Environmental impacts of mining on biodiversity and ecosystem services

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ABSTRACT

Mining is an important economic sector that ensures continuous flow of income, employment, and business opportunities. Mining furthermore can promote education, improve health facilities, and improve community infrastructure. However, mining often causes undesirable impacts on biodiversity and the ecosystem services they underpin. This thesis presents results from a systematic review of the mining literature, historical analysis of satellite imagery, field-based biodiversity assessments and interviews with a wide range of stakeholders involved in mining operations and communities living within mining areas. Combined, these different approaches assess the environmental impacts of mining on biodiversity, ecosystem services, and the potential for restoration of mining landscape across the globe, and land use and land cover change through time and across space in Tanzania.

Results from the systematic review revealed that, out of 2,093 studies reviewed, 99.8%, reported some form of negative impact of mining on biodiversity and ecosystem services. However, while 95% reported on the direct impacts, only 5% reported on the indirect impacts. Furthermore, out of 830 reviewed restoration studies, most focused on remediation experiments (43.9%, n = 364) while 26.3%, n = 216 focused on reclamation, 14.9%, n = 124 focused on rehabilitation and 14.9%, n = 124 focused on restoration.

Results also revealed that, commercial gold mines have escalated the rate of land cover changes and pulled illegal mining adjacent to mine leases. This is associated with impacts that manifest largely outside operational boundaries. This was observed in two older mine sites, where aboveground carbon and tree stem density are significantly higher within lease boundaries compared to outside, while there is no such effect at the new site.

I recommend on rigorous, integrated impact assessments and conservation planning in mining landscapes to mitigate social and environmental impacts and balance outcomes across the mining sector to support livelihoods, development, and conservation agendas.

Keywords: biodiversity, ecosystem services, indirect impacts, land use change, mining

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DECLARATION

I declare that this thesis is a presentation of original work, and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References.

Modified versions of one of the analytical chapters has been published at Biological Conservation Journal. I can confirm that as a lead author of this paper, I was responsible for conceptualization of the concept, designing the methodology, carrying out all data collection and analysis, developing arguments, and writing and revising the manuscripts throughout the review process. As supervisors and co-authors, Rob Marchant, Andy Marshall, Jessica Thorn, Deo Shirima and Phil Platts, and other co-authors including Yahya Abeid, Neil Baker and Mark Annandale provided guidance and commented on drafts. Mark Anandale and Neil Baker and helped in bringing in the context of mining and bird distribution in Tanzania respectively.

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CHAPTER ONE

1 Introduction

1.1 Why conducting research on mining impacts on biodiversity and other ecosystem services?

The environmental and social-economic impacts of mining have been a global concern for the number of decades (Murguía et al., 2016). The evolution of international organizations and standards such as International Council on Mining and Metals (ICMM), Global Reporting Initiative (GRI) International Cyanide Management Code (ICMC) and Extractive Industries Transparency Initiative (EITI) came out as initiatives to harmonize mining sector with environment and socio-economic perspectives. The aim of these initiatives among others, is to ensure that the mining sector is being operated within the international standards to maximize positive impacts and minimize the negative impacts from mining operations. For example, one of the key elements of ICMC is to provide comprehensive guidance for best practice in the use and management of cyanide at gold and silver mines (Gibbons, 2005; Mudder et al., 2004). These kinds of initiatives provide a platform for sustainable mining and are undergoing regular improvements and updates through different scientific research. However, most research is centred towards identifying the sink impacts of mining on the environment rather than the source impacts. Definitions and explanations of what are sink and source impacts of mining are shown in chapter 3. Thus, there is a great understanding of how sink impacts interact with the environment in the mining context unlike source impacts because of the focus to determine how much mining discharges an ecosystem can take before surpassing the threshold (Franks et al., 2010a). In line with that, lack of scientifically designed baseline studies to understand different environmental components before and after impacted states make source impacts difficult to understand.

Concurrently, source impacts of mining can extend across project footprints and research need to unpack that by understanding the historical events that has occurred in mining areas within and beyond project footprints (Sonter et al., 2018). Therefore, it is important to direct research efforts on examining environmental impacts of mining on biodiversity and other ecosystems services within and beyond project foots prints. This approach is aiming at identifying the direct, indirect, and cumulative impacts of mining from multiple projects around the mining as influenced by the presence of large-scale gold mining sites. Three gold mining sites and 6 gold mining districts in Tanzania were used as case studies to understand how mining can impacts biodiversity and other ecosystems services and how land use dynamics can be influenced by mining activities.

1.2 Why conducting research on environmental impacts of gold mine?

Extraction of gold represent one of the potential threats on tropical ecosystems (Rudke et al., 2020). It drives extensive deforestation of tropical forests and has big influence on land use change in mining areas (Sonter et al., 2017, 2014). This is largely influenced by the increase in global demand for gold and increase in gold price (Alvarez-Berríos and Aide, 2015; Swenson et al., 2011). Gold price has increased from USD193/ounce in 1978 to USD1225/ounce in 2010 and since then the price has consistently been above $1000/ounce (Alvarez-Berríos and Aide, 2015; Melas, 2012; World Gold Council, 2019). The current price for gold is relatively higher than its historical trend (Figure 1) and has more stability in world market (Mudd, 2007). This increase in price and global demand for gold has fuelled the establishment of new gold mining activities by large scale mining companies, small-scale and artisanal gold miners worldwide (Alvarez-Berríos and Aide, 2015; Betancur-Corredor et al., 2018; Carvalho, 2017).

The increase in gold price and improvement on gold extraction technology, especially the increasing use of explosives and heavy machinery, has also triggered the extraction of low-grade gold deposits from areas that were previously deemed not cost effective (Betancur-Corredor et al., 2018; Carvalho, 2017). Even in the recent COVID-19 pandemic, gold prices have increased quite impressively (Depren et al., 2021), because gold is considered a safe-haven to preserve the dying economy (Akhtaruzzaman et al., 2021).

line with that, the extent of the environmental impact of subterranean mining for solid metals and minerals varies with extraction process (Maliganya and Paul, 2016; Mbowe et al., 2016; Virah-Sawmy et al., 2015). For example, large scale and other legalized small scale gold miners uses cyanide and artisanal miners uses mercury to extract gold from ore (Wai et al., 2009), thus, when cyanide and mercury are not well managed, environmental and socio-economic impacts of gold mining is more detrimental to the environment than other metals that do not use chemicals during ore extraction (Donato et al., 2017; Ogola et al., 2002; UN Environment, 2017). Therefore, while large-scale mining activities are not considered as top drivers of environmental destruction because of the relatively small area being directly affected (Murguía et al., 2016a), gold mining can cause significant environmental alternation which may exert pressures on biodiversity by degrading wildlife habitats, directly and indirectly, and its impacts may extend through spatial scales (Betancur-Corredor et al., 2018; Murguía et al., 2016a). However, gold mining is often overlooked as potential drivers of loss of biodiversity and ecosystems services (Betancur-Corredor et al., 2018). This thesis unpacked the spatial extent of gold mining impacts on biodiversity and ecosystem services to fill that existing gap using Tanzania as a case study.

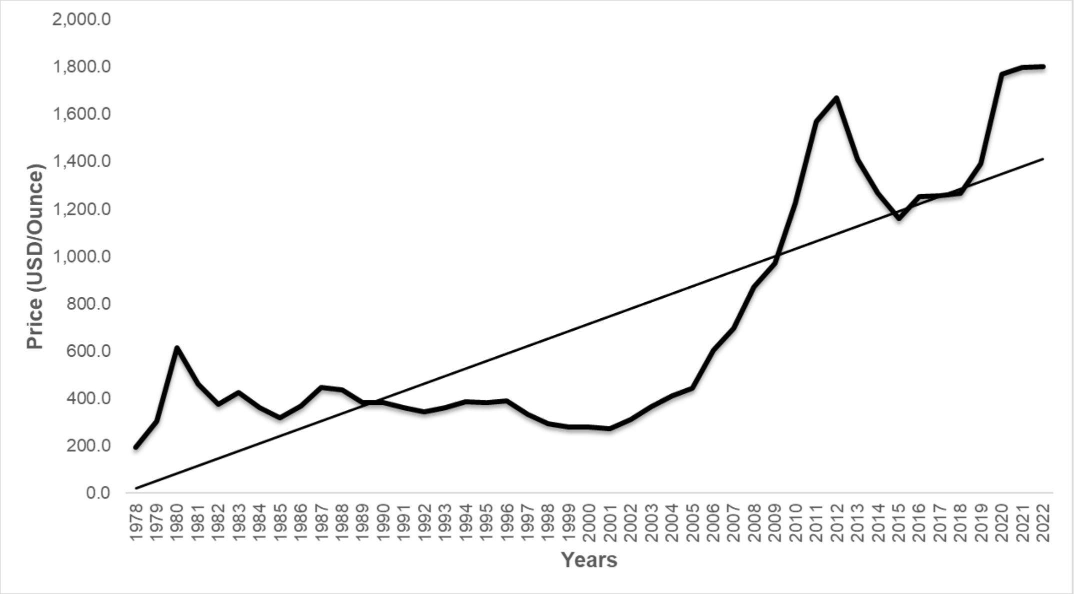

Figure 1: The annual historical trend of gold price from 1978 to 2022

Source: World Gold Council, 2022

1.3 Research aims and questions.

The aim of this research was to explore the environmental impacts of mining on biodiversity and ecosystem services by employing systematic review, GIS, and remote sensing to analyse historical trends of land use in mining landscapes and that fed on current day assessment of the indirect impacts of mining on specific sites in Tanzania. This aim was achieved by addressing the following questions: -

i. What research evidence exists on the impacts of subterranean mining on biodiversity and ecosystem services across the mined solid metals and minerals?

ii. What is the effectiveness of restoring the degraded ecosystems on mining landscapes?

iii. What are the direct and indirect drivers of commercial mining on land use change?

iv. What are the perceptions of historic drivers of land use change before and after mines were leased between 1990 and 2019?

v. What are the indirect impacts of commercial gold mining on adjacent ecosystems?

1.4 Thesis and chapter structure

Chapter one of this thesis sets out the rationale for this research by explaining the significance of researching the impact of gold mining on biodiversity and ecosystems services, in the past, current time and in the future. This chapter also introduced the aim of the research imbedded with its five research questions (section 1.3).

