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REVIEW PAPER

Remote monitoring of land degradation in the mining context: an updated review focusing on potentials and challenges

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Abstract

Land degradation is a global challenge with profound impacts on both people's livelihoods and the environment. Mining activities present significant environmental challenges, necessitating effective monitoring and management strategies for land impacted by post-mining activities. Remote sensing has emerged as a crucial tool for monitoring land degradation and its spatial patterns in mining regions. However, there are several challenges that impede the successful application of earth observation data in these contexts. This paper comprehensively examines the importance of earth observation data in understanding trends and occurrences of land degradation in mining and post-mining areas. Firstly, it provides background information on the extent, causes, forms, and dynamics of land degradation in these regions. Subsequently, an overview of available earth observation data is presented, encompassing remote sensing variables, parameters, characteristics, and associated challenges in using them for monitoring land degradation in mining areas. Lastly, the paper discusses the primary obstacles to the promotion and utilization of these data for environmental monitoring in mining activities.

Keywords Remote sensing · Land degradation · Monitoring · Challenges

Overview

Despite significant efforts worldwide to improve the models and techniques used to evaluate and monitor land degradation, the problem persists in various regions. Mining areas belong to these hotspot regions where the exploration and use of mineral resources engender the deterioration of the natural environment.

The increasing number of post-mining sites worldwide (Fig. 2) requires effective and reliable methods of monitoring the condition of these areas. Kretschmann and Nguyen (2020) state that the processes affecting the post-mining environment should be regarded as continuous and treated as such; For example, secondary ground deformations may occur decades after the end of the underground extraction of minerals, in the form of residual subsidence (Vervoort and Declercq, 2017). Uplift is caused by a change of rock mass conditions due to the saturation of previously drained rock formations (Park et al. 2014; Sedlák and Poljakoviˇc 2020; Dudek et al. 2020; Barvels and Fensholt, 2021). Meanwhile, discontinuous deformations occur owing to the destruction of old, especially shallow, voids underground (Strzałkowski and Scigała 2020; Karagüzel et al. 2020).

Subsided zones may experience water-logging or flooding resulting from the restoration of the original groundwater table. All the above-mentioned phenomena have a significant impact on the land and vegetation of post-mining areas.

Land degradation caused by mining activities refers to the deterioration or loss of land quality, productivity, or ecological balance owing to mining operations. It occurs when mining activities disturb or alter the land's natural state, resulting in negative environmental, social, and economic impacts.

Land degradation involves the disturbance, removal, or contamination of the land surface, vegetation, soil, and water resources owing to mining activities, leading to a decline in land quality, loss of biodiversity, reduced ecosystem functioning, and impaired land productivity. This degradation can have far-reaching ecological and socioeconomic consequences, including habitat destruction, soil erosion, soil

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organic carbon, water pollution, air pollution, loss of agricultural potential, displacement of local communities, and disruption of ecosystem services (Lorenz et al. 2019).

However, human activities in mines can also cause and accelerate these processes. The Food and Agriculture Organization (FAO 2021) (FAO) defines land degradation as a long-term decline in ecosystem function and productivity and reports an increase in the severity and extent of land degradation in many parts of the world, with more than 20% of all cultivated areas, 30% of forests, and 10% of grasslands undergoing degradation. Figure 1 illustrates a map of global soil degradation collected by the Global Assessment of Human-Induced Soil Degradation (GLASOD), which is the most widely cited land degradation assessment reference.

The visual comparison and assessment of Figs. 1 and 2 reveal a significant concentration of mines in areas characterized by a high density of critical mines (used to extract materials for renewable energy and technology). These areas also exhibit extreme and strong degradation of soil. This clear observation emphasizes the susceptibility of mine areas to land degradation.

In regions with arid and semi-arid climates, vegetation is typically sparse and soils often lack essential nutrients. As a consequence, these areas commonly exhibit distinctive "badlands" landscapes, characterized by steep slopes, rills, gullies, and salinization. Land degradation can vary in both temporal and spatial scales, and quality. Land degradation indicates a drop in rank or status and signifies the loss of utility (including particular current use or possible intended future uses) or the reduction, loss or change of features or organisms that are hard, if not entirely impossible, to replace (Berhe 2007).

The aim of this review study was to examine the importance of multi- and cross-scale analyses in remote-sensing-based land degradation monitoring in mining and post-mining areas. This review provides an overview of land degradation and its causes over these regions and discusses the role of remote sensing in assessing land degradation. Additionally, common remote-sensing-based variables used as proxies for land degradation are presented. The study also discussed current gaps in remote-sensing-based land degradation assessments in the mining context and the importance of multi- and cross-scale analyses in these assessments.

Addressing the challenges of land degradation resulting from mining activities requires comprehensive evaluation and monitoring approaches. Remote sensing technologies have shown potential in assessing and monitoring land degradation, allowing for more holistic understanding of its spatial extent and severity. This review aims to provide a comprehensive analysis of the potentials and challenges associated with remote monitoring of land degradation in the context of post-mining areas. By synthesizing recent research and examining advancements in remote sensing techniques, this review contributes to enhancing land management strategies and supporting decision-makers in mitigating the impacts of land degradation caused by mining activities.

This updated review on the monitoring of land degradation in the mining context based on earth observation data provides crucial information on the topic from more than 20

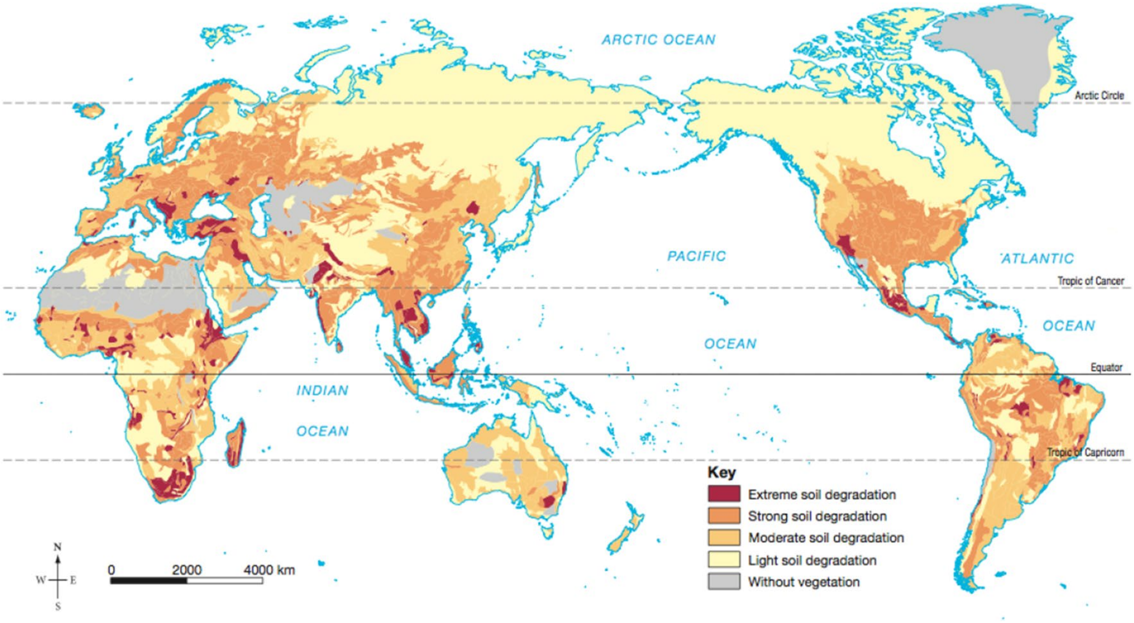

Fig. 1 Map of global soil degradation. The data gathered by the Global Assessment of Human-Induced Soil Degradation (Bridges and Oldeman 1999)

