 to 2 t ha^{-1} $month^{-1}$, and similarly, in the Baganuur area, soil loss rates in a 31 ha open-pit mining site ranged from 1 to 2 t ha^{-1} $month^{-1}$, with peak soil erosion rates recorded in both areas in July during periods of highest precipitation, reaching around 7.8 t ha^{-1} $month^{-1}$ in Erdenet and 9.4 t ha^{-1} $month^{-1}$ in Baganuur; spatially, higher soil loss rates were observed near the mines and adjacent industrial sites (Sodnomdarjaa et al., 2023). Monthly soil erosion rates tend to be higher near mining and other anthropogenic activities; for example, in July 2018, in the Erdenet mining area, soil loss rates exceeded 5 t ha^{-1} $month^{-1}$ in a 5 ha area within the tailing storage facility, while open-pit mining sites covering 20 ha experienced rates ranging from 1 to 2 t ha^{-1} $month^{-1}$. Similarly, in the Baganuur area, soil loss rates in a 31 ha open-pit mining site ranged from 1 to 2 t ha^{-1} $month^{-1}$, with peak soil erosion rates recorded in both areas.

2. *What is the correlation between contamination and distance in the mining cities of Erdenet and Baganuur?*

This study, which aimed to determine the correlation between soil HMM concentrations and proximity to the TSF and open-pit mining sites in the Erdenet and Baganuur areas, revealed the following important findings: Zn levels were approximately 2.8 times higher, and As levels were three times higher than the MPL in the Baganuur area, whereas in the Erdenet area, As was found to be 2.4 times higher and Cu up to eight times higher in the vicinity of the mining areas, industrial regions in both areas, and the TSF in the Erdenet mining site. Overall, there was a consistent trend of decreasing HMM contents with increasing distance from the TSF and open-pit mine sites in both regions (Figure 6.6 and Figure 6.7). Specifically, in the Erdenet area, correlations for Ni, Zn, and Pb did not reach significance at the $\alpha=0.05$ level, while significant correlations were observed for Cu, As, and Cr. Conversely, in the Baganuur area, no significant correlations were found for Cu, Zn, and Cr, but significant correlations were evident for Ni, As, and Pb. The absence of significant correlations for Ni, Zn, and Pb in Erdenet, and Cu, Zn, and Cr in Baganuur, may be attributed to the relatively low contents of these elements at their respective source areas. Despite the findings by Battogtokh et al. (2014) and Solongo et al. (2021) regarding increased Cu concentrations detected even 10 km away from the mining sites and Tailings Storage Facility (TSF) in the Erdenet area, it is fortunate that these did not significantly impact groundwater sources due to the lengthy discharge period; however, Jarsjö et al. (2017) highlighted the contribution of mining-related soil losses to heightened pollutant transport within the mining area. Additionally, Park et al. (2020) discovered that As levels exceeded the national standard (MNS 5850:2008) in the soils, with soil contamination primarily visible in the city center due to dust in the Baganuur mining area.

3. *Can rehabilitation plans be formulated effectively by considering the overlapping spatial distribution of soil erosion and contamination in the mining cities of Erdenet and Baganuur?*

Despite the establishment of initiatives aimed at environmental improvement within specific mining operations in Mongolia, such as the Erdenet mining operation's internal environmental monitoring department in 2019, which initiated a reforestation project covering approximately 38 hectares in an abandoned tailings area (erdenetmc.mn), and the efforts by the Baganuur mining company between 1999 and 2017 to implement biological rehabilitation both inside and outside the mining fence, covering a total area of 180.5 hectares, with intentions to rehabilitate an additional 100 hectares, including the planting of approximately 25 thousand trees (erdenesmongol.mn), there remains a scarcity of research on the rehabilitation of mining sites and the management of mining waste in Mongolia, a concern underscored by Frauenstein et al. (2021). This shortage of research persists despite the significance of even the largest open-pit mining sites, which have been operational for approximately 50 years and play a crucial role in the country's economic development. However, the open-pit mining process in these areas may have significant environmental impacts, particularly in terms of desertification, as observed by Park et al. (2020), with common environmental impacts including the degradation of forests and prairies, leading to air, water, soil pollution, and land degradation, mainly attributed to the TSF, which has been documented in several previous studies. The waste from ore processing is commonly pumped to a TSF about 3 to 4 km north of the plant, posing notable risks to environmental and human health, along with contamination of ground and surface water in downstream areas near the TSF, as noted by Lkhagvajargal et al. (2018). Worlanyo and Jiangfeng (2021) further highlight that stockpiles, sludges, gullies, and TSFs impact soil biodiversity and ecosystem functions, contributing to significant environmental problems in mining regions. Therefore, to ensure a sustainable future for both mining operations, it is crucial to address these environmental issues. Planning can be an effective way to implement successful rehabilitation projects. For example, in the Erdenet copper and molybdenum mining operation, particular focus is on rehabilitating the TSF due to the current TSF operating at around 60% capacity (Schwarz et al. 2016). Therefore, it is essential to build a new TSF with a focus on reducing post-closure monitoring, minimizing costs, managing ongoing liabilities, and advancing environmental sustainability in the next decade (Dagva et al., 2016). Furthermore, to improve the current situation, promoting modern technologies and research for developing construction materials from the TSF is crucial (Jargalsaikhan et al., 2023). In Baganuur, continuous monitoring around the mining site and effective environmental management from both the mining company and the government is crucial in this regard (Park et al., 2019). Pecina et al. (2023) noted that numerous soil contamination studies focused on Mongolia are based on inappropriate methodologies or an insufficient number of samples, compromising the quality of their results and the relevance of their conclusions. Considering the anticipated long-term expansion, a meticulous assessment of heavy metal contamination becomes crucial. Based on these findings, future research on pollution in Mongolia should prioritize investigations into drinking water, street, and mining dust pollution. Yakovleva et al. (2017) highlighted that in alignment with these efforts, to ensure sustainable mining activities that promote environmental sustainability and human well-being, it is essential to implement strategies aligned with the Sustainable Development Goals (SDGs) introduced in 2015, particularly SDG 6 (clean water and Sanitation), SDG 12 (responsible consumption and production), and SDG 15 (life on land). The successful implementation of SDGs requires active engagement and collaborative participation of both public and private parties to achieve meaningful progress toward the proposed goals.