Chapter two sets insights from literature review by unpacking the concept of mining in a broader context, looking at the global significance of mining sector and the history of mining in developing world. This chapter also discussed different stages of mining, socio-economic impacts of mining, and international initiatives that oversee the sustainability practices in mining sector. This chapter build into the global systematic review (chapter three and four) on the ecological impacts of subterranean mining for solid metals and minerals and the potential for restoration in mining landscapes, that gave a global overview of how different mining activities affects biodiversity, ecosystems services, cultural heritage, and archaeological sites, protected areas, and other key biodiversity areas, all of which sustains social-ecological systems. Findings from the systematic review are presented in a paper format just like chapter five and six. Each chapter consists of its own introduction, methodology, results, and discussion, formatted as stand-alone papers, each to be submitted for internationally peer-reviewed journals, according to the requirements of the target journal for each chapter.

Chapter five unpacks mining induced land use changes and its impacts to different land covers, biodiversity, and ecosystem services. This chapter analysed land use practices associated with mining activities that exert pressure on biodiversity and other ecosystem services. Historical trend for land use changes was investigated before mining and during/after mining activities using satellite images and was validated by ground truthing and social-economic survey.

Chapter six discussed the indirect impacts of commercial gold mining on biodiversity using plants, birds, and butterflies as indicator taxa, through a case study in Tanzania. Field assessment for present day biological data for identified taxa was conducted in three selected mining sites.

Chapter seven provides a general discussion relating to the overall thesis aim and objectives, a conclusion and recommendations for desirable future and the probability of impacts to KBAs from future gold mining activities. It gave a layout of how far the research objectives were achieved, stating the challenges, and suggesting areas for further research.

1.5 Definitions of key terms

Throughout the whole thesis, the terms biodiversity (different biodiversity indicator taxa), ecosystems and ecosystem services are the common terms used. The definitions of these key terms are provided below.

1.5.1 Biodiversity

Biodiversity is defined as the variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems (CBD, 1992). Biodiversity can also be defined as the sum total of all biotic variation from the level of genes to ecosystems (Purvis and Hector, 2000). In this thesis, all categories of biodiversity were studied through systematic literature review and field surveys in Tanzania.

1.5.2 Ecosystem services

Ecosystem services are well explained in chapter four. They are defined as benefits that people obtain from ecosystems (MEA, 2005), or the direct and indirect contributions of ecosystems to human well-being (TEEB, 2010), or contributions of ecosystem structure and function to human well-being (Burkhard et al., 2012). This thesis reported all types of ecosystem services reported on reviewed literature and through socio-economic surveys conducted in Tanzania. The difference between ecosystems and ecosystem services is that, ecosystems comprise of plant, animal, and microorganism communities and the non-living environment interacting as a functional unit (MEA, 2005). The sustainability of ecosystem services depends very much on the healthy ecosystems. In this thesis, indirect impacts of commercial gold mining to adjacent ecosystems and the implications to the provision of ecosystem services are discussed in the chapter six.

1.6 Focus of the thesis

This thesis has used mixed method to achieve the main objectives and answer the research questions described in section 1.3 above. I used systematic review to achieve the objectives in chapter three and four. In this chapters, mining impacts from all types of solid metals and minerals were systematically reviewed and reported. This was done to evaluate the most impactful mined commodity on biodiversity and ecosystems services across the globe. Additionally, in the systematic review chapters, all types of mining methods (i.e., surface, underground etc), and all scale (i.e., small, large/commercial) were included. Inclusion and exclusion criteria are described in chapter three (SM 3.10.1).

Through systematic review, I was able to identify that, impacts of gold mining on biodiversity are rapidly increasing to increasing gold demand and gold price. This implies that, to effectively balance the increasing demand for gold and the sustainability of natural ecosystems, proper recommendations should be made from the rigor and scientific research as suggested by Dias et al., (2017. To this end, the context for studying the impacts of gold mining on biodiversity was established and Tanzania was used as case study for the chapters five and six.

1.7 Conceptual framework

Several conceptual frameworks to assess the effects of environmental change on biodiversity and ecosystem services exists (Maier et al., 2019; MEA, 2005b; Rounsevell et al., 2010). All of these existing frameworks were designed to understand the relationship between environmental change and biodiversity conservation and ecosystem services to provide evidence-based decision-making (Takacs and O’Brien, 2023). Similarly, this thesis was designed to evaluate impacts of mining induced environmental changes to biodiversity and ecosystem services.

For this study, the concept of biodiversity was developed following the general detention from CBD, where mining impacts on all reported biodiversity indicator taxa were evaluated through the systematic review. Three biodiversity indictors (i.e., plants, birds, and butterflies) were evaluated on the ground using Tanzania as a case study. Restoration effectives in mining landscapes was also evaluated to determine the potential of recovery in mining impacted areas to support global initiatives for making our world greener. For ecosystem services, I adopted the four categories of ecosystems services comprising supporting services, regulating services, provisioning services and cultural services as elaborated by TEEB (2010).

The conceptual framework for this study is based on identifying drivers of change both direct and indirect, impacts on biodiversity and ecosystem services and response from mining companies, governments, and other stakeholders in the mining sector (especially restoration initiatives after mineral extraction). Indirect driver of changes that affects biodiversity and ecosystem services include population increase, infrastructure improvement and technology (MEA, 2005b). These result in changes to ecosystem services with the knock-on impacts on human well-being (MEA, 2005). Figure 2 illustrates how this study was conceptualized.

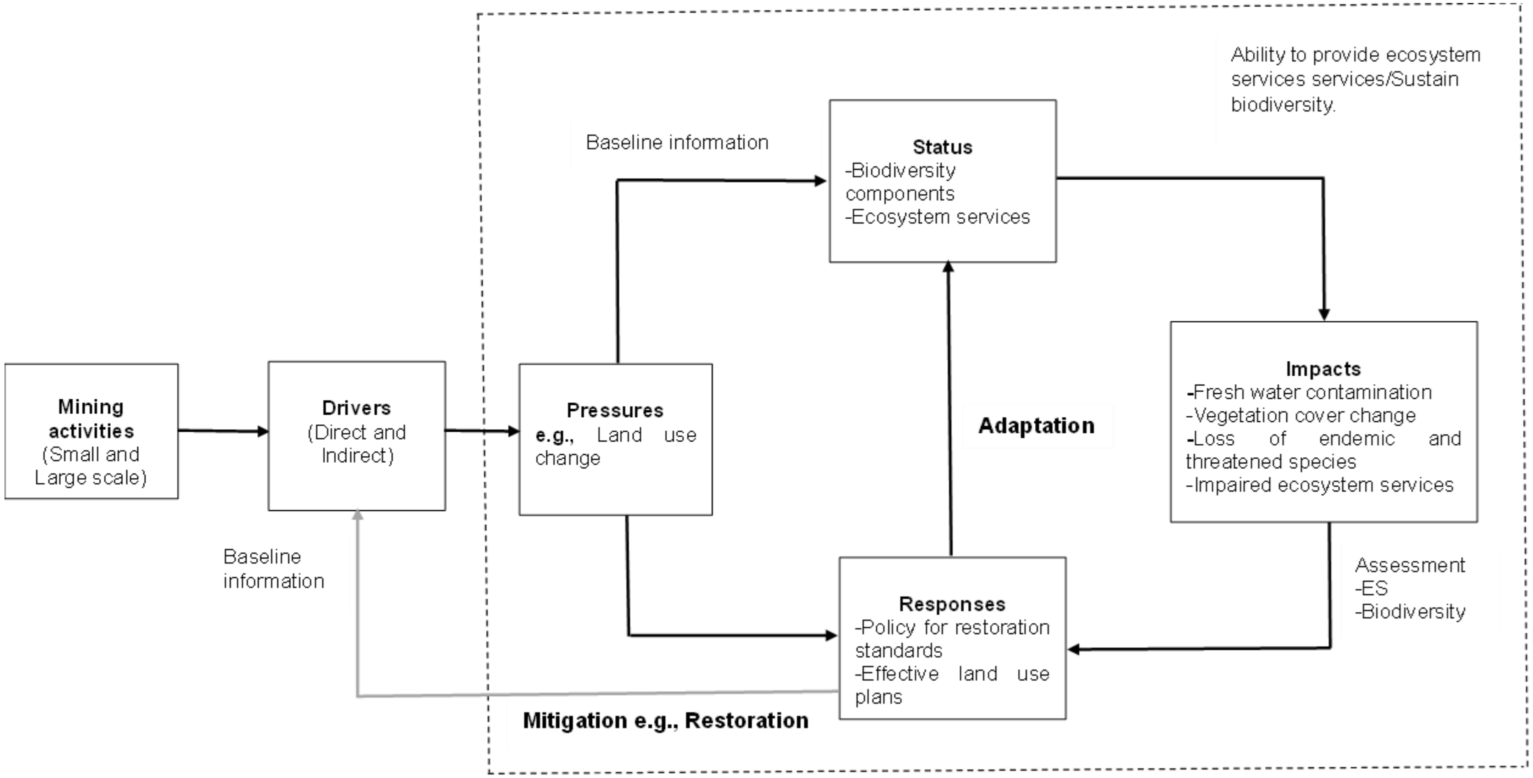

Figure 2: A conceptual framework for assessing mining impacts on biodiversity and ecosystem services. Ideas for this conceptual framework was adapted from Millennium Ecosystem Assessment, Franks et al., 2010 and Rounsevell et al., 2010.

CHAPTER TWO

2 Literature review

2.1 Definition of mining in the study context

In the context of this research, mining is defined as the process of extracting subterranean minerals and solid metals. The extracted materials usually occur naturally as ore deposit under the earth's surface. There are a variety of commodities that can be extracted by mining such as gold, diamonds, copper, coal, gemstones, graphite, uranium, gypsum, and can also include gravel (Hartman and Mutmansky, 2002). Mining sector is a substitute to obtain all the substances that cannot be acquired by other sector such as agriculture and other processing industries but can be used to accelerate their production (Carvalho, 2017). For example, mining supplies materials for cement production which are used for housing purposes and improvement of infrastructure, and supply fertilizers to agriculture sector to enable food production (Carvalho, 2017; Schneider et al., 2011). In a wider context, mining includes the extraction of any resource that cannot be renewed (Sonter et al., 2020).

2.2 Mining historical background

The discovery of minerals in ancient times provided a key feature of the early global economy. During that time, mining activities were unregulated, uncontrolled, and operated on a small scale (Nriagu, 1996). Because of the poor technology, minerals were not recovered to its fullest, and many abandoned ancient mining sites were rediscovered with advancement of extraction technology in the 16th Century (Carvalho, 2017; Fernández-Lozano et al., 2015). Since then, mining has boomed in many parts of the world and fuelled the development of the industrial economy (Nriagu, 1996).