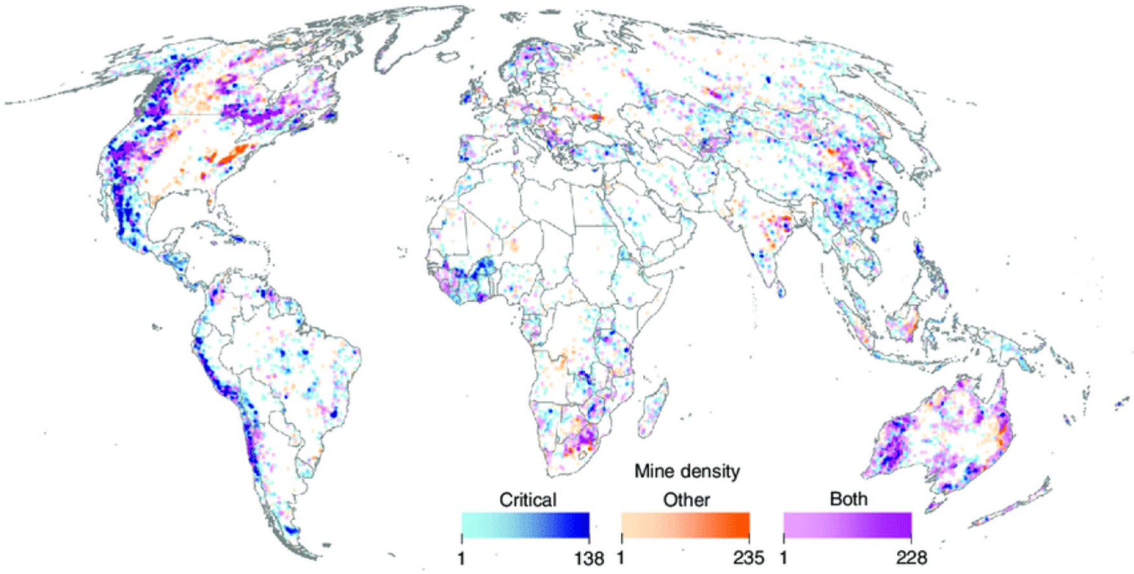

Fig. 2 Global mining areas and their density. Mining areas were mapped using a 50-cell radius around 62,381 pre-operational, operational, and closed mining properties. Mining areas with properties targeting materials critical for renewable energy technology and infrastructure are shown in blue, areas with properties targeting other materials are shown in orange, and those targeting both commodity types are shown in pink. Color shading (light to dark) indicates the density of mining areas, i.e., the number of mining properties within a 50-cell radius of each 1-km cell (Sonter et al. 2020)

original research papers with a focus on using earth observation data to assess land degradation in various climatic conditions, such as arid, semi-arid, dry-subhumid areas, and woodlands.

It addresses several questions regarding the detection and monitoring of land degradation through the use of satellite imagery, including:

1. How effective is the detection of land degradation from satellite imagery over mining areas?
2. What parameters can be derived from current space-borne sensors?
3. What types of land degradation in mining regions can be monitored remotely over mining areas?
4. What are the extent and dynamics of land degradation over investigated mining regions?
5. What are the requirements to monitor trends in land degradation using earth observation over mining areas?
6. What challenges exist in promoting and utilizing satellite data for land degradation monitoring in the mining context?

Additionally, this review offers insights into the existing space-borne sensors, encompassing their distinctive features, areas of application, and challenges related to data provision. We envision future studies building upon our framework to explore emerging technologies, refine methodologies, and address evolving challenges in sustainable mining practices and environmental management.

How effective is the detection of land degradation from satellite imagery over the past three decades?

The detection of land degradation from above has improved significantly during the last three decades, thanks to advancements in remote sensing technology. Satellite imagery and other remote sensing data can now be used to detect and monitor land degradation with a high degree of accuracy. These advancements have significantly enhanced our capacity to comprehend the magnitude and drivers of land degradation, enabling the formulation of more efficient mitigation strategies. Nevertheless, the precision of detection may vary owing to factors such as image resolution, the specific type of degradation, the size of the mine, and interference posed by cloud cover.

The data archives of earth observation (EO) sensors provide retrospective assessment of the circumstances and development of land on different spatial and time scales. Satellite imagery adheres to the principles of objectivity and repetitiveness, which are essential prerequisites in the context of land degradation monitoring. As a result, remote sensing typically furnishes efficient and suitable data for integrated methodologies that integrate remote sensing information with specialized techniques, geographic information system (GIS) analysis, and modeling methodologies (Röder et al. 2008).

Since the advent of satellite remote sensing data in the early 1970s, there has been a notable evolution in the volume and precision of the information available for monitoring land degradation in mining areas. This progress can be attributed to advancements in spatial and information technologies, which have enhanced the spectral and spatial resolution of satellite imagery. It is essential to recognize that satellite data primarily comprise digital images, encompassing arrays of pixels captured across various spectral bands—ranging from visible and near-infrared to infrared and microwave wavelengths—depending on the specific mission or satellite platform.

In the realm of land degradation monitoring within mining contexts, remote sensing emerges as a pivotal tool, offering a cost-effective and efficient approach to assess extensive areas. This methodology contrasts significantly with resource-intensive in situ studies, which typically focus on localized field assessments. Importantly, satellite-based monitoring serves as a critical asset, especially in regions with limited financial resources and infrastructural capacity, such as less-developed nations.

Spatial coverage and uncertainty

When discussing spatial coverage, it is imperative to consider the extent, granularity, and consistency of satellite data in capturing land degradation dynamics across mining areas. The spatial resolution of satellite imagery determines the level of detail and accuracy in depicting land surface features and changes over time. However, it is crucial to acknowledge the inherent spatial uncertainty associated with remote sensing data due to various factors, including sensor characteristics, atmospheric conditions, and data processing techniques.