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Thank you all for your immense support, guidance, and encouragement throughout this journey. This PhD would not have been possible without each and every one of you.

4. Supplementary material to Chapter 4

S4.1 Soil samplings' location in Baganuur and Erdenet mining areas

Table S4.1 Soil samplings' location for pXRF (2020) in both areas

ID	2020 (samples for pXRF)			
	Baganuur		Erdenet	
	x	y	x	y
1	108.2949	47.8124	104.13083	49.116944
2	108.3044	47.7998	104.13417	49.119167
3	108.2262	47.723	104.13639	49.124444
4	108.244	47.7112	104.16194	49.157222
5	108.2542	47.6984	104.15222	49.089444
6	108.2458	47.6831	104.16	49.090556
7	108.3505	47.7295	104.16639	49.088333
8	108.3468	47.7461	104.18333	49.087222
9	108.3557	47.7667	104.21306	49.080833
10	108.3879	47.7618	104.28417	49.078333
11	108.3833	47.7707	104.35472	49.075278
12	108.365	47.7865	104.40889	49.049444
13	108.346	47.7959	104.08381	49.115806
14	108.3811	47.802	104.08375	49.115889
15	108.3883	47.7924	104.06814	49.112083
16	108.4101	47.7763	104.12394	49.079778
17	108.4109	47.7688	104.12211	49.0795
18	108.4651	47.7856	104.12503	49.111167
19	108.4673	47.7603	104.10028	49.044167
20	108.4129	47.7392	104.06347	49.140656
21	108.3421	47.6648	104.07289	49.141683
22	108.3428	47.6534	104.07844	49.073806
23	108.3647	47.6388	104.08575	49.071694
24	108.3084	47.643	104.04622	49.0465
25	108.285	47.6458	104.03861	49.040389
26	108.2645	47.6633	104.06226	49.013072
27	108.30322	47.7435	104.05149	49.0087
28	108.30686	47.702306	104.15279	48.9828
29	108.28725	47.67625	104.05481	49.115
30	108.32886	47.710528	104.1649	48.977206
31	108.26986	47.675639	104.09088	48.991403
32	108.29836	47.689306	104.10904	48.987261
33	108.41694	47.725417	104.09081	48.992278
34	108.25319	47.830528	104.05814	49.109361
35	108.25928	47.844	104.05442	49.116222
36	108.22881	47.846528	104.05906	49.119833
37	108.262	47.784944	104.06058	49.126611
38	108.28817	47.774222	104.07117	49.129222
39	108.29944	47.761833	104.08575	49.091528

40	108.22758	47.762139	104.01783	49.018194
41	108.20628	47.732306	104.03372	49.025472
42	108.19453	47.709667	104.02319	49.034917
43	108.25933	47.71425	104.01056	49.036472
44	108.25647	47.682556	103.99464	49.047083
45	108.26156	47.676972	103.99811	49.058083
46	108.29028	47.670111	104.00678	48.979528
47	108.27539	47.669722	104.02217	48.963139
48	108.27247	47.655806	103.96244	48.9595
49	108.27225	47.644722		
50	108.27392	47.633111		

Table S4.2 Soil samplings' location for sXRF (2020) and ICP-OES (2022) in both areas

ID	2020 (samples for sXRF)				2022 (samples for ICIP-OES)			
	Baganuur		Erdenet		Baganuur		Erdenet	
	x	y	x	y	x	y	x	y
1	108.3468	47.7461	104.13083	49.116944	108.28543	47.72075	104.05691	49.01868
2	108.3557	47.7667	104.13417	49.119167	108.269	47.66894	104.06809	49.01637
3	108.3879	47.7618	104.13639	49.124444	108.3201	47.67712	104.11034	48.99012
4	108.3833	47.7707	104.16194	49.157222	108.33041	47.67562	104.12466	48.97536
5	108.365	47.7865	104.15222	49.089444	108.33023	47.67565	104.12736	48.97971
6	108.346	47.7959	104.16639	49.088333	108.3529	47.64392	104.16688	49.07437
7	108.3883	47.7924	104.18333	49.087222	108.35324	47.64385	104.16484	49.07529
8	108.4101	47.7763	104.21306	49.080833	108.37599	47.62923	104.16717	49.07884
9	108.4109	47.7688	104.28417	49.078333	108.3757	47.62929	104.15057	49.10449
10	108.4673	47.7603	104.35472	49.075278	108.39902	47.6112	104.14133	49.11478
11	108.4129	47.7392	104.40889	49.049444	108.399	47.61101	104.21365	49.07629
12	108.2645	47.6633	104.08381	49.115806	108.38302	47.59336	104.21349	49.07671
13	108.30322	47.7435	104.08375	49.115889	108.34473	47.5915	104.26128	49.07928
14	108.30686	47.702306	104.06814	49.112083	108.39417	47.58652	104.26126	49.0794
15	108.28725	47.67625	104.10028	49.044167	108.39336	47.58681	104.3442	49.0731
16	108.32886	47.710528	104.04622	49.0465	108.44308	47.69035	104.3447	49.07338
17	108.25319	47.830528	104.03861	49.040389	108.37374	47.77705	104.37478	49.07061
18	108.22881	47.846528	104.06226	49.013072	108.37013	47.78806	104.3748	49.0696
19	108.25647	47.682556	104.02319	49.034917				
20	108.26156	47.676972	104.01056	49.036472				
21			103.99464	49.047083				
22			103.99811	49.058083				
23			104.00678	48.979528				
24			104.02217	48.963139				