Mining activities in Africa began 20000 years ago (African Union, 2009). This is evidenced by the existence of the oldest mines in the world including Ingwenya mine in Swaziland (African Union, 2009). Before the colonial era, African countries were involved in extraction of gold from shallow pits and much from alluvial collection mostly referred as unsophisticated way of gold extraction (United Nations Economic Commission for Africa (UNECA), 2011). Technology started to emerge, and the use of open cast and underground mining started to develop. In the later mining development stage, during colonial era, colonial leaders used indigenous knowledge from experienced Africans to identify suitable areas for mineral extraction. They did so by using relatively advanced technology of mineral exploration and extraction (UNECA, 2011). The mining sector started to expand particularly during 2000s, when exports of hydrocarbons and minerals grew, which contributed to the economic growth of many African countries (Chuhan-Pole et al., 2017).

In Tanzania, legal and policy development in the mining sector has undergone political and social-economic transformation for years (Muhanga and Urassa, 2018), which in turn shaped the mining industry to the current state (Society for International Development (SID), 2009). The transformation began with unregulated and uncontrolled local mining activities during the pre-colonial era when different tribes such as Sukuma and Waha were involved in search for salt along the shores of Lake Victoria and Lake Tanganyika. During that time, Sumbawanga was a famous region for smelting iron for production of farming equipment.

The first discovery of gold was then made in 1894 along the shore of Lake Victoria following relatively advanced mineral exploration and prospecting techniques during the German colonial era (Bryceson et al., 2012; Society for International Development, 2009). This went along with the discovery of other minerals such as mica, copper, and iron elsewhere in the country (Bryceson et al., 2012). During this period, the cultivation of sisal was the main source of economy to Tanzania, and gold production received little attention. However, the high German endeavour to base its currency on gold encouraged further explorations of gold, and Sekenke gold mine became the first large scale gold mining site of that era (Global Business Reports, 2012), which was opened in 1909 and closed in 1959 after fifty years of its operation (Global Business Reports, 2012; Magai and Márquez-Velázquez, 2011).

Sekenke and Kirondatal gold mines were the only gold mines between pre-colonial era and second world war the latter being opened in 1934 and closed in 1950 after only 16 years of operation. Tanzania's gold production experienced a boom in 1940 with an average of 4 tones/year before the massive drop of gold production in 1960s (Global Business Reports, 2012; Magai and Márquez-Velázquez, 2011). The decline in gold production was largely contributed by the shift of the government support from gold to diamonds production (Society for International Development, 2009). According to Society for International

Development (2009), mining sector during pre-colonial era was characterized by natural resource control governance whereby every resource whether below or above the ground was owned by the colonial government. Thus, every company or individual who wish to conduct mineral extraction should be permitted by the colonial government.

After independence in 1961, there were strict regulation to control the mining sector imposed by the late president Julius Kambarage Nyerere. This was influenced by his campaign to transfer the mining sector and other sectors from private to state control. The amendment of the Mining Ordinance Bill in 1969 gave mineral power to the minister to control mining licences. This was followed by the establishment of the State Mining Corporation (STAMICO) through the Act of Parliament in 1972 under the Public Corporations Act, 1969 (SID, 2009; STAMICO, 2019). When the government of Tanzania took the control of mining sector, there was limited large-scale mining operations and emergency of small scale and artisanal mining activities. This combining driving forces cause the massive decline in commercial gold mining from 3 tonnes/year in 1960s to 10 kg/year in 1970s and the record for commercial gold production was completely lost after 1972 (SID, 2009).

In making the effort to revive the commercial gold production in Tanzania, there was an enaction of the first Mining Act in 1979 that gave power for mineral exploration and prospecting to STAMICO. These has helped to discover most of the gold mine concessions which was then set aside for small scale miners. Although the foreign owned companies were not allowed to hold mining concessions during that period, there was booming of small-scale gold production and thus increased the government revenue from USD 1million in 1989 to USD 40 million in 1992 (SID, 2009). However, these government efforts were not enough to boost the mining sector in Tanzania, there was still a need for big changes in regulation to accommodate foreign companies which were still limited to own mining concession and thus limiting the potential for large scale production activities.

In 1992, the government of Tanzania had undergone privatization and liberalization of several sectors including mining sector under the influence of the International Monetary Fund (IMF) and World Bank (Pedersen et al., 2019). The main objective of this act was to relax the government regulations to accommodate big investment from foreign mining companies through policy reforms. The process of legal policy reforms was closely monitored and supported by IMF and World Bank and resulted in the formation of the mineral policy of Tanzania of 1997 and Mining Act of 1998 that incorporated most of the changes following the legal reform of the mining sector. The government of Tanzania became the regulator of the mining sector and withdrawn to have a total control over mining resources. After these reforms, there was an increase in exploration and mining activities from foreign mining companies such as AngloGold Ashanti and African Barrick Gold. Since then, mining in Tanzania has expanded rapidly which in turn increased gold production and employment opportunities.

The results of this rapid growth in mining industry have also amplified socioeconomic and environmental impacts, both in project and vicinity areas (see chapter five) (Edwards et al., 2014). These negative externalities generated by mining activities need to be properly understood using well designed scientific research to inform policy changes about the management of mining sector.

2.3 Overview of the global mining sector

The Mining industry is a globally significant sector as a major source of GDP and in 2013 gold mining contributed about USD171.6 billion to the global economy (World Gold Council, 2013). The sector is particularly important in several developing countries where it provides important employment opportunities to people (Mancini and Sala, 2018), in mineral-rich countries such as Tanzania (Kitula, 2006), South Africa (Cole and Broadhurst, 2020), Ghana (Aryee, 2001) and Mali (Traore, 2016), as shown in Table 1. Despite the benefits accrued from the mining sector, mining operation can cause undesirable impacts on the environment, biodiversity, and ecosystem services (Buggenhoudt, 2017; Owusu et al., 2018). The impact on biodiversity can be more significant when mining operations are in remote or key biodiversity areas (Murguía et al., 2016; Owusu et al., 2018). For example, in Tanzania large mining operations such as North Mara gold mine, Bulyanhulu gold mine, Geita gold mine and Tulawaka gold mine are located along the Lake Victoria ecosystem (Mwalyosi, 2004) and Serengeti ecosystem (Tiamgne et al., 2022) which are recognized as global biodiversity hotspot (van Soesbergen et al., 2018) and an important ecosystem that provide livelihood support to about 30 million people. The same case is also happening in Colombia and Indonesia, where the Cauca and Magdalena rivers which form a complex wetland ecosystem with high rich in biodiversity (Betancur-Corredor et al., 2018), and Batang Gadis National Park (Sloan et al., 2019) respectively, are vulnerable to mining activities. These few examples give a snapshot of how global overlap of key biodiversity areas with mining activities can exert pressure on biodiversity and the ecosystem services they provide (Durán et al., 2013).

Before the 18th century most of mining impacts were unquantified and unregulated due to lack of environmental regulation, good record keeping and environmental awareness (Carvalho, 2017). After the global expansion of mining activities in the 18th and 19th centuries due to policy reforms across the globe and increase in mineral and metal prices especially for gold as explained in section 1.2 (Carvalho, 2017; Swenson et al., 2011); regulations to mitigate negative environmental impacts began to develop (Carvalho, 2017; Thornton, 1996). However, these regulations were early adopted and made strict in developed countries and slower to advance in developing countries (Carvalho, 2017). This caused most of the foreign mining companies to move from developed countries to developing countries where there were less strict environmental regulations (Carvalho, 2017; World Bank and International Finance Corporation, 2002).

These combinations of circumstances resulted into the booming of mining activities in many developing countries especially in Africa (Figure 3); with associated increased impacts on biodiversity and ecosystem services such as water contamination, soil erosion and deforestation (Magai and Márquez-Velázquez, 2011; Ogwang et al., 2018; Sonter et al., 2017). Despite good practice guidelines to manage such impacts (e.g., International Council on Mining and Metals (ICMM), 2006), there is uneven adoption across the sector, and often guidelines are too general, and legacy impacts of older mining operations remain on the key biodiversity areas such as Serengeti World Heritage Site (Bowell et al., 1995; Kideghesho et al., 2006).

These past and present mining activities and other development projects associated with mining activities can cause cumulative impacts on biodiversity and ecosystem services (Sonter et al., 2017). However, most of these cumulative impacts are left unquantified because of the complexity in their driving pathways (Sonter et al., 2017), since they cannot be effectively managed by focusing on the individual project or development activities (Franks et al., 2010). Complexity of cumulative impacts evolves when management of cumulative impacts must consider all development activities that are contributing to environmental impacts (Franks et al., 2010). Therefore, for effective management of cumulative impacts, there is a need for collaboration and coordination from diverse stakeholders as they are caused by multiple actors (Franks et al., 2010).

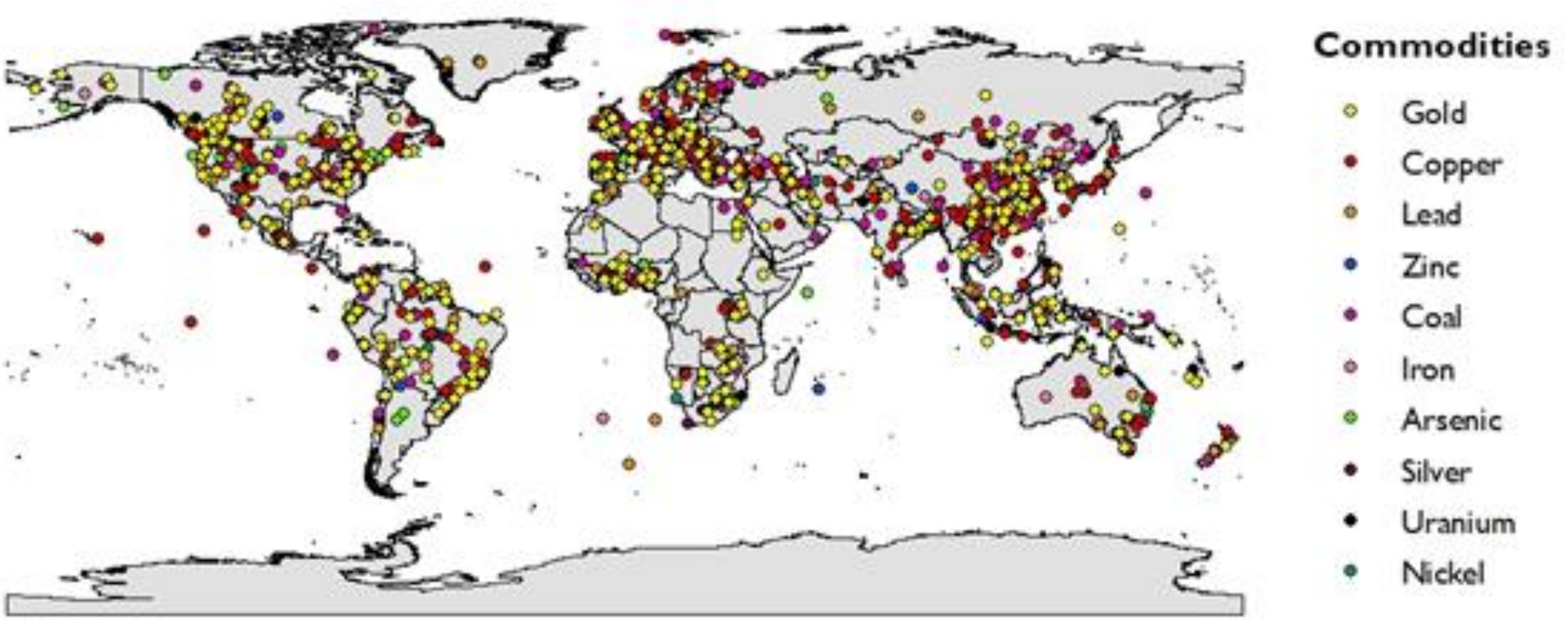

Figure 3: Map showing the distribution of various commodities across the globe.