Addressing spatial uncertainty involves assessing and mitigating potential errors, inconsistencies, and limitations in spatial data interpretation and analysis. This entails employing rigorous methodologies, validation techniques, and uncertainty quantification approaches to enhance the reliability and credibility of land degradation assessments. By integrating spatial coverage considerations with a comprehensive evaluation of spatial uncertainty, remote sensing technologies can effectively support evidence-based decision-making, policy formulation, and environmental management strategies in mining-affected regions.

The temporal component is also a critical aspect of land degradation assessment in mining areas, as it provides insights into the dynamics, trends, and patterns of environmental changes over time. Understanding the temporal dimension allows researchers, policymakers, and stakeholders to monitor, evaluate, and respond to land degradation processes and impacts associated with mining activities effectively. Therefore it is important to consider the following temporal components in land degradation assessment of mining areas:

Temporal dynamics

Long-term monitoring

Conducting long-term monitoring using multitemporal satellite imagery enables the detection of gradual changes in land cover, vegetation health, soil erosion, and water quality over extended periods. Analyzing temporal trends helps identify persistent degradation patterns, assess cumulative impacts, and evaluate the effectiveness of mitigation measures and regulatory interventions.

Seasonal variability

Recognizing seasonal variations and cycles is crucial, as mining activities may exhibit differential impacts across seasons owing to factors such as weather patterns, precipitation, temperature fluctuations, and vegetation growth cycles. Seasonal analysis facilitates the identification of seasonal degradation trends, vulnerability periods, and the optimal timing for restoration and rehabilitation efforts.

Time-series analysis

Utilizing time-series analysis techniques, such as trend analysis, change detection, and anomaly detection, facilitates the quantification of land degradation rates, trajectories, and hotspots within mining areas. These analytical approaches enable the comparison of historical data with current observations, highlighting significant changes, disruptions, and degradation trends over time.

Since 1974, many spatial and temporal assessment techniques and methods have been applied to monitor land degradation globally and over mining regions.

What parameters can be derived from current space-borne sensors?

There are many different parameters that can be derived from imagery acquired by current space-borne sensors to monitor land over investigated mining regions, including:

- Land cover and land use: This includes information about the types of vegetation, urban areas, and other land cover classes present in an image.
- Vegetation indices: These include measures such as the normalized difference vegetation index (NDVI), which can indicate the health and productivity of vegetation.

- Topography: Elevation and digital elevation models can be derived from stereo imagery to provide information about the terrain.
- Soil moisture: Space-based sensors have the capability to approximate the moisture content of soil.
- Surface temperature: This can be quantified through thermal imaging techniques, enabling the assessment of land surface conditions and alterations in land cover.
- Surface water: Space-borne sensors can be used to detect and monitor the presence and changes in surface water bodies.
- The normalized difference water index (NDWI) can be used to identify water bodies.
- The land surface temperature (LST) can be used to identify urban heat islands and hotspots and for fire detection.
- Aerosols: Remote sensing techniques, employing both passive and active sensors, can be leveraged to identify and quantify atmospheric aerosols, including dust, smoke, and pollutants.
- Wind speed and direction: Remote sensing can be used to measure the speed and direction of winds in the atmosphere using lidar and radar sensors.
- Precipitation: Through the utilization of both passive and active microwave sensors, remote sensing can estimate precipitation, encompassing rain- and snowfall.
- Ozone: Remote sensing techniques employing ultraviolet and infrared sensors enable the measurement of the ozone concentration in the atmosphere.
- Carbon dioxide: Remote sensing, employing both passive and active sensors, facilitates the measurement of the carbon dioxide concentration in the atmosphere.

These are some of the parameters that can be derived from current space-borne sensors, but this list is not exhaustive, and new sensors and techniques are being developed all the time.

The three typical primary attributes of earth observation (EO) data include spatial resolution (the ground area covered by one pixel), the spectral resolution (the range of spectral wavelengths recorded by the sensors), and the temporal resolution (the time interval between two satellite passages over the same area) (Lantieri 2003). Many studies incorporate these characteristics to generate the above-mentioned parameters and assess the general trend of land degradation or the ecosystem health circumstances in the mining context.

Several research papers have utilized statistical approaches, such as principal components analysis, ordinary least squares, or geographically weighted regression, to analyze the aforementioned parameters. Additionally, machine learning techniques such as random forests, support vector machines, and others are employed for classification and regression purposes (Glantz 1999, Bouaziz et al. 2019; Adeel et al. 2005; Aw-Hassan et al. 2016).

Spaceborne remote sensing allows for the accurate assessment of vegetation habitats and soil degradation in vast, inaccessible areas. Based on the spectral, spatial, and temporal resolution, remote sensing enables the identification and mapping of various aspects related to vegetation, including overall vigor and soil characteristics, in the mining context. Such mapping can range from general assessments to precise classifications of soil types and individual plant species. Vegetation observed through remote sensing data is typically described using derived variables such as vegetation indices, e.g., the normalized difference vegetation index (NDVI), soil-adjusted vegetation index (SAVI), enhanced vegetation index (EVI)), leaf area index (LAI), tree cover density, net primary productivity (NPP), biomass, canopy moisture, canopy height, and expected crop yield. These variables provide valuable insights into vegetation vigor, height, age, density, productivity, and biodiversity, as well as stress and disturbances. Vegetation cover serves as an integrated indicator of how vegetation responds to environmental factors such as rainfall, temperature, soil, topography, and human activities, which are often derived from land cover and land use (LULC) information, including irrigated agriculture. By linking the dynamics of vegetation cover with climatic and anthropogenic factors, a better understanding of changes in vegetation cover and ecosystem responses to natural stresses (e.g., droughts) and mining activities can be achieved. Furthermore, certain changes in LULC, such as deforestation or the encroachment of invasive species, are considered contributing factors to land degradation. Therefore, remote sensing-based monitoring of vegetation cover dynamics across various scales provides vital information for supporting sustainable land management (SLM) decisions on post-mining rehabilitation.

Numerous systematic techniques have been developed for analyzing vegetation dynamics and detecting changes using satellite images, particularly time series or multitemporal images. Among the popular methods are those that calculate vegetation-related parameters, such as phenometrics, and subsequently analyze their spatiotemporal dynamics over a specified observation period.

The temporal dimension of such analyses can be performed in a bitemporal, multitemporal, or hypertemporal manner. Current studies on derived parameters for land degradation assessment can also be tackled using remote-sensing-derived information, but the debate on a standardized set of parameters is ongoing.

Which land degradation types and phenomena can be remotely monitored over mining areas?