5. Supplementary material to Chapter 5

S5.1 Monthly soil erosion from 1989 to 2018 rate in Erdenet mining area

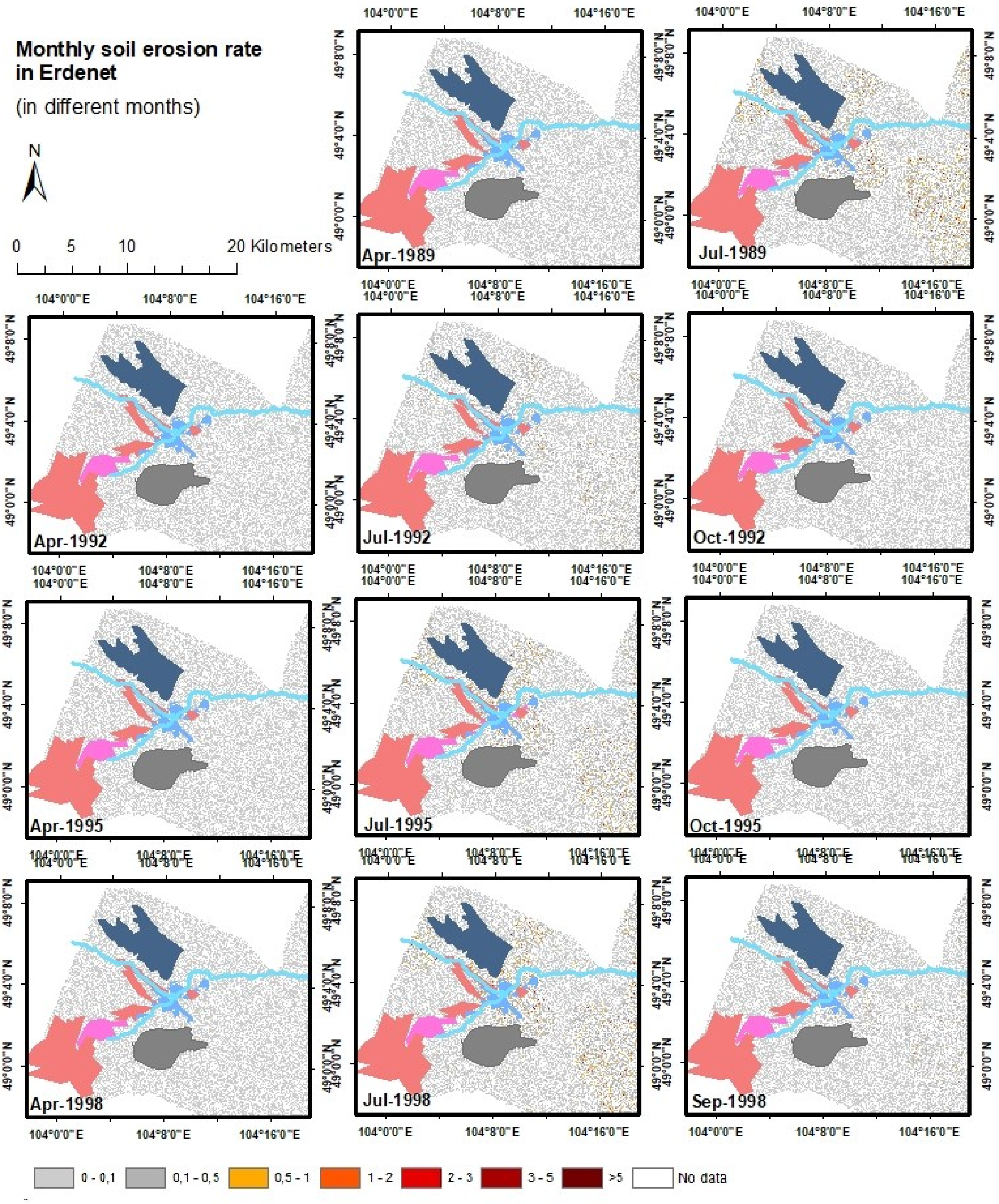

Figure S5.1 Monthly soil erosion rate in Erdenet mining area (1989, 1992, 1995, and 1998)