Source: Hamidu Seki

Table 1: Gold Production of African countries (tonnes) from 2010 - 2021

Country	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Ghana	94.3	96.8	106.0	105.8	106.3	95.4	131.4	133.3	149.1	142.4	130.3	129.2
South Africa	210.0	205.3	179.8	179.5	168.6	157.0	155.0	147.3	126.1	113.2	102.5	113.6
Burkina Faso	44.9	59.7	56.9	61.6	62.2	54.6	57.0	74.6	78.0	82.6	93.4	102.8
Mali	42.7	42.6	47.6	55.9	60.4	71.4	82.1	73.9	88.3	96.8	92.4	98.7
Sudan	29.3	32.6	33.9	57.6	60.9	67.8	77.5	88.0	76.7	78.0	81.8	85.1
DR Congo	18.0	21.0	24.8	25.3	35.9	42.7	45.4	49.6	65.9	65.4	58.9	63.3
Guinea	25.8	25.7	24.3	25.4	32.1	41.0	45.6	46.8	50.8	57.6	56.9	60.5
Zimbabwe	17.1	19.0	22.7	23.0	23.2	25.5	26.5	34.5	51.9	44.4	40.9	46.4
Tanzania	47.5	54.4	56.3	52.0	51.8	53.2	55.3	54.6	46.3	46.5	45.4	45.4
Ivory Coast	7.8	13.2	13.0	14.5	19.4	22.2	23.6	25.7	24.1	32.5	38.0	41.9
Senegal	5.4	4.8	7.4	8.2	8.6	8.7	10.2	11.6	16.5	17.3	15.9	20.7
Liberia	10.0	10.0	11.0	10.0	10.0	10.5	14.4	13.7	19.7	18.6	18.8	20.5
Niger	6.6	7.4	9.6	9.1	8.7	10.9	8.7	12.7	10.7	14.5	18.5	18.5
Madagascar	10.0	10.4	10.8	11.1	11.1	11.7	13.5	13.3	14.0	14.5	13.8	15.5
Mauritania	9.0	8.8	8.2	9.9	10.0	9.1	8.1	10.1	10.7	15.1	15.6	8.1
Other	43.4	60.1	66.6	69.6	73.2	87.9	104.7	108.5	107.6	103.6	101.2	111.0
Total	**621.8**	**671.9**	**678.9**	**718.5**	**742.3**	**769.5**	**859.0**	**898.2**	**936.5**	**942.9**	**924.0**	**981.1**

Source: World Gold Council, 2022

2.4 The context of the mining sector in Tanzania

Tanzania's inherent natural capital is gifted with mineral deposits of great economic importance including gold, iron, silver, copper, diamonds, tanzanite, ruby, gypsum, coal, and recently discovered uranium and graphite (Figure 4). Mining activities range from small to large-scale operations with nine significant mines: seven for gold, one for diamonds and one for tanzanite (Table 2,TEITI, 2018).

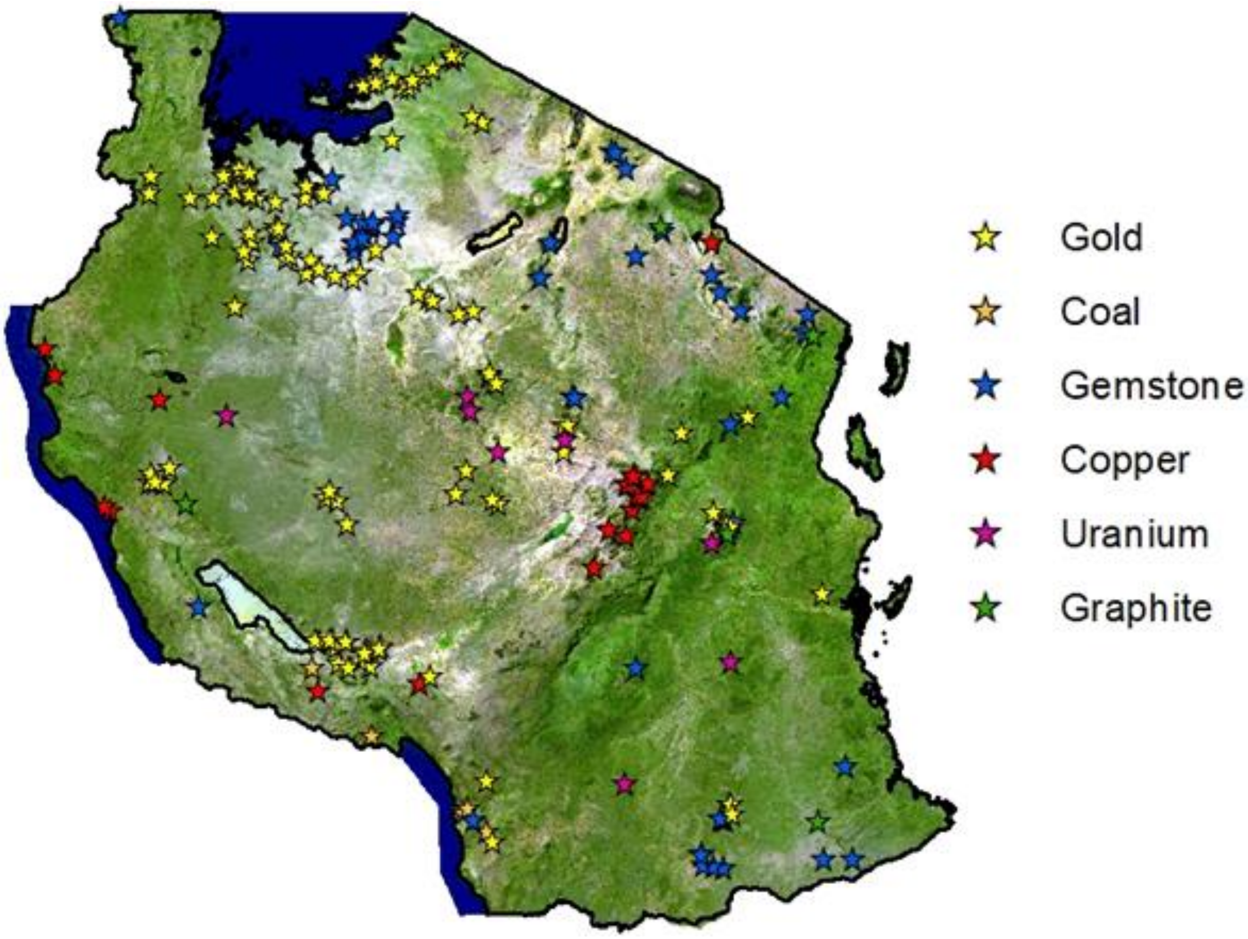

Figure 4: Distribution of selected mineral deposits in Tanzania

Source: Tanzania Geological and Mineral Information System (www.gmis-tanzania.com)

Table 2: List of large-scale mines in Tanzania.

SN	**Mining site**	**Company**	**Region**	**Commodity**	**years in operation**
1	North Mara	African Barrick Gold	Mara	Gold	20
2	Bulyanhulu Gold Mine	African Barrick Gold	Shinyanga	Gold	19
3	Buzwagi	African Barrick Gold	Shinyanga	Gold	13
4	Tulawaka Gold Mine	African Barrick Gold	Kagera	Gold	11
5	Geita Gold Mine	AngloGold Ashanti	Geita	Gold	22
6	Golden pride	Resolute Mining Limited	Tabora	Gold	20
7	Mwadui Diamond Mine	Petra Diamonds/GVT of Tanzania	Shinyanga	Diamonds	82
8	New Luika Gold Mine	Shanta Gold Shanta Mining Company LTD	Songwe	Gold	10
9	Singida Shanta mine	Shanta Gold Shanta Mining Company LTD	Singida	Gold	0
10	Tanzanite One Mine	Tanzanite One Mining Ltd	Manyara	Tanzanite	info not available

Note: Study sites are highlighted

According to Word Gold Council (2022), Tanzania is among the top ten African countries in gold production, accounting for approximately 1.3% of total global production (Figure 5, URT, 2015). The observed high production was much influenced by the advice from the World Bank and IMF to provide opportunities for large-scale investment by foreign companies through policy reforms as explained in section 2.2 (Lange, 2006; SID, 2009). However, despite Tanzania being on the map as one of the major gold producers, the government of Tanzania received less revenue from the mining sector than anticipated (Bryceson et al., 2012). This is because, mining companies were given higher percentage of royalties on production of gold and other precious metals than the government (Lange et al., 2018). Even with the slight amendment of the Mining Act of 1998 in 2010 to cover those challenges, there were still imbalanced benefits between mining companies and the government (Fisher, 2007). However, with changed legislation setting, mining sector became the second fastest growing sector after tourism (URT, 2015). Gold production increased from less than 1t/a in 1998 to 40t/a in 2013, contributing to 1% of the total employment in Tanzania (URT, 2015). Thus, contributing about 3.5% of the GDP annually (URT, 2015; TEITI, 2018). The combination of all sectors in extractive industry that included mining, oil and gas contributed to about 12% of the total government revenue. This figure has increased by 28% from US$ 602m – US$ 754m between 2013 – 2014 due to increased gold production, increased in gold prices and revenue from corporate taxes payment from Ophir Energy Plc which added 30% of total sector revenue in 2014 (EITI, 2018).

Suprisingly, this contribution of the mining sector to the economy of Tanzania was still in doubt and opposed by number of researchers and opposition leaders in the parliament of Tanzania. The argument was based on the poor conditions set forth by the government to attract foreign large-scale investment (Lange, 2006). This discussion has been going for several years through the leadership of three different presidents apart from J.K.Nyerere.