Human activities in mines can accelerate the environmental impact through various mechanisms. It can expedite environmental degradation. There are various types of land

Table 1 Land degradation forms and commonly used remote sensing indices in the mining context

Land degradation types	Characteristics	Remote sensing indices applied	Most common earth observation data
Soil erosion	This is the removal of fertile topsoil owing to wind or water, leading to the loss of soil structure and fertility Formation of gullies, washout of topsoil, decreased soil depth, loss of vegetation, and reduced soil fertility	Vegetation indices such as the normalized difference vegetation index (NDVI), soil adjusted vegetation index (SAVI), and bare soil index (BSI)	Synthetic aperture radar (SAR), optical data from Landsat and Sentinel satellites, and aerial photography are mainly used to assess soil erosion
Desertification	This phenomenon takes place when productive land undergoes a transition into a desert as a result of alterations in climate patterns and human actions, including excessive grazing, forest clearance, and unsustainable land utilization methods. Consequences of this process encompass the emergence of sand dunes, vegetation depletion, diminished soil fertility, heightened water runoff, and decreased water accessibility	Primarily, the normalized difference vegetation index (NDVI), as well as the enhanced vegetation index (EVI) and the normalized difference drought index (NDDI), are commonly utilized in this context	Optical data from Landsat and Sentinel satellites, as well as ground-based measurements
Deforestation	The removal of forested land for agriculture, urban development, and other uses leads to land degradation: Loss of vegetation, reduced water retention, increased water runoff, soil erosion, and reduced biodiversity	The normalized difference vegetation index (NDVI), vegetation continuous fields (VCF), Landsat-based forest change detection (FCD), and vegetation condition index (VCI)	Optical data from Landsat and Sentinel satellites, as well as ground-based measurements and aerial photography
Salinization	As a result of salt accumulation in the soil, soil salinity intensifies, resulting in a decline in soil fertility.: Formation of white crusts on the soil surface, reduced plant growth, and decreased soil fertility	The normalized difference water index (NDWI), normalized difference salinity index (NDSI), and vegetation health index (VHI)	SAR and optical data from Landsat and Sentinel satellites, as well as ground-based measurements
Soil degradation	The deterioration in soil quality as a result of a variety of factors, including overuse, nutrient depletion, and soil compaction	The normalized difference moisture index (NDMI) and soil brightness index (SBI) are used to assess soil degradation	SAR and optical data such as Landsat and Sentinel satellites, as well as ground-based measurements, are most commonly used to assess soil degradation
Soil acidification	This phenomenon takes place when the soil pH decreases, resulting in diminished soil fertility and hindered plant growth. Consequently, it leads to reduced soil fertility and limited availability of nutrients.	The NDVI and tasseled cap (TC) indices	Optical data from Landsat and Sentinel satellites, as well as ground-based measurements

degradation that can be remotely monitored using various remote sensing techniques (Table 1), including:

1. Deforestation and habitat destruction: Remote sensing is an effective tool for detecting changes in forest cover, including activities such as clear-cutting or selective logging. By analyzing satellite imagery, these changes can be identified and monitored over time.
2. Land subsidence: Underground mining can cause the ground to sink, resulting in land subsidence, which can damage infrastructure and affect surface water drainage patterns.
3. Soil erosion: Remote sensing can be used to map and monitor soil erosion by analyzing changes in land surface features such as slope, drainage patterns, and vegetation cover.
4. Desertification: Remote sensing is a valuable tool for detecting changes in vegetation cover, land use, and surface temperature, providing insights into the expansion of desert areas. By monitoring these variables using remote sensing data, it becomes possible to identify and track changes associated with desertification processes.
5. Contamination and soil degradation: Improper handling and disposal of mine waste, including tailings, overburden, and waste rock, can lead to soil contamination. Toxic substances from waste materials can permeate the soil, rendering it unsuitable for agriculture and affecting vegetation growth.
6. Land use changes: Remote sensing is instrumental in detecting changes in land use, such as urban expansion, conversion of natural habitats to agricultural land, and alterations in land cover owing to mining or other extractive activities. Through remote sensing analysis, these changes can be identified and assessed, providing valuable information for land management and planning.
7. Soil acidification: This is the process of decreasing the pH of soil, making it more acidic. Soil pH is a measure of the acidity or alkalinity of soil, with a pH of 7 considered neutral, a pH less than 7 considered acidic, and a pH greater than 7 considered alkaline. Soil acidification can lead to decreased soil quality and reduced soil fertility, making it more difficult to grow crops and maintain healthy ecosystems.
8. Water management: Remote sensing plays a crucial role in detecting changes in water levels, surface temperature, and vegetation patterns, providing insights into the impacts of water management on land degradation. By analyzing remote sensing data, such as satellite imagery, changes in water resources can be identified and monitored, highlighting potential issues related to land degradation caused by water management practices.

Remote sensing has evolved into an increasingly accessible tool, readily deployable to uncover patterns and facets of land degradation within the scope of mining activities. It empowers us to discern various forms of land degradation that are distinct to mining locales, encompassing soil erosion, salinization, and desertification (as outlined in Table 1). For instance, through the utilization of multispectral data, alterations in soil moisture indicative of soil erosion or shifts in vegetation cover signaling desertification can be promptly identified.

Comparing remote sensing data across diverse time frames emerges as an invaluable methodology for detecting alterations in land degradation within mining regions across temporal dimensions. Scrutinizing and contrasting satellite imagery or other remote sensing data collected at varying intervals empowers us to precisely ascertain and evaluate the magnitude of shifts in land degradation over time. This analytical approach is facilitated by the examination of multitemporal data, which in turn facilitates the discernment of evolving trends and patterns within the realm of land degradation.

The utilization of remote sensing data for the monitoring of these forms of land degradation presents a cost-effective and efficient mechanism to monitor shifts in land quality over time and to pinpoint areas particularly susceptible to degradation in the context of mining operations. The insights garnered from remote sensing exercise influence over land management decisions and steer the prioritization of tailored conservation initiatives tailored to the mining landscape. Furthermore, remote sensing data corroborate findings from ground-based observations, thereby deepening our comprehension of the spatial and temporal dynamics tied to land degradation in mining contexts. The fusion of remote sensing data with on-site information fosters a holistic comprehension of land degradation, thereby underpinning informed decision-making and the precise implementation of interventions aimed at effective land management and conservation within the mining realm.

Within Table 1, a thorough exposé of distinctive forms of land degradation pertinent to mining settings is provided, alongside exhaustive delineations of their characteristics. In tandem, the table illuminates commonly utilized remote sensing indices and data formats germane to the assessment and monitoring of these forms of land degradation within mining regions.

Besides these forms of land degradation, others can occur but are difficult to monitor through EO, such as sinkholes that can take place in the course of mining operations or several years after mining. There are different types of collapses, in an array from single, immature sinkholes to multiple, mature sinkholes. These two types of collapse could result in a significant hazard to the public (Canbulat et al. 2017). The development of most sinkholes is because of the progressive collapse of roof strata or chimney formation to the surface. A sinkhole usually looks like a small, deep hole in the surface, which with time will expand to take the form of a conical-shaped depression as unconsolidated surface deposits erode into the depression (Canbulat et al. 2017).