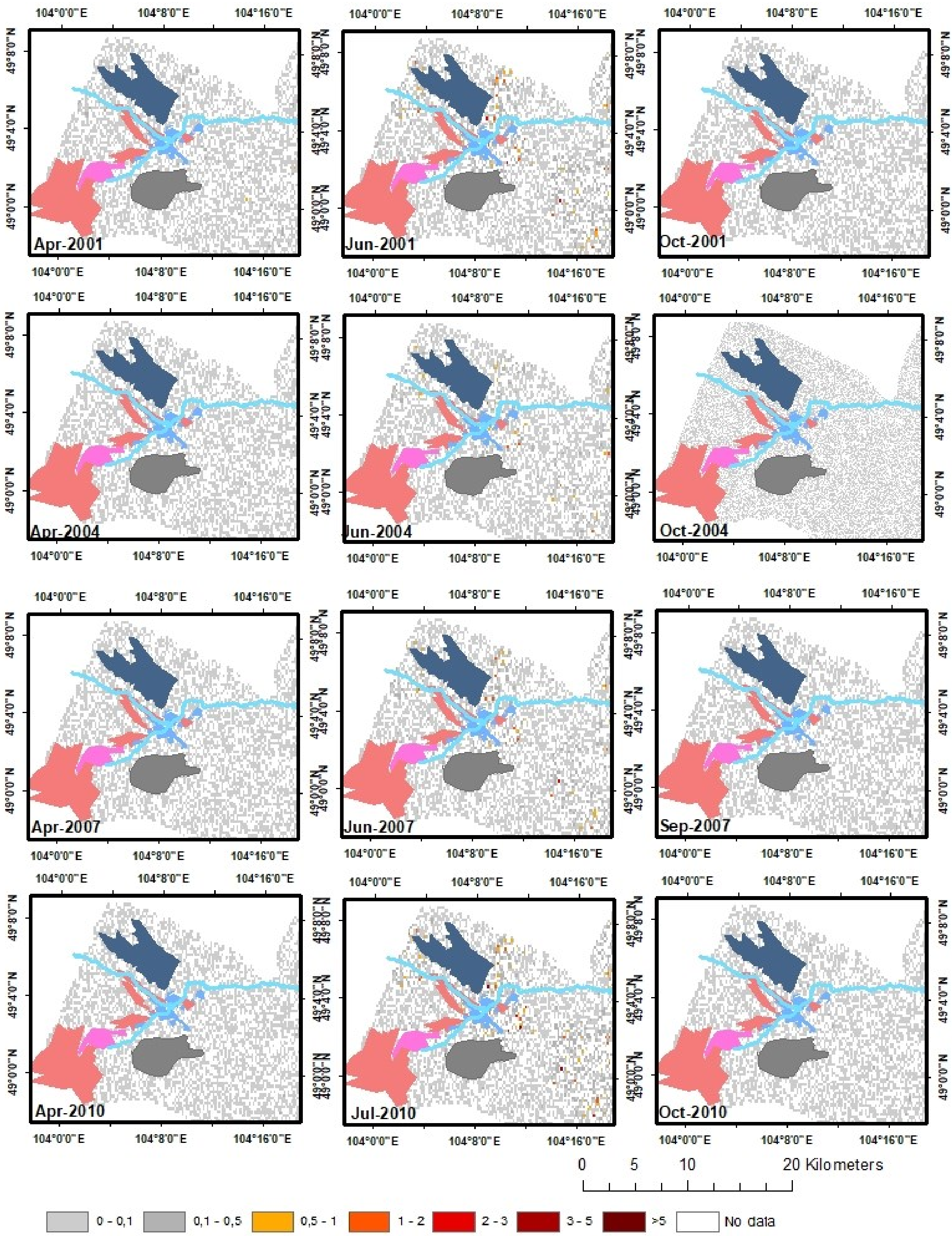

Figure S5.2 Monthly soil erosion rate in Erdenet mining area (2001, 2004, 2007, and 2010)

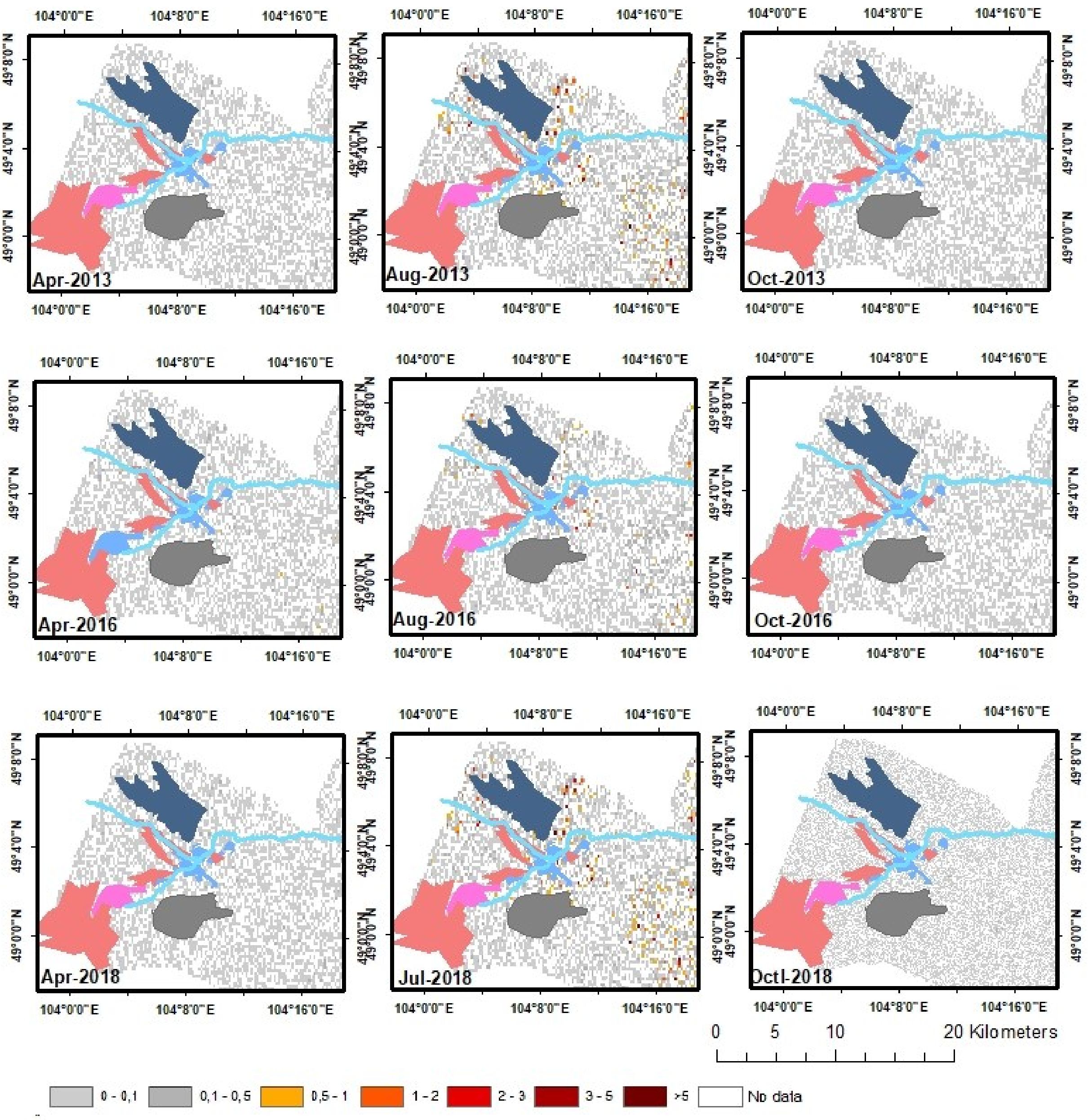

Figure S5.3 Monthly soil erosion rate in Erdenet mining area (2013, 2016, and 2018)