When the late President Magufuli came into power in 2015, he pushed to overhaul Tanzania's mineral legislation to overcome those challenges. He did so by giving directives for the enaction of three acts, namely (i) the Natural Wealth and Resources (Permanent Sovereignty) Act, 2017 (ii) the Natural Wealth and Resources Contracts (Review and Re-Negotiation of Unconscionable Terms) Act, 2017, and (iii) the Written Laws (Miscellaneous Amendments) Act 2017 (TEITI, 2018). The main aim was to increase the financial benefits to the government from the mining sector by regaining control over extractive industries (Jacob and Hundsbæk, 2018; Poncian, 2018). The new acts have changed the legal framework for the management of the natural resource in Tanzania and influenced the royalty rates on gold to increase from 4% to 6%, and it has become mandatory for a country to own a 16% share of mining companies' stock (Jacob and Hundsbæk, 2018). The new acts have also created a better environment for the local communities by strengthening, corporate social responsibility (CSR) policy by regulating better implementation of contractual arrangements in the extractive sectors (Ovadia, 2017). Though the reforms were meant to maximize benefit sharing between the government and large investors, these new laws have the potential to slow down investment in the mining sector. However, the endeavour of the government to focus on revenue accumulation has ignored the consideration of environmental impacts, especially on biodiversity and other ecosystem services as an important aspect. Even the existing Environmental Act of 2004 outlines the general principles for managing the environment in Tanzania, administration and institutional arrangements, environmental planning, and management. Environmental impact assessment's (EIA) are part of this Act but only include biodiversity in a very general sense (United Republic of Tanzania, 2004).

Although an EIA is mandated to monitor and ensure environmental protection in many countries, they have had limited effect on un-environmentally friendly projects (Alshuwaikhat, 2005). Globally, poor conducted EIAs are recommending on the approval of projects that can destroy irreplaceable habitat and threatened species (Hayes and Morrison-Saunders, 2007). Examples of such environmentally unfriendly projects include: housing project carved out of Panama's tropical forest can potentially impacts over 121 bird species that was not reported the EIA report (Laurance, 2022); a 900-kilometer highway through the heart of Brazil's Amazonian rainforest which is estimated to cause net increase in deforestation of 39 million hectares (Laurance, 2022); a hydropower project in North Sumatra cutting through the limited habitat of the Tapanuli orangutan which are critically endangered and believed to be the world's rarest great ape species (Laurance, 2022), ESKOM Wind-turbine Demonstration Facility (South Africa) which didn't take into account the ecology of the migratory birds (Kakonge, 2006). This scenario needs to be looked from different angle as we aim to maximize financial gain from mining sector, we also need to be aware of conserving Key Biodiversity Area (KBAs)s that sustain (Gardner et al., 2013).

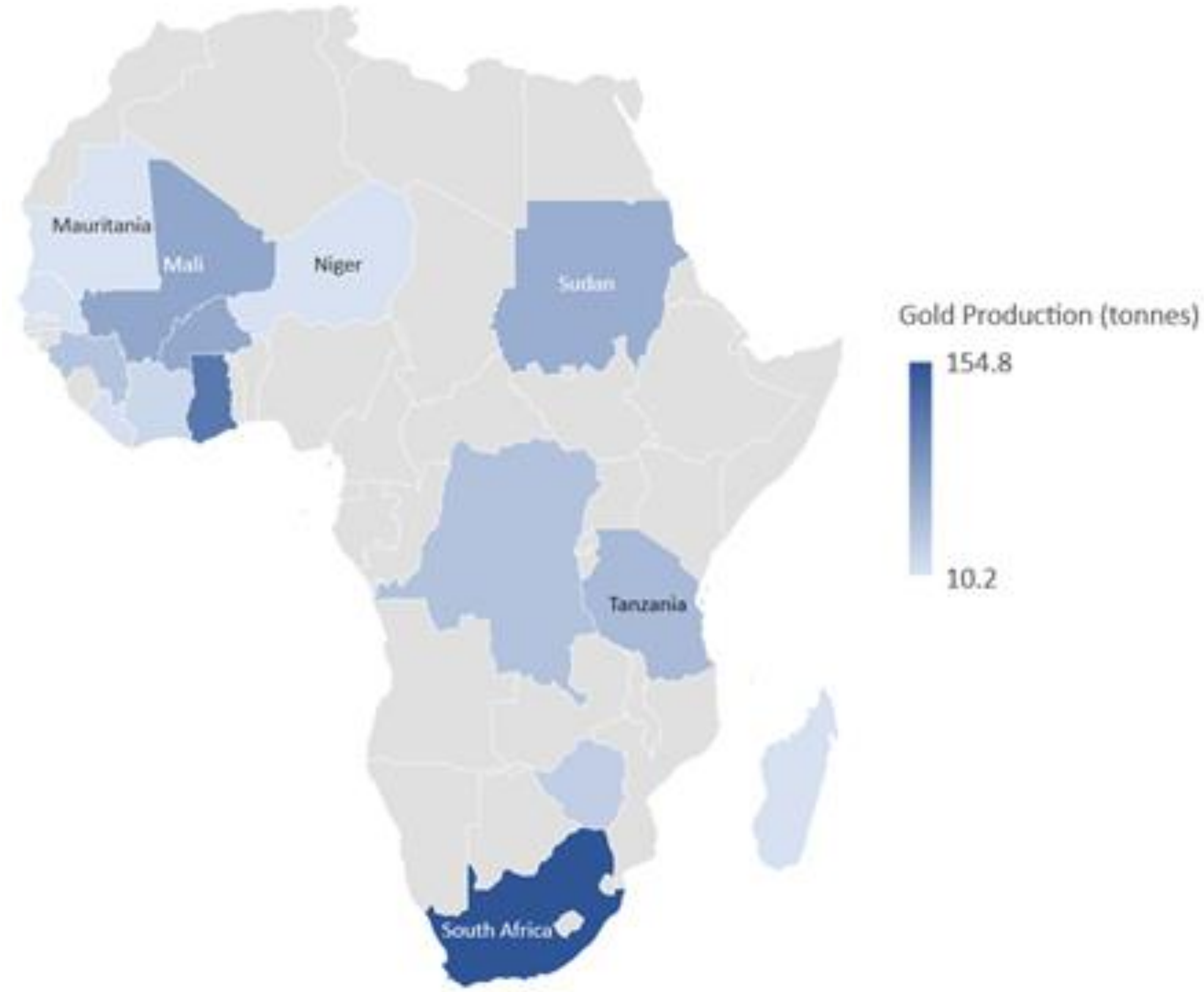

Figure 5: Average annual gold production for the African gold producer countries, 2010 – 2021

Source: World Gold Council, 2022

2.5 Stages of mining

The process of mining is undergoing several stages including obtaining a prospecting licence, obtaining mining licence, mining development, resource extraction and mining closure which involves site restoration and/or rehabilitation (Carvalho, 2017; Hartman and Mutmansky, 2002). All stages of mining require the interdisciplinary team of experts with first two stages of mining being dominated by Geologists and mining engineers (Hartman and Mutmansky, 2002). With increasing concepts of sustainable development, mining requires closure plan after exhaustion of the resource reserve under extraction. The closure plan *inter alia* requires solid baseline studies before and during mine operations to set the desired objective for the restoration and/or rehabilitation purposes. In this stage, environmental and ecologist experts take charge to make sure mining is conducted in a sustainable manner. Restoration and rehabilitation plan of the mined areas has increasingly become core of the mine life cycle because of the increased concern for cleaner production and sustainable development (Fourie and Brent, 2006; Hartman and Mutmansky, 2002; Mulligan, 2014; Zhou et al., 2015). Stages of mining operation are briefly summarized below.

2.5.1 Prospecting and exploration stage

A term prospecting stands for the search for mineral-bearing ores and/or targeted minerals such as gold, diamonds, gemstone (Hartman and Mutmansky, 2002). It is required by law in many countries to first obtain prospecting licence before the beginning of the search for minerals and other valuable metals (Carvalho, 2017). Such permits for minerals and other valuable metals exploration must be granted by the legal authority to the individuals or companies to get legal rights to conduct prospecting activities. Different prospecting methods in mining exist; these methods are direct observation which employs visual examination of the mineral deposits that are found above the earth’s surface or along the rivers for the case of alluvial gold and indirect methods for the deposits that are found under the earth’s surface and requires to expose the deposit to the surface for examination (Hartman and Mutmansky, 2002). The use of indicator plant species or vegetation type is also a widely used technique to determine the type of existing mineral ore in the area under search (Brooks, 1979; Sonter et al., 2018). With current advanced technology, mineral deposits can also be located by remote sensing techniques through structural and vegetation analysis (Hartman and Mutmansky, 2002; Murguía et al., 2016).

Prospecting and exploration often are two stages that goes simultaneously. Thus, after locating the mineral deposit of interest in the prospecting stage, the next step is to accurately determine the available reserve and possibly the value of the deposit in the exploration stage (Hartman and Mutmansky, 2002). To determine the extent of the mineral deposit, first the targeted area for exploration is prepared (e.g., clearing of vegetation), then representative samples are collected by chipping outcrops, trenching, and drilling (Hartman and Mutmansky, 2002; ICMM, 2006). The collected representative samples consisting of chips or core are then used to create a model of the underground geometry of mineralization (Tsuji et al., 2018). This can give accurate estimation of the available mineral ore deposit, its economic benefit and estimated number of years for ore reserve exhaustion (Hartman and Mutmansky, 2002).

2.5.2 Development and extraction stage

Before beginning of mining activities, an individual or company must obtain the mining licence (permit) from the legal authority (Carvalho, 2017). The permit is obtained after the submission of the Environmental and Social Impact Assessment (ESIA) report to the environmental management authorities for approval (Hartman and Mutmansky, 2002). For example, in Tanzania, the National Environment Management Council (NEMC) is given mandate by the Environmental Management Act No. 20 of 2004 to oversee environmental management issues. Its function among others is to review the Environmental Impact Statements (EIS) obtained from the individual or company wishing to conduct mining activities in Tanzania. When the mining is in remote area with no development, an individual or mining company should undertake development activities to enhance the project. In this stage of the mining life cycle, there can be intensive clearance of vegetation for mining development purposes such as establishment of access roads, administrative offices, areas for processing plants, mining pit areas, campsites, and tailing storage facilities (TSF) (Hartman and Mutmansky, 2002). After vegetation clearance, careful removal of topsoil for the areas allocated for open mining pits and TSF must be conducted if the ore is to be extracted by open cast (Ghose, 2001; Hartman and Mutmansky, 2002). It is widely recommended that, stripping of the topsoil should be conducted when the soil is dry to avoid compaction and damage of the soil structure (Ghose, 2001).