What are the extent and dynamics of land degradation in mining regions?

Land degradation can occur on a variety of scales, from small plots of land to entire regions. The extent and dynamics of land degradation in mining regions can vary widely depending on several factors such as the type of mining, mining practices, regulations, and the level of environmental management and reclamation efforts. The dynamics of land degradation in mining areas is complex and multifaceted, being influenced by factors such as continual expansion, regulatory changes, reclamation efforts, technological advancements, community engagement, and long-term environmental monitoring. Effective management and responsible mining practices are essential to minimize the impact of mining on the land and promote sustainable resource extraction.

The dynamics of land degradation, in these areas, can also vary depending on the type of degradation. As an example, desertification generally takes place gradually over an extended period, whereas soil erosion can occur rapidly in response to a singular event such as a heavy rainfall.

It is worth noting that land degradation is a complex and multidimensional phenomenon whose dynamics and extension can vary from place to place and from time to time.

Degradation processes exhibit a high degree of spatial variability worldwide. Degraded areas can be found in the immediate vicinity of seemingly stable ecosystems, and both degrading and recovering systems can occur under a wide range of climatic and geomorphological conditions. Understanding whether and where land degradation is primarily driven by climatic conditions or human impacts first requires a thorough understanding of degradation dynamics and knowledge of the spatial and temporal extent of stable and endangered ecosystems at the local scale (Fig. 3).

Remote sensing systems are believed to have the potential to contribute to solving issues in land-degraded areas due to mining activities. Earth observation provides a method for mapping degraded regions and is virtually the only data source that allows for repeated monitoring of land degradation trends and dynamics. Both cartographic mapping and continuous monitoring are essential requirements for formulating and implementing development strategies and policy choices concerning the sustainable utilization of land resources from mines.

A concrete example lies in the environmental monitoring of the United Schleenhain mine, including the regions of Peres and Groitzscher Dreieck, situated in Schleenhain, Germany. This monitoring approach used Sentinel-2 satellite data, employing a range of indices such as the NDVI, EVI, SAVI, MSAVI2, and NDMI to assess land degradation across post-mining areas (Dynowski and Benndorf, 2022). The study employed various remote sensing and statistical techniques, such as LandTrendr and Getis-Ord Gi, to explore the environmental condition of the post-mining landscape. The collective outcomes drawn from these diverse methodologies effectively facilitated the monitoring of land degradation trends within the Schleenhain mining site.

The proposed study of the Schleenhain mine used several GIS methods to investigate the state of the post-mining

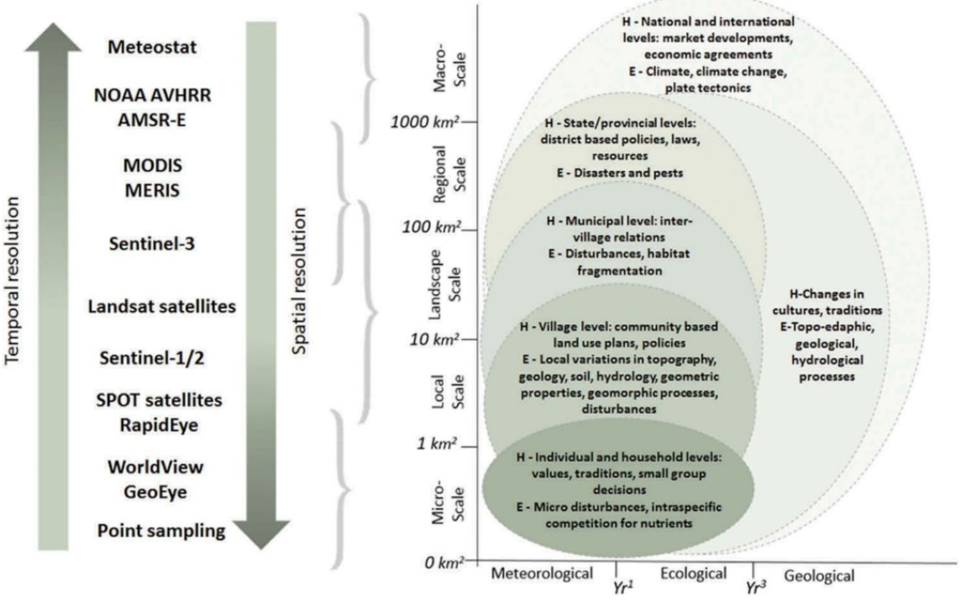

Fig. 3 A schematic illustration showcasing the diverse spatial and temporal resolutions of satellite imagery in relation to various scales of environmental and human processes associated with land degradation (Adopted from Buenemann et al. 2011)

landscape. The findings from all the methods show that patterns in the temporal distribution of the values of indices are a reliable argument in the assessment of vegetation changes and trends to assess degradation in the mine area.

What are the requirements to monitor trends in land degradation using earth observation?

Monitoring land degradation through earth observation over mining regions requires careful planning, data acquisition, processing, and analysis. The following requirements must be met:

1. Sufficient spatial and temporal resolution: Earth observation data must have high enough spatial resolution to accurately identify changes in land use and land cover as well as temporal resolution that allows for the detection of changes over time.
2. Sufficient spectral resolution to distinguish between different types of minerals, land cover, and land use, such as crops, forests, and deserts.
3. Robust data processing algorithms: Earth observation data must be processed using robust algorithms to extract meaningful information on land degradation. This may include image processing techniques to correct for atmospheric effects and correct for distortions caused by topography.
4. High-quality remote sensing data: Acquiring high-quality remote sensing data is crucial for accurate and reliable monitoring. High-resolution satellite imagery with multispectral or hyperspectral capabilities can provide valuable information about land cover changes, vegetation health, and soil conditions.
5. Availability of ancillary data: Ancillary data, such as climatic parameters, is needed to provide context to earth observation data and enhance the interpretation of land degradation trends.
6. Integration of GIS: Geographic information systems (GIS) play a vital role in analyzing and integrating remote sensing data with other mining spatial information, such as land use, hydrology, and topography. GIS allows for the spatial representation and analysis of land degradation trends.
7. Ground truthing and validation: Earth observation data should be complemented by ground-based observations to validate and refine the information obtained from satellite images. By incorporating such measures, it is possible to enhance data accuracy and gain deeper insights into the patterns of land degradation.
8. Long-term monitoring plan: Land degradation monitoring using remote sensing is most effective when conducted over the long term. Establishing a monitoring plan that spans multiple years allows for the identification of trends, changes in land degradation intensity, and the assessment of the effectiveness of management practices.
9. Collaboration and data sharing: To achieve comprehensive understanding of land degradation, effective collaboration among experts in various disciplines such as earth observation, geography, ecology, geology, and related fields is essential.