S5.2 Monthly soil erosion from 1989 to 2018 rate in Baganuur mining area

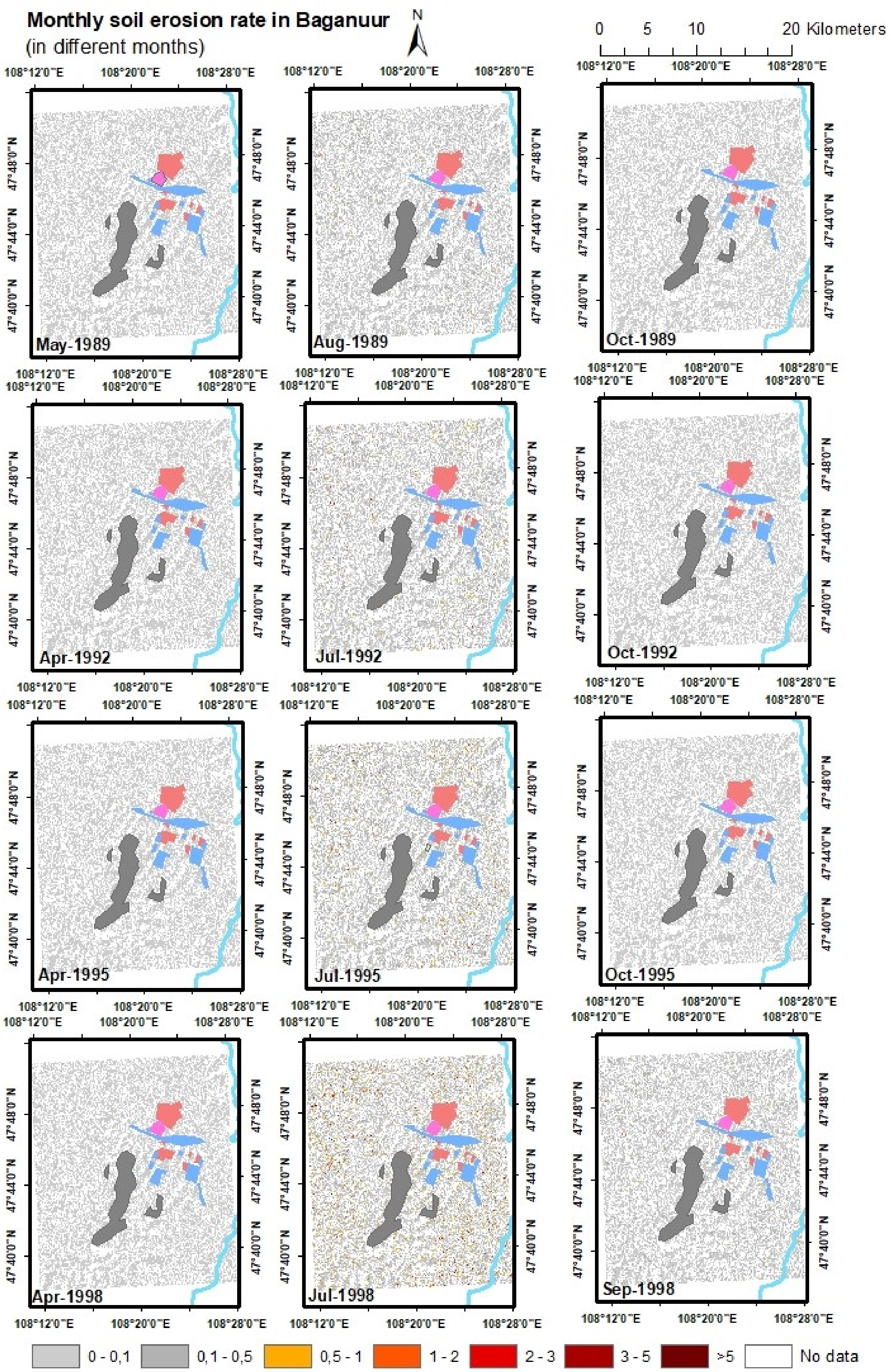

Figure S5.4 Monthly soil erosion rate in Baganuur mining area (1989, 1992, 1995, and 1998)