Before stripping of the topsoil, a thorough soil survey should be conducted across the entire leased area and especially areas to be disturbed. This should be done by the qualified and experienced soil experts to determine depth, and soil properties (chemical and physical). Stripping of the topsoil should be completed in one location of interest before moving to another and should start at shallower soil to deeper soil to avoid unnecessary contamination and down slope progression. The stripped soil should be properly managed to protect its physical and chemical properties (Ghose, 2001). It should be well preserved and managed in storage facilities for use during mining rehabilitation. However, long term stockpile may cause changes in chemical properties such as available nutrients, soil pH and organic matter (Abdul-Kareem and McRae, 1984). It can also lead to impacts on soil organism such as Earthworms which can affect the potential for natural restoration (Boyer et al., 2011). Therefore, it is highly recommended for the topsoil to be stockpiled when redistribution of the soil takes longer time in mining life cycle (Ghose, 2001).

Underground mining does not require neither extensive vegetation clearing nor stripping of soil because a small amount of topsoil is removed to gain access to the ore deposit via tunnels or shafts (Hartman and Mutmansky, 2002). Thus, it is less environmentally destructive however, it is associated with high operation costs with greater safety risks (Hartman and Mutmansky, 2002). This makes global adoption of open cast mining in ore extraction unsurprising.

2.5.3 Mining closure

Mining closure occurs when mineral ore extraction is no longer cost-effective (Smith and Underwood, 2000). This is the stage where mining operation ceases to operate and the individual or company commences the decommissioning of the site infrastructure and give up the rights to the mining concession (Mchaina, 2001). It is the final stage of mining activity associated with mining rehabilitation and restoration. Planning for mining closure occurs in the early stages of the mining operation for mining companies to become ready for closure (Mchaina, 2001). It requires an interdisciplinary team of experts from different departments of the mining company to form integral part of the planning process (Mchaina, 2001). For an effective mining closure plan, a series of baseline studies and research should be conducted to determine the closure completion criteria. These criteria can be further adjusted through different stakeholder meetings to determine what should be ideal targets of the closure plan. It is very important for mining companies to get concerns from the adjacent communities for mining closure to work effectively.

The key objectives of the mining closure among others, is to (i) recreate productive and sustainable ecosystem for all stakeholders (ii) to eliminate environmental impacts caused by mining operations (iii) remediate all impacted systems that pose health risks (iv) maintain various infrastructure that provides socio-economic benefits. For mining that operates through open cast, the set criteria of the mining closure can be to return the mine site to the original or close to the original ecosystem before mining. The primary practice for this is to revegetate the site with native species and wait for fauna colonization in the latter stages (Thompson and Thompson, 2007). However, current practices require also to get concerns from the adjacent community of whether mining pits should be filled and levelled or should be left to accommodate other land use such as acting as fishing ponds (Laing and Moonsammy, 2021; McCullough et al., 2020).

2.6 Socio-economic impacts of mining

Development projects such as mining of minerals and metals generates various social-economic impacts (Mancini and Sala, 2018). Impacts can bring benefits, such as improved infrastructure which makes remote areas accessible and increases employment (Kitula, 2006; Mteki et al., 2017). Some of the socio-economic impacts are summarized below: -

2.6.1 Socio-economic development

Mining of minerals and metals can improve a country's economy through increase in exports, and GDP (Esteves, 2008; Hajkowicz et al., 2011; Kitula, 2006). Mining activity can increase employment and other business opportunities for adjacent communities such as increased guest house and hotels to accommodate large number of incoming people, increased food markets and food restaurants (Kitula, 2006; Petkova-Timmer et al., 2009; Weldegiorgis and Ali, 2016). Mining can also be beneficial to communities through CSR activities by creating education and health services (Kitula, 2006; Nguyen et al., 2018; Persson et al., 2017). Mining can raise government revenue through taxes from enterprises (Hajkowicz et al., 2011; Hilson and Monhemius, 2006; Kitula, 2006), thereby contributing to poverty eradication.

2.6.2 Increased inequality

Mining can also negatively impact the economy by increasing corruption, theft, and gender inequalities. Increased business opportunities and employment given to non-residents can result in demographic changes of the mining communities (Hajkowicz et al., 2011; Nguyen et al., 2018; Soberanis et al., 2015), and thus inequality. This can also result in increased diseases, HIV risks, food insecurity, social violence, changes in social norms, culture and tradition which can result in complete social upheaval (Nguyen et al., 2018).

2.6.3 Conflicts

The increase in conflicts associated with mining operations is also highly recognized as important trade-off of mining activities (Hilson, 2002), including those between mining companies, government, artisanal miners, and the surrounding communities (Erb, 2016; Mensah and Okyere, 2014; Persson et al., 2017). It is well acknowledged for the mining companies to succeed there should be an agreement between the companies and the local communities to gain social licence (Komnitsas, 2020). However, this is often not the case as there is increasing exclusion of stakeholders and indigenous communities in making decisions around mining areas (Owen and Kemp, 2015; Terminski, 2012).

Conflicts could arise from increasing exploration for resource deposits in the mining vicinity or different attitudes in relation to the value of the extracted product (Mensah and Okyere, 2014; Nikitina, 2014). For example, the mining sector is considered very significant to the national economy through different forms of gained revenue. However, this preposition is highly contested by activists who are dedicated to protecting environmental ecosystems. They argue that ecosystem services provided by mining inhabited areas may be more important than any economic benefits to be gained by minerals and metal production (Erb, 2016; Nikitina, 2014; Persson et al., 2017). There is a need to better understand these impacts which can lead to the identification of weak policies and suggest or propose strategies that the government and industry can adopt to mitigate or avoid such conflicts (Owen and Kemp, 2015).

2.6.4 Resettlement

Mining can lead to negative impacts, such as displacement and involuntary resettlement by acquiring community-owned land, changes in land use and increased deforestation (Kitula, 2006; Lillywhite et al., 2015; Mteki et al., 2017; Owen and Kemp, 2015; Terminski, 2013). Land use change brought by mining activities makes adjacent communities vulnerable to long term disadvantages (Lillywhite et al., 2015; Schueler et al., 2011; Terminski, 2013). Most of the people that depend on agriculture to sustain their daily livelihoods are often denied their right to continue farming and are relocated in areas that are compounded with land shortages, population growth and infertile soil for agriculture (Papworth et al., 2017; Terminski, 2012). Even though different mining companies takes responsibility of providing some social-development projects for the resettled and the whole adjacent community such as development of schools. Displaced people can lose their means of livelihoods and unemployment can increase upon mining closure because most of the people once employed by a certain mining company can lose their job when mining ceases to operate (Ali et al., 2017; Carrington et al., 2011; Nguyen et al., 2018; Tonts et al., 2012). However, prolonged mining induced land use change and their effects to surrounding community’s livelihood either remain unquantified or quantified with no linkages with change in livelihood (Maliganya et al., 2013; Schueler et al., 2011).

2.7 International sustainable development initiatives related to mining sector

There are several initiatives that are determined to assess or promote global sustainability goals in development projects. The following sections describe those that are related to the mining sector.

2.7.1 UN Sustainable Development Goals (SDGs)

Among the setbacks to the achievement of Millennium Development Goals (MDGs) were the increasing conflicts, climate change issues and environmental degradation (Lomazzi et al., 2014; United Nations, 2015). This was in some part caused by inadequate inclusion of stakeholders from developing countries during agenda discussion which led to the failure of achieving most of the developing countries targets (Fehling et al., 2013).

To address this important global aspect new vision have been set by the United Nations. Sustainable Development Goals (SDGs) are the current vision to transform the current state of the globe to better global society by 2030 (UN General Assembly, 2015). This world's plan of action has set 17 goals imbedded with 169 different targets cutting across social-economic and environmental sustainability (Mancini and Sala, 2018; Mant et al., 2016; UN General Assembly, 2015). To achieve these goals all stakeholders starting with the government and non-government organizations, business enterprises and private sectors from the global, regional, national to local level are obliged to promote the achievement of the SDGs (Mancini and Sala, 2018).

Mining is one of the globally important sectors creating employment opportunities and an important source of government revenues (Kitula, 2006; Schueler et al., 2011). However, they are often located in remote area with less development and important ecological systems (Mant et al., 2016). Mining sector, if well managed can contribute to economic development by supporting other manufacturing industries and creating incomes and job opportunities, thus contributing to the achievement of the SDGs. When mining is practiced in the opposite i.e., poor management, it will create trade-offs which will deny the achievement of SDGs such as protection and restoration of terrestrial ecosystems, clean water and sanitation and good health and wellbeing creating environmental degradation, human resettlement, increased conflict, and diseases (Mancini and Sala, 2018b; Mant et al., 2016; UN General Assembly, 2015).

The relationship between good practices in mining sector and the SDGs is well explained in the atlas by CCSI (2016), and if the atlas is properly adopted can boost the achievement of the global goals for the better future. However, the question remains how SDGs can be incorporated in mining good practices especially in developing countries, Tanzania included if there are no standard quantification of the impacts of the mining to ecosystem services and wellbeing. Decision making is based on the quality data collected with sufficient survey effort, intensive sampling with consistency methodology to detect real changes occurring on the observed locality (Dias et al., 2017; Salem, 2003). Thus, more efforts are needed to quantify impacts of mining to the natural ecosystems and the potential trade-offs to the wellbeing of the adjacent communities. These data are essential in improving governance settings towards the achievement of SDGs from mining sector and create good environment towards the achievement of the sustainable development.

2.7.2 International Council on Mining and Metals

ICMM is an international organization formed by 27 mining and metals companies to oversee environmental and social performance issues of mining activities and a benchmark to promote sustainable mining in the sector. To contribute to the global vision of achieving better society through production of minerals and metals, ICMM has revised its principles established in 2003 to accommodate the new vision of the United Nation. Ten principles that encompasses most of the global goals to achieve better society were revised and set to the direction towards achieving SDGs (ICMM, 2015). Mining cut across most of the SDGs and there is no primary point of connection between mining and one single SDG unlike other sectors (CCSI, 2016). Mining operations have the potential to contribute to more than one goal set forth by the United Nations to achieve environmental, and socio-economic sustainability (ICMM , 2012; CCSI, 2016). In making sure there is clear understanding on how mining can contribute to the achievement of SDGs, some initiatives have been taken to map the interconnections between mining sector and the SDGs with the aim of encouraging large- and small-scale miners in assimilating relevant SDGs in their daily production activities (CCSI, 2016; Mant *et al.*, 2016). Collaboration between the mining sector and other stakeholders is of high concern in the successful achievement of the of the SDGs (CCSI, 2016).