By meeting these requirements and employing appropriate remote sensing techniques, researchers and stakeholders can gain valuable insights into the extent, dynamics, and patterns of land degradation in mining areas. Such information is essential for formulating sustainable land management strategies and minimizing the environmental impact of mining activities.

Moreover, there are several space-borne data sources that can be employed to meet the aforementioned requirements for monitoring and identifying trends in land degradation. These data sources play a crucial role in assessing the environmental impact of mining activities and include:

- Radar data: Radar data enable the detection of soil moisture changes and facilitate the monitoring of erosion and sediment transport dynamics.
- Thermal imaging: Thermal imaging can be used to measure surface temperature, which can provide information about land surface conditions and land cover changes.
- Lidar data: Lidar data can be utilized to generate digital elevation models, allowing for the monitoring of topographic changes and identification of erosion indicators.
- Multispectral data: Multispectral sensors can be used to detect changes in vegetation health, land cover, and land use.
- Synthetic aperture radar (SAR) data: These data enable the identification of alterations in soil moisture, vegetation cover, and aquatic features.
- Crowdsourced data: Platforms such as OpenStreetMap can be used to collect information about land use and land cover changes from local communities.
- Ground measurements: Field measurements can be used to validate and complement the information obtained from space-borne sensors.

These data sources can be utilized synergistically alongside other information, such as meteorological data, to track long-term patterns of land degradation in both mining and post-mining contexts and to develop effective strategies for its mitigation.

This review thoroughly examines the characteristics of different spatial, spectral, and temporal scales, utilizing a diverse range of optical and radar sensors, including unoccupied aerial vehicles (UAVs), PlanetScope, Sentinel-1 and

-2, Gaofen, Landsat, MODIS, PROBA-V, SPOT VGT, and AVHRR (as delineated in Table 2). The methodological framework of the studies integrates supplementary datasets sourced from remote sensing imagery, such as the Shuttle Radar Topography Mission (SRTM) digital elevation model or Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) precipitation estimates.

Within the archives of Earth observation, an extensive array of optical and radar sensors are available for monitoring land degradation, particularly relevant to both mining and post-mining contexts. Optical/multispectral sensors form one category characterized by low to medium spatial resolutions (ranging from 1 km to 100 m) and near-global coverage at temporal resolutions ranging from weekly to daily intervals. In contrast, a separate group of radar and optical sensors offers spatial resolutions ranging from 30 m to submeter levels (indicated by the yellow ellipse in Fig. 3). However, they do not achieve daily global coverage, not even on a monthly or annual scale. While sensors such as AVHRR and MODIS acquire data frames extensively, enabling global coverage, others such as Landsat, Aster, TerraSAR-X, Radarsat, and World-View gather data for specific tasks. As a result, achieving daily, weekly, monthly, or even annual coverage using data from these sensors is uncommon. The Landsat science team has assembled mosaics providing global coverage by amalgamating datasets amassed over periods of up to 5 years. Additional global products based on this higher spatial resolution data, such as the global urban footprint (Esch et al. 2009), also encompass aggregations of scenes spanning multiple years.

For the purpose of monitoring land degradation within both mining and post-mining contexts, and their implications for biodiversity, the sensors in the green ellipse in Fig. 4 are particularly suitable. They facilitate the mapping of habitat boundary conditions on a national to global scale using physical index and thematic variables. These sensors offer daily coverage, enabling analyses of time-series data and the derivation of means, deviations, anomalies, variability, and trends tied to climate change (Cracknell et al. 1997). For instance, Dietz et al. (2014) employed 30 years of daily-available AVHRR-derived snow cover data to demonstrate shifts in the snow season in Central Asia over the decades, manifesting in later first snowfalls and earlier onset of snowmelt. Such climate change-related assessments are feasible solely with daily data. Sensors encompassed by the “yellow ellipse” (depicted in Fig. 3) facilitate precise mapping and multi-temporal monitoring at local scales, particularly relevant in both mining and post-mining contexts. These sensors possess the ability to map with high resolution, even down to species levels if the species occupies a sufficiently sizeable area (comprising a few pixels). Furthermore, they can derive texture-related variables of image segments or objects, crucial for species differentiation. Advanced optical sensors such as GeoEye, WorldView, QuickBird, or IKONOS hold potential for identifying individual animals and estimating population counts, even in mining environments.

Moreover, radar data have been increasingly utilized for post-mining environmental assessment owing to their unique capabilities to penetrate vegetation cover, detect surface changes, and provide valuable insights into terrain characteristics and land surface dynamics. For example, synthetic aperture radar (SAR) data are used to detect and monitor ground subsidence resulting from mining activities. By analyzing interferometric SAR (InSAR) data, researchers can identify subsidence patterns, quantify displacement rates, and assess potential (Fig. 5).

What challenges exist in promoting and utilizing satellite data for land degradation monitoring?

Promoting and utilizing satellite data for land degradation monitoring in a mining context comes with various challenges. These challenges can affect the effectiveness and accuracy of monitoring efforts. Some of the key challenges are as follows:

- Spatial resolution: The spatial resolution of satellite imagery might not always be sufficient to capture small-scale changes and specific land degradation features caused by mining activities. Some forms of land degradation, such as soil erosion and localized habitat destruction, may require higher-resolution data that are not always readily available from satellites.
- Temporal resolution: Frequent and consistent data acquisition is essential for monitoring trends in land degradation over time. However, some satellite missions may have limitations in their revisit time, meaning that regular coverage of mining areas might not be achievable, leading to gaps in data availability.
- Cloud cover and weather conditions: Cloud cover and adverse weather conditions can obstruct satellite observations, especially in regions with frequent cloud cover. Persistent cloud cover can limit the availability of cloud-free imagery, hindering regular monitoring efforts.
- Data costs and accessibility: Acquiring and accessing satellite data, particularly high-resolution and up-to-date imagery, can be costly and might not be financially feasible for some researchers or organizations. Data availability and accessibility may also be restricted owing to licensing and data sharing agreements.
- Data processing and analysis: Satellite imagery requires significant processing and analysis to extract meaningful information about land degradation. Advanced image processing techniques and skilled personnel are necessary for accurate data interpretation, which may pose challenges in regions with limited technical expertise.