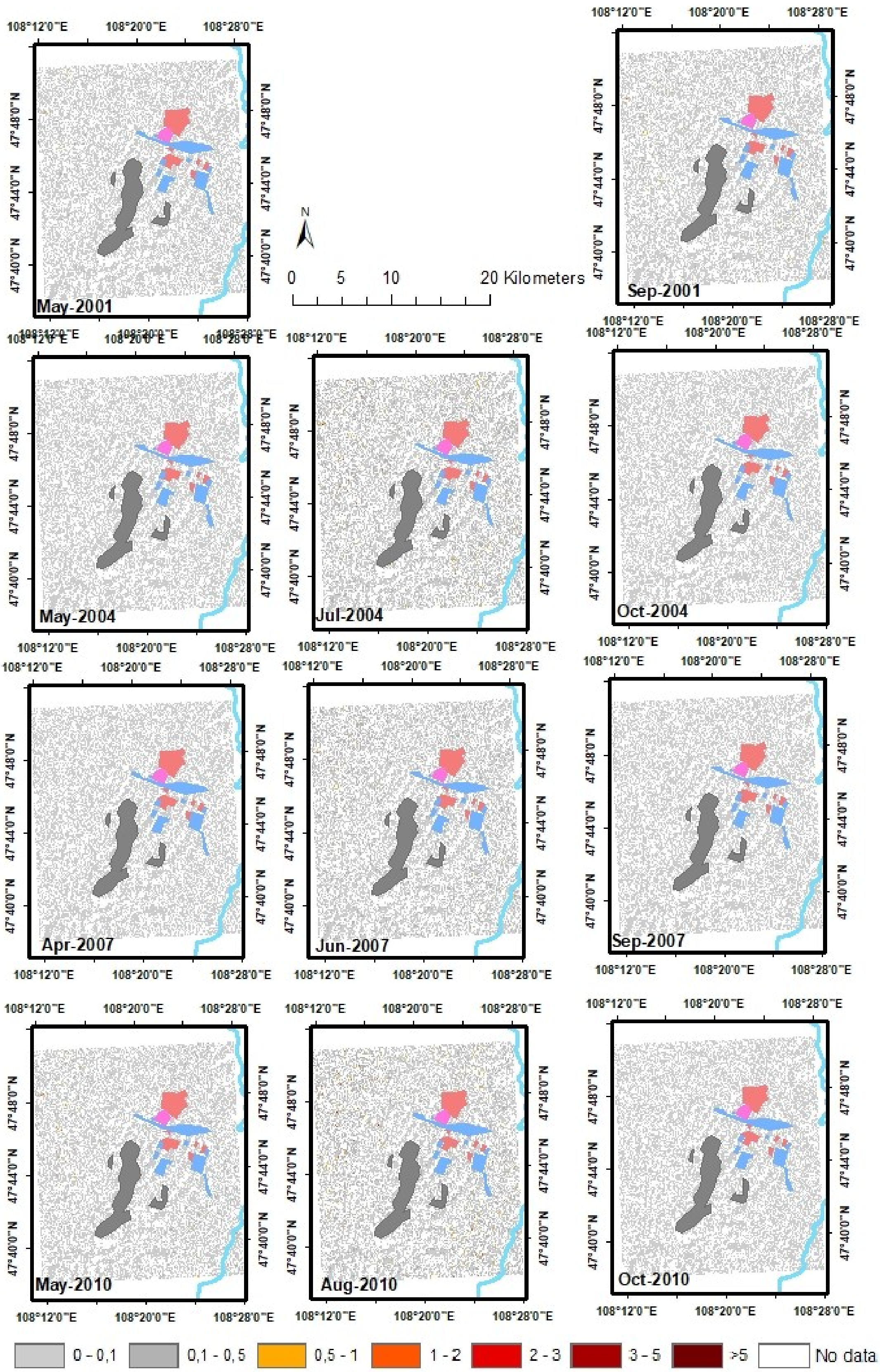

Figure S5.5. Monthly soil erosion rate in Baganuur mining area (2001, 2004, 2007, and 2010)

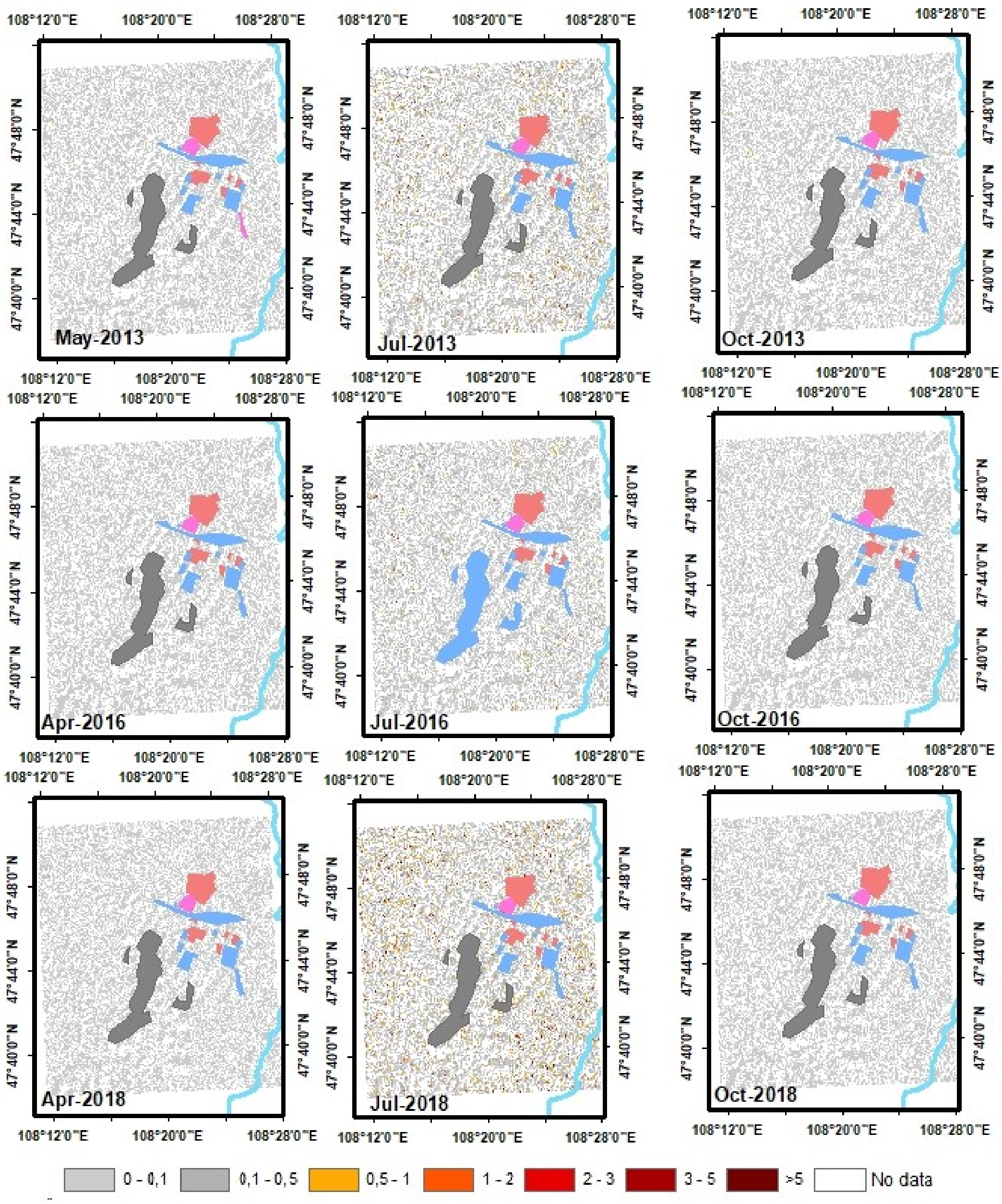

Figure S5.6. Monthly soil erosion rate in Baganuur mining area (2013, 2016, and 2018)

6. Supplemental material to Chapter 6

S6.1 Spatial distributions of HMM contents below or above MPL of MNS5850:2019 in Erdenet mining area