Among the principles of the ICMM, one specifically addressed biodiversity issues that was strengthened by formal terms of reference (TOR) set forth by the collaboration between ICMM, International union for Conservation of Nature (IUCN) and other stakeholders to balance the interest of mining and the protection of different ecosystems wildlife and human sustainability (ICMM, 2006). These terms of reference aimed to: *(i) respect legally designated protected areas (ii) disseminate scientific data on and promote practices and experiences in biodiversity assessment and management (ii) support the development and implementation of scientifically sound, inclusive, and transparent procedures for integrated approaches to land use planning, biodiversity, conservation, and mining* (ICMM, 2006).

This initiative has pinpointed mining as the high-risk sector for natural resources due to its continuous threat to the environment (F&C Asset Management plc, 2004), as such the impacts of minerals extraction to present and future sustainability should not be overlooked (IUCN, 2010). The vulnerability can be more intense when there is no proper impact assessment to make proper restoration and rehabilitation plans during and after mine closure (Cummings, 2014; Dias et al., 2017).

Moreover, biological resources within and adjacent a mining site can be a potential to the adjacent communities as they are strongly linked with the ability to provide ecosystem services (MEA, 2005; Díaz *et al.*, 2006; CCSI, 2016; Mant *et al.*, 2016). Thus, mining sites should be subjected to proper impact assessment on a regular basis to monitor any changes that may occur because of project implementation (Dias et al., 2017). The assessment should be in line with international standards and national environmental regulations and for those countries with less strict mining regulation, should make the regulations stricter to achieve sustainability in mining sector.

2.7.3 Global reporting initiatives

Increasing in business companies, mining included, calls for the need to set indicators for the sustainable business. The plan to get long term benefits should go along with the implementation of the environment and socio-economic sustainability practices (Global Reporting Initiative (GRI), 2015). GRI have set the interrelated standard to be implemented by different development organization to prepare a sustainability report. The GRI standards cut across socio-economic and environmental aspects. Thus, development organisations can use general standards or specific standards to report their projects.

In mining sector, the indicators of sustainability performance are imbedded in Corporate Social Responsibilities which are promoted by among others, the Global Reporting Initiatives (GRI) that is an independent international organization that has introduced the sustainability reporting since 1997. GRI helps global governments, businesses enterprises and other organisation to understand and communicate their impact on critical socio-economic and environmental sustainability (GRI, 2015; Mancini and Sala, 2018). To achieve this, GRI has developed disclosures containing guidance on reporting practices. Since mining sector requires exploration, mining and primary metal processing, these performance indicators cover the complete project life cycle, from project development to closure and post-closure (GRI, 2013). However, some of the impacts from mining sector are not included in their list of performance indicators elaborated by GRI (Mancini and Sala, 2018).

The issues of gender imbalance and migration to the mining community that may lead to deterioration of cultural, aesthetic values, increasing thefts and accidents and prevalence of temporary jobs resulting into windfall income are not well captured by GRI (Carrington et al., 2011; Mancini and Sala, 2018). This setback questioned the the effectiveness of the GRI reporting guidelines claiming that, reports that follows GRI guideline are misleading the policy and decision makers dealing with sustainability in the sector (Fonseca et al., 2014; Nguyen et al., 2018). To achieve meaningful and accurate information about sustainability, several changes must be incorporated in the GRI reporting framework including systematic consideration of site-level performance, scenario building to project future changes, and assessing the post-mining impacts (Fonseca et al., 2014)

2.7.4 Extractive Industries Transparency Initiative

The Extractive Industries Transparency Initiative (EITI) is the global standard launched in 2003 to promote open and accountable management of extractive resources including oil, gas, and minerals (Rustad et al., 2017). It is currently implemented by 51 countries, including the top ten African gold producers. It is guided by the slogan that a country’s natural resources belong to its citizens (EITI, 2018). Therefore, all information regarding extractive industries in specific countries must be disclosed to their citizens. This information includes stating how the government collects revenues from extractive industries and how will they be channelled to benefit the public citizens. It requires the member countries to timely report on how they are managing the extractive industries including allocation of licences, tax collection, royalties, and CSRs of the companies to the community in the vicinity (Lujala, 2018).

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CHAPTER THREE

3 A global systematic review on the impacts of subterranean mining on biodiversity and ecosystem services

3.1 Abstract

Extraction of minerals and metals is vital to national and regional economies but produces enormous impacts on biodiversity and ecosystem services. Yet, evaluations of ecological impacts of mining are still limited and to date there has been no comprehensive evaluation of scientific evidence of mining impacts. Here, we review the academic literature on the biodiversity and ecosystem service impacts of mining.

Of 2,093 studies reviewed, 99.8%, reported some form of negative impact of mining on biodiversity and ecosystem services. However, while 95% reported on the direct impacts, only 5% reported on the indirect impacts. Also, the majority (87%) reported on sink impacts (i.e., mining materials added to the environment), while only 13% of studies reported on source impacts (i.e., materials removed or extracted from the environment by mining). The most highly reported sink impacts were surface water contamination (51.0%), soil contamination (48.1%) and bioaccumulation (35.0%), while vegetation cover (12.1%) was the most reported source impact. Minimal positive impacts were also seen (0.2% of studies), through deliberate establishment of water ponds for mining purposes and through water ponds caused by subsidence, that attract freshwater biodiversity.

The review finds that mining exert pressure to at least 15 biodiversity hotspots, with negative impacts on biodiversity, conservation areas, vegetation cover, land use change, wildlife habitats, threatened and endemic species, coral reefs, and forest carbon stocks. We identified several knowledge gaps, especially on evaluating source impacts of mining, carbon sequestration and key marine ecosystems. Mining sustainability would likely be improved if they were to implement a priori mitigation measures, through stakeholder engagement and establish long-term evaluation and monitoring programmes.

Keywords: conservation; species; environmental risk; extractive industry; key biodiversity area; source and sink impacts; resource extraction; metal; minerals; mining.

3.2 Introduction

Mining for minerals and metals is vital to the improvement of multiple national economies, and critical to the production of daily goods and services (Agboola et al., 2020). In the abstraction and processing, mining produces enormous impacts on the ecosystems (Farjana et al., 2019), ecosystem services (Boldy et al., 2021) and the wider environment (Haddaway et al., 2019a). However, we lack evidence of the extent of impacts and how this varies with (i) mined commodity, (ii) type of ecosystem, (iii) extraction method, and (iv) the quantity of ore removed (Festin et al., 2019).

Extraction of some metals such as gold can generate higher ecological impacts due to the use of chemicals (Orimoloye and Ololade, 2020). It can result into massive liquid and solid wastes intensifying impacts on terrestrial, fresh water, and marine ecosystems even for decades beyond the life of a mine (Farjana et al., 2019). While less impacts are seen in areas with high mineral deposit than areas with low deposit (Sonter et al., 2018), different forms of mining can also exert different kind of impacts, for example surface mining contributes to more than 80% of the total annual ore production globally (Ramani, 2012), thus generating higher ecological impacts (Kamino et al., 2020) than underground mining (Zhang and López, 2019).

Impacts of mining on adjacent ecosystems can be from direct and indirect mining activities (Murguía et al., 2016). Direct impacts can result from exploration through to extraction mining stages. For example, early impacts can result from the use of heavy equipment on the project sites leading to clearing of vegetation to create room for drill sites and new access roads often required for movement of supplies and mining equipment (Agboola et al., 2020). This can lead to opening of undisturbed or relatively intact ecosystems impacting wide range of flora, fauna, and numerous ecosystem services (Sonter et al., 2017). Indirect impacts can result from improved infrastructure and livelihood opportunities in mining areas driving population increase in mining landscapes (Mancini and Sala, 2018). This can escalate loss of biodiversity, loss of wildlife habitats, deforestation, emission of forest carbon, change in land use and land and cover on adjacent ecosystems (Sonter et al., 2014).

Following the high rate of global biodiversity decline in mining landscapes (Whitehorn et al., 2019), mainstreaming of biodiversity into the mining sector is vital to halt losses of natural ecosystems (Karlsson-Vinkhuyzen et al., 2017). Mainstreaming is framed to integrate biodiversity values into the development policies, legislation, and land-use planning (Ginsburg et al., 2018), to ensure conservation and sustainable use of biodiversity across production sectors (Mijatović et al., 2018). In mining regions, mainstreaming should consider the whole production landscape by considering ecological fragile areas ranging from government to privately owned land (Manuel et al., 2016), and collaboration from relevant stakeholders (e.g., NGOs; government and production sectors (large, medium, and small). This copmehensive intergration of knowledege can help restore natural ecosystems while meeting human needs (Milner-Gulland et al., 2021).

While the literature on environmental impacts of mining has grown in recent years, there have been few global syntheses. Therefore, understanding the wide impacts (direct, indirect, sink and source) of mining across various commodities is critical to plan for potential trajectories of change to ensure biodiversity management and sustainable flow of ecosystem services, not only in mining leases but across whole mining landscapes that are indirectly impacted by mining activities.

In this systematic review, we identified the combined environmental impacts of mining and how they vary. We asked four specific questions: (1) What is the evidence base regarding of the direct, indirect, source and sink impacts on biodiversity and ecosystem services? (2) How do impacts vary across commodities, geographical location and across the life of the mine? (3) Where are current vulnerable biodiversity hotspots from mining? (4) What are the geographic and knowledge gaps for determining mining impacts?

3.3 Materials and Methods

We followed an established procedure for systematic literature (Collaboration for Environmental Evidence, 2018). We used the widely used PICO tool (Methley et al., 2014).

3.4 Search strategy

The systematic search was conducted between 31st December 2020 and 1st March 2021 to identify relevant articles for inclusion in the review. The search was performed on bibliographic databases, web-based search engines (online searches), relevant organisational websites and key international journals. The search results were all imported to Mendeley for information updates and then to Publish or Perish V7 (Harzing, 2007) to create a database showing title, abstract, year of publication, journal type and publisher.

We developed the search strategy for finding relevant articles to include in our literature review, through consultation with 40 academic colleagues and 25 mining practitioners. All engaged stakeholders helped to define the scope, keywords, key elements of the review questions, search strategy, and sources of publications.

3.5 Bibliographic database searches

To search for relevant studies, we tested a Boolean search string with wild cards by performing 32 tests in the Thomson ISI Web of Science Core Collection and generated a test library (SM 3). The same search string (SM 4) was used in other bibliographic databases with slight alteration of the input syntax and Boolean operators (Thorn et al., 2016). Search results were then exported to create a master database in Excel. The following bibliographic databases were searched:

i. Web of Science™ Core Collection http://apps.webofknowledge.com/
ii. Elsevier’s SCOPUS https://www.scopus.com/
iii. AGRIS https://agricola.nal.usda.gov/
iv. ProQuest https://www.proquest.com/

3.5.1 Web-based search engines

Web based searches was performed in Google Scholar and YorSearch for academic and grey literature. These were chosen because of the wide recognition as effective websites for retrieving grey literature (Haddaway and Bayliss, 2015).