Table 2 Land application-related sensors (adopted then adapted after Kuenzer et al. 2014)

Satellite	Sensor	Pan	Multispec status	Designed by	Owner	Launched	Altitude	Nadir repeat	Lifetime
KOMPSAT-3	AEISS	0.7	2.8 active MS: 2.2 m	Korea Aerospace	KARI	5/17/2012	685	28	4
KOMPSAT-3A	AEISS-A, IIS	0.55	IR: 5.5 m active	Korea Aerospace	KARI	3/25/2015	528	28	4
Landsat-7	ETM +	15	30 active	NASA	NASA	4/15/1999	705	16	5
Landsat-8	OLI, TIRS	15	30, 100 active	NASA	NASA	02.11.2013 12/17/2011	705	16	5
Pliades 1A & 1B	HiRI	0.5	2 active	Airbus	CNES	12/1/2012	694	26	5
QuickBird		0.65	2.62 inactive	EarthWatch In	Digital Globe	10/18/2001	450	3	
RapidEye	REIS		5 inactive	Surrey Satellite	Planet	8/29/2008 A6/23/2015	630	5	7
Sentinel-2	MSI	–	10, 20, 60 active	Airbus	ESA	S2B 3/7/2017 S3A 4/16/2016	786	10	7
Sentinel-3	OLCI		300 active	Thales	ESA	3B 4/25/2018 S3A 4/16/2016	814	27	7
Sentinel-3	SLSTR		500, 1000 active	Thales	ESA	S3B 4/25/2018	814	27	7
SkySat-1	SS-MSI	0.5	2 active	Skybox Imaging	Planet	11/21/2013	587		6
SkySat-2	SS-MSI	0.5	2 active	Skybox Imaging	Planet	07.08.2014	587		6
SkySat-3	SS-MSI	0.5	2 active	Skybox Imaging	Planet	6/22/2016	500		6
SkySat-4–7	SS-MSI	0.5	2 active	Skybox Imaging	Planet	9/16/2016	695		6
SkySat-8 to 13	SS-MSI	0.5	2 active	Skybox Imaging	Planet	10/31/2017 9/9/2012	500		6
SPOT 6 & 7	NOAMI	1.5	6 active	Airbus	EADS Astrium/ Azercosmos	6/30/2014	694	26	10
SuperView-1		0.5	2 active		Beijing Space View Technology	2018	530	2	8
Terra	ASTER	–	15, 30, 90 active	NASA	NASA	12/18/1999	705	16	6
Terra	MODIS	–	250, 500: active	NASA	NASA	12/18/1999	705	16	6
TripleSat-1–3 &	S:VHRI-100	0.8	3.2 active	SSTL	DMCii	7/10/2015 & 9/1	651	1	7
Vivid-i 1 to 5	HRI	0.6	active	SSTL	Earth-i	01.12.2018	500	1	5
VNREDSat-1A	NAOMI	2.5	10 active	(EADS)	VAST	05.07.2013	704		5
VRSS-1	PMC	2.5	10	active	China Academy	ABAE	2012	640	4
VRSS-1	WMC	16	16	Active	China Academy	ABAE	2012	640	4
VRSS-2	IRC	30	60	Active	CGWIC	ABAE	2007	645	
VRSS-2	PMC-2	1	4	Active	CGWIC	ABAE	2007	645	
WorldView-1	WV-60	0.5	–	Active	Maxar	Maxar	2007	496	
WorldView-2	WorldView-110	0.46	1.85	Active	Maxar	Maxar	01.07.1905	770	

Table 2 (continued)

Satellite	Sensor	Pan	Multispec status	Designed by	Owner	Launched	Altitude	Nadir repeat	Lifetime
WorldView-3	CAVIS	–	30	Active	Maxar	Maxar	2014	620	5
WorldView-3	WV-3 imager	0.31	1.24	Active	Maxar	Maxar	2014	620	5
WorldView-4	SpaceView 110	0.31	1.24	Inactive	Maxar	Maxar	2014	617	
ALOS-PALSAR	ALOS	10	10	Inactive	ALOS	ALOS	2006	650	46
Hyperion	NASA		240	Inactive	NASA	ESA		650	16
Sentinel 5P	ESA			Active	ESA	ESA	2017	814	1
Landsat 9	NASA	15	30	Active	NASA	NASA	2021	750	16
VRSS-1	PMC	2.5	10	active	China Academy	ABAE	2012	640	4
VRSS-1	WMC	16	16	Active	China Academy	ABAE	2012	640	4

HRG high resolution geometrical, *IMC* infrared multispectral camera, *LISS* linear imaging self scanner, *MERSI* medium-resolution spectral imager, *HRVIR* high-resolution visible, *WFI2* Wide-Field Imager Camera 2, *HRV* high resolution visible, *MVISR* multispectral visible and infrared scan radiometer, *ASTER* Advanced Spaceborne Thermal Emission and Reflection Radiometer, *ASAR* advanced synthetic aperture radar, *ALI* Advanced Land Imager, *LISS-IV* Linear Imaging Self Scanner III, *OLI* Operational Land Imager, *AVHRR* Advanced Very High-Resolution Radiometer, *TM* Thematic Mapper, *HRC* high-resolution camera, *ETM* enhanced thematic mapper, *HR Pan* high-resolution panchromatic, *AWFI* advanced wide-field imaging camera, *PAN/MS* panchromatic/multispectral, *AWiFS* advanced wide-field imager, *MUX* multispectral, *MODIS* moderate-resolution imaging spectroradiometer, *PANMUX* panchromatic and multispectral, *AATSR* advanced along-track scanning radiometer, *HR CCD* high resolution CCD, *ATSR-1*, Along-Track Scanning Radiometer-1, *MUXCAM* multispectral camera, *ATSR-2* Along-Track Scanning Radiometer-2, *MVISR* multispectral visible and infrared scan radiometer, *VHRR* very high-resolution radiometer, *VIIRS* Visible/Infrared Imager Radiometer Suite, *WFI* wide-field imager camera, *HSI* hyperspectral imager, *WVC* wide-view CCD camera, *HiRI* high-resolution imager, *SLIM6* Surrey Linear Imager Multispectral 6 channels

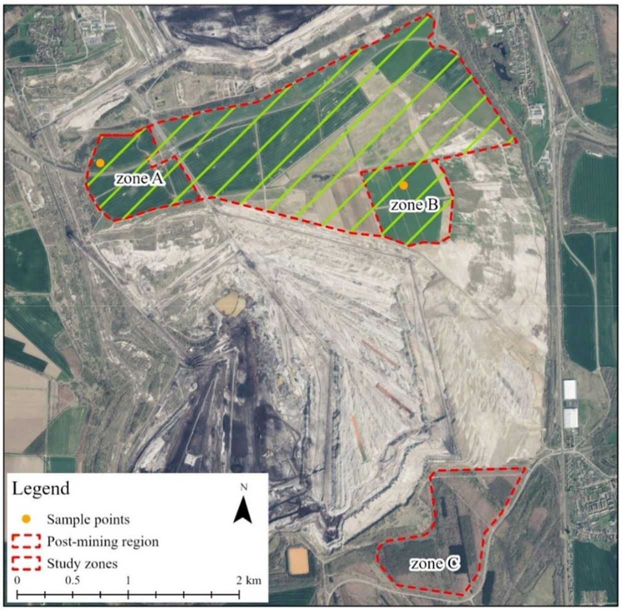

Fig. 4 Location of the post-mining region and study zones (Dynowski and Benndorf 2022)