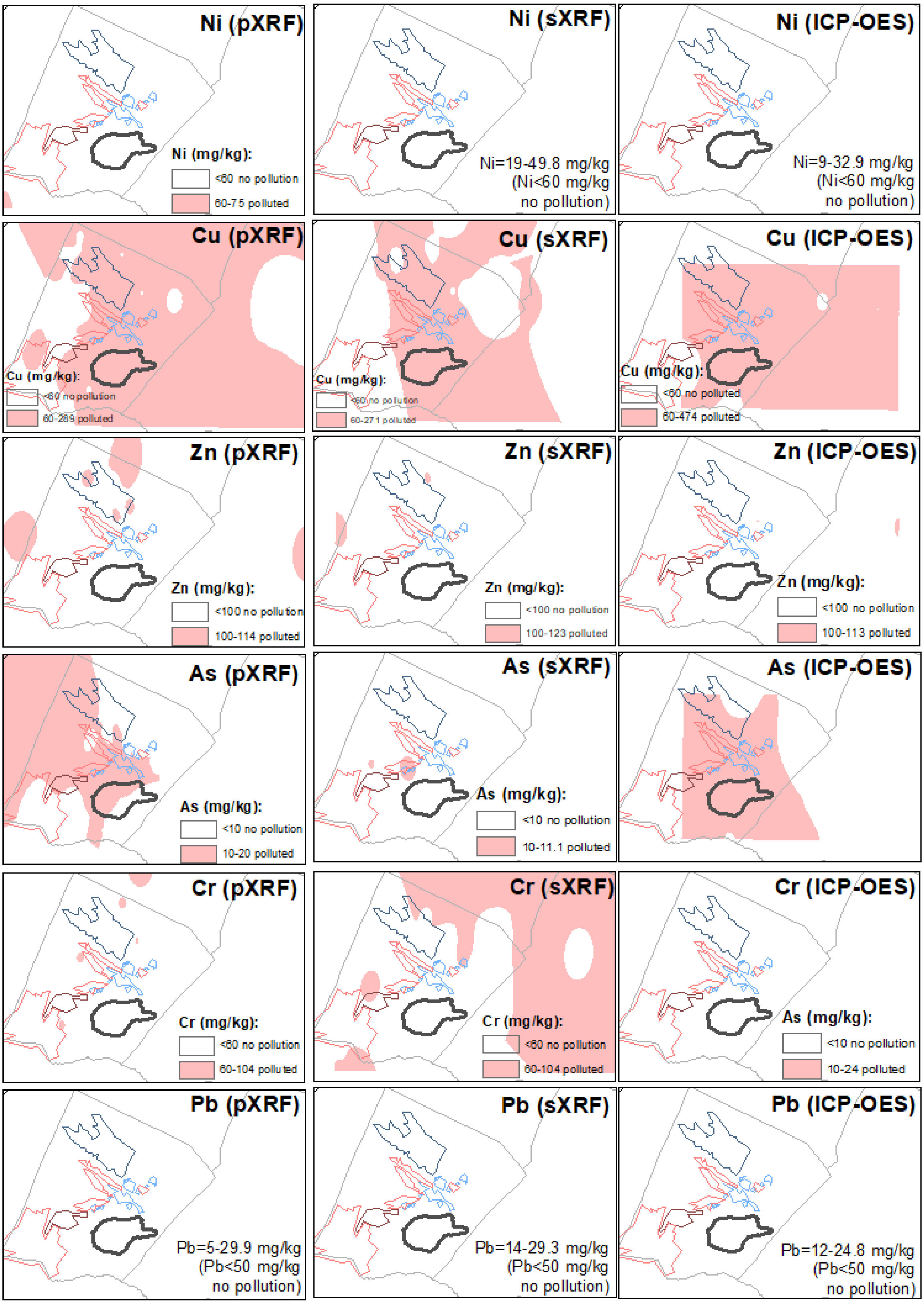

Figure S6.1 Spatial distributions of HMM contents compared to MPL in Erdenet area

S6.2 Spatial distributions of HMM contents below or above MPL of MNS5850:2019 in Baganuur mining area

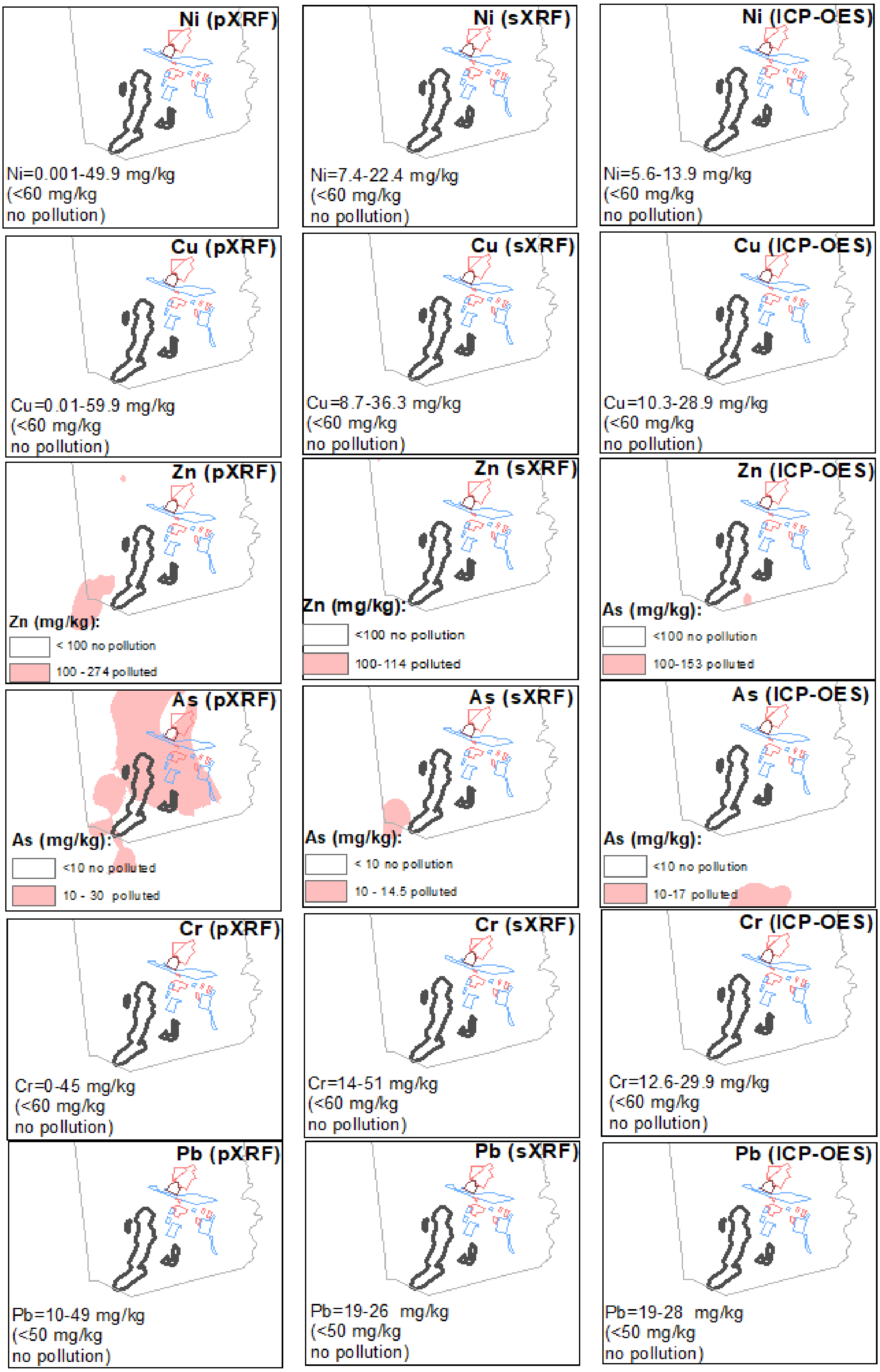

Figure S6.2 Spatial distributions of HMM contents compared to MPL in the standard in Baganuur area

7. Supplemental material to Chapter 7

S7.1 The rehabilitation pyramid

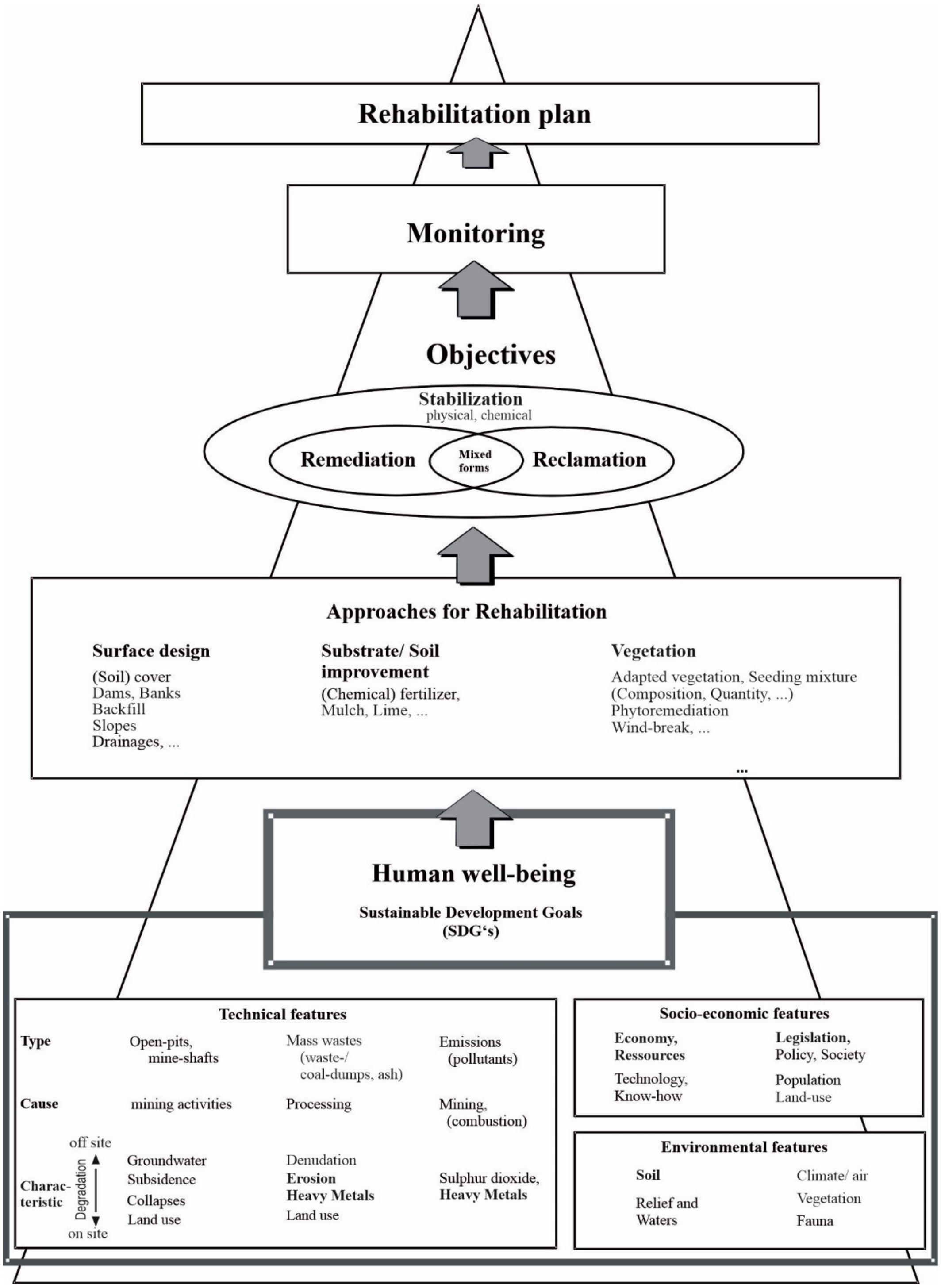

Figure S7.1 The rehabilitation pyramid (adapted from the figure by Knippertz 2005)

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