- Validation and ground truthing: Validating satellite-derived information is crucial to ensure the accuracy and reliability of the results. However, ground truthing and field validation can be challenging, especially in remote mining areas or areas with restricted access.
- Complex landscapes and land cover changes: Mining regions often have complex landscapes, including mixed land cover types. Distinguishing natural changes from mining-induced degradation can be challenging, requiring advanced image classification and change detection algorithms.
- Consistency and standardization: When monitoring land degradation over time, ensuring consistency in data acquisition, processing methodologies, and classification schemes is essential for reliable trend analysis. Changes in satellite sensors or methodologies can introduce inconsistencies in the data, making comparisons challenging.
- Regulatory and policy barriers: Incorporating satellite data into land degradation monitoring programs may face barriers related to regulatory frameworks or policy support. Ensuring data utilization aligns with existing environmental policies can be complex, particularly when addressing land degradation in mining areas.
- Data integration and interoperability: Integrating satellite data with other types of geospatial data, such as GIS and ground-based information, is critical for a comprehensive understanding of land degradation in mining regions. Achieving seamless data interoperability can be technically challenging.

Fig. 5 Photo from the mining exploitation in Schleenhain mine, Germany (Dynowski and Benndorf, 2022)

- Limited capacity: Limited capacity to process and interpret space-borne data may also be a barrier to its use, especially in developing countries.

To overcome these challenges, it is important to promote the development of cost-effective and user-friendly tools for processing and interpreting space-borne data, and to increase the availability of training and capacity-building opportunities for users. Furthermore, fostering partnerships and collaborations among remote sensing specialists, land degradation experts, and decision-makers is crucial to effectively utilize the information derived from space-borne data in informing land management decisions.

Improving data accessibility, advancing processing techniques, and investing in capacity building for local stakeholders can enhance the effectiveness of satellite data utilization for land degradation monitoring in mining contexts. However, to date, there is no complete analysis of the developments in this research area. Aznar-Sanchez et al. 2018 recently partially filled this gap by analyzing the dynamics of the research into mining waste and its sustainable management from 1988 to 2017 on a global scale. Their results revealed that there is an increase in research of waste from mining operations and most studies focused on waste management accounting to about 40% of the total.

In the context of monitoring land degradation in areas impacted by mining activities, the implementation of a multi- and cross-scale approach assumes heightened significance. This approach is pivotal for comprehending the intricate dynamics of land degradation, particularly over extended periods and diverse geographical extents, which often encompass various forms of degradation (Vogt et al. 2011). Within mining regions, where environmental and socioeconomic disparities are pronounced, these long-term observations using satellite time-series data become paramount.

Effectively unraveling the complexities of land degradation processes in mining areas necessitates macroscale observations. These observations enable the inclusion of a broad spectrum of environmental fluctuations, thus allowing for the differentiation between the impacts of climate variability and those stemming from human-induced mining activities. Remote-sensing-based tools and techniques, while are invaluable for assessing land degradation, possess inherent limitations in revealing the root causes of degradation. Factors such as land policies, tenure systems, economic pressures, poverty, migration, and other socioeconomic dimensions are often omitted from direct consideration in remote sensing analyses (Nkonya et al. 2016). Hence, achieving a holistic understanding of land degradation within mining contexts mandates the integration of remote sensing insights with in-depth socioeconomic investigations. This integration extends to factors such as the impacts of drought or the influence of atmospheric CO_2 concentration on land. This integration arises from the unavailability of crucial image datasets tailored to land degradation analysis, particularly at the spatial and temporal scales that are most relevant to mining activities.

Similar to the way in which mapping degraded areas relies on scale dependency, the determinants of vegetation dynamics and degradation in mining regions also exhibit scale-dependent characteristics. This scenario introduces conflicts across various scales and underscores the scarcity of suitable multiscale datasets, posing considerable challenges in land degradation analysis. A pertinent example is the disparity between national-level mining policies and localized land management decisions. This mismatch can lead to a disconnect between the scales of decision-making and the data available. This challenge accentuates the pressing need to harmonize policy frameworks and data availability across multiple scales. Such alignment is pivotal in effectively addressing land degradation issues specific to mining regions. It also facilitates the formulation of tailored management strategies that are attuned to the unique complexities of mining-related land degradation.

Additionally, while our paper provides a comprehensive analysis based on available data and methodologies, we recognize several limitations, including potential spatial and temporal constraints in data availability and uncertainties associated with remote sensing interpretations. These limitations highlight opportunities for future research to address gaps, enhance methodologies, and foster collaboration among stakeholders to mitigate land degradation impacts effectively.

Conclusions

Land degradation is a complex and multifaceted field that draws on the expertise of various disciplines, spanning geography, ecology, climate science, and sociology. This interdisciplinary approach is indispensable for comprehending the intricate web of factors driving land degradation, particularly within the realm of mining activities. The integration of knowledge from these diverse fields equips researchers with a holistic perspective on the nuanced interplay between natural processes and human interventions that underpin land degradation dynamics. By aligning these insights, effective strategies can be devised to curtail and counteract the adverse impacts of land degradation caused by mining activities (Vogt et al. 2011). It is worth noting that the ongoing discourse regarding the definition of land degradation and its measurement further accentuates the complexity of this subject (Reynolds et al. 2011).

In the specific context of mining, remote monitoring emerges as a potent tool for assessing and comprehending the environmental transformations triggered by mining operations. This approach empowers data-informed decision-making and fosters the implementation of sustainable resource management practices tailored to the mining sector. However, maximizing the potential of remote monitoring mandates the resolution of challenges tied to data accessibility, expert collaboration, and knowledge dissemination. Advances in remote sensing technologies and analytical methodologies serve as catalysts in bolstering the effectiveness of monitoring endeavors, thus fostering the cultivation of responsible mining practices.

The insights and methodologies delineated in this review bear significance in shaping development plans and policy frameworks that mitigate land degradation and endorse sustainable land utilization within mining areas.

Despite the strides made in remote sensing, it is pertinent to acknowledge that comprehensive environmental monitoring within mining regions remains an ongoing challenge. The limitations intrinsic to remote sensing data might hinder in-depth assessments of internal energy dynamics, even when sophisticated vegetation monitoring techniques are applied. As we cast our gaze into the future, the steady march of progress in remote sensing satellite technologies holds the promise of democratizing monitoring within mining sites. This forward momentum is anticipated to translate into greater accessibility, cost-effectiveness, and efficiency in monitoring endeavors, accentuated by improvements in both spatial resolution and data precision. Simultaneously, the prospect of multidimensional surveillance through an array of remote sensing satellites and the holistic evaluation of mining area ecosystems through diverse data sources is poised to redefine the landscape of mining-related environmental monitoring.

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Declarations

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