3.5.2 Key international journals

We selected five key international journals whose topic areas closely aligned with the research questions. This included *Restoration Ecology; Biological Conservation; Environmental Pollution; Science of the Total Environment* and *Journal of Environmental Management*.

3.5.3 Organisational websites

We conducted search on thirteen subject-specific organisational websites, including nongovernmental organizations and public and research where reports, conference proceedings, policy briefs, book chapters, and individual research papers (Table 3). Where automatic searches were not available, we used hand searches (Richards, 2008).

Table 3. Specialist organizations and online databases searched in the systematic review. Website links were correct as of 01 March 2021.

No.	**Organization**	**Website**
1	The World Bank	https://www.worldbank.org/
2	International Union for Conservation of Nature	http://www.iucn.org
3	Africa Biodiversity Collaborative Group	http://www.abcg.org/bbop
4	World Gold Council	https://www.gold.org/
5	NGO Mining Working Group	https://miningwg.com/
6	International Council on Mining and Metals	https://www.icmm.com/
7	The Extractive Industries Transparency Initiative	https://eiti.org/
8	UN Environment World Conservation Monitoring Centre	https://www.cambridgeconservation.org/organisation/unep-wcmc/
9	Birdlife International	https://www.birdlife.org/
10	Worldwide Fund for Nature	https://www.worldwildlife.org/
11	The Nature Conservancy	https://www.nature.org/en-us/
12	Global Reporting Initiative	https://www.globalreporting.org/
13	Key Biodiversity Areas	http://www.keybiodiversityareas.org/home

3.5.4 Article screening and study eligibility criteria

Reporting of the excluded and included studies followed the PRISMA protocol (Figure 6) (Moher et al., 2015). Screening was carried out by six reviewers (i.e., lead author, one supervisor and other four co-authors, trained by the lead author). Screening of eligible studies began with the removal of duplicate articles, that are common in search results to avoid double-counting of data. After duplicate removal, screening of eligible studies was conducted on titles, abstract and full text by six reviewers, to determine article relevance. Since the inclusion of required data were often not clear from title and abstracts, exclusion was conservative pending full text review (Haddaway et al., 2019). The lead author checked for consistency throughout the process. This was further checked using Randolph's free-marginal kappa, for 25% randomly chosen studies, aiming for a target value of 0.75 - 0.85 to indicate consistency in data collection (Randolph, 2015).

Full texts of all screened studies were retrieved using university library subscriptions, excluding any that were not accessible. Variables shown in SM 3.10.1 were then extracted and coded from the retrieved texts. Data extraction was conducted by the team, who regularly met to discuss and resolve inconsistencies. Authors were contacted where there was ambiguity in some studies.

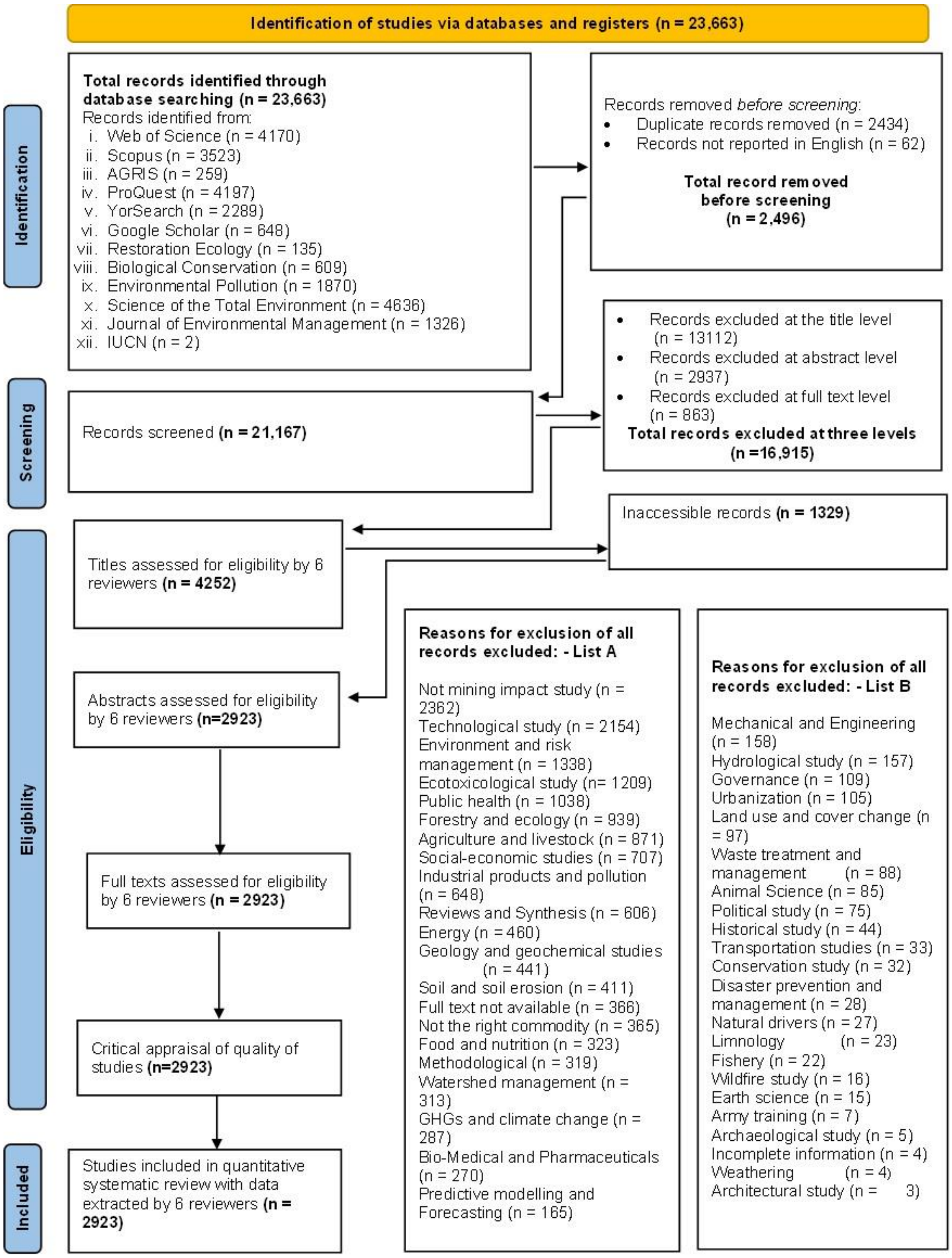

Figure 6: Overview of article screening and inclusion in the systematic review (adapted from PRISMA-P (Moher et al., 2015)).

3.5.5 Analysis

Following the completion of data extraction, all data were coded for whenever there was a multiple response, a binary data was created. We used basic graphical and GIS techniques to summarise and map the data. Spatial point pattern analysis was also performed to understand variation in the density of mining in relation to biodiversity hotspots (Ben-Said, 2021; Zhang et al., 2014). The point locations of mines extracted from each reviewed study were overlaid with 3,000 randomly extracted points from the biodiversity hotspot data for all reviewed commodities. Analysis was conducted in R using *spatstat* package (Baddeley and Turner, 2005) and ArcGIS version 10.6.

3.6 Results and discussion

3.6.1 Temporal evolution

Scientific research on mining impacts on biodiversity is growing. There is an exponential increase in the number of studies evaluating mining impacts in the last century with the first paper being published in 1922 (Fig. 7). However, the pace for research in mining impacts on biodiversity was slow before 2000 with an average of 8 papers per year. The pace of research increased exponentially after 2000 with an average of 87 paper pr year.

The increase in research evaluating mining impacts on biodiversity and wider environment could be influenced by the increasing demand for significant research effort to overcome current knowledge deficits (Sonter et al., 2020).

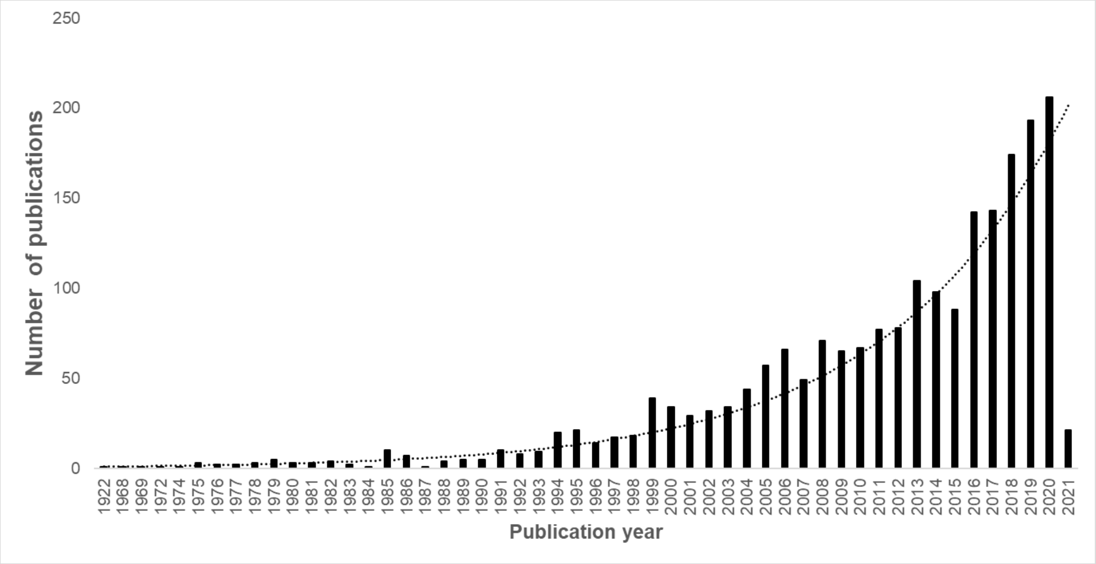

Figure 7: Increasing number of articles addressing mining impacts on biodiversity and ecosystem services.

3.6.2 Geographic distribution

Studies were distributed across five continents (Figure 8). Europe (30.2%, *n* = 633) and Asia (26.8%, *n* = 561) were studied the most, followed by North America (18.7%, *n* = 391), South America (11.2%, *n* = 234), Africa (9.5%, *n* = 199) and

Oceania (3.6%, *n* = 75). These studies were distributed across 111 different countries, but the majority (13.5%, *n* = 291) were reported in China, followed by USA (9.8%, *n* = 209) and Spain (7.3%, *n* = 156).

Most of the studies were conducted at specific sites (80.5%, *n* = 1685), followed by national scale (15.4%, *n* = 322) and regional scale (3.6%, *n* = 76), while only (0.5%, *n* =10) studies were conducted at global scale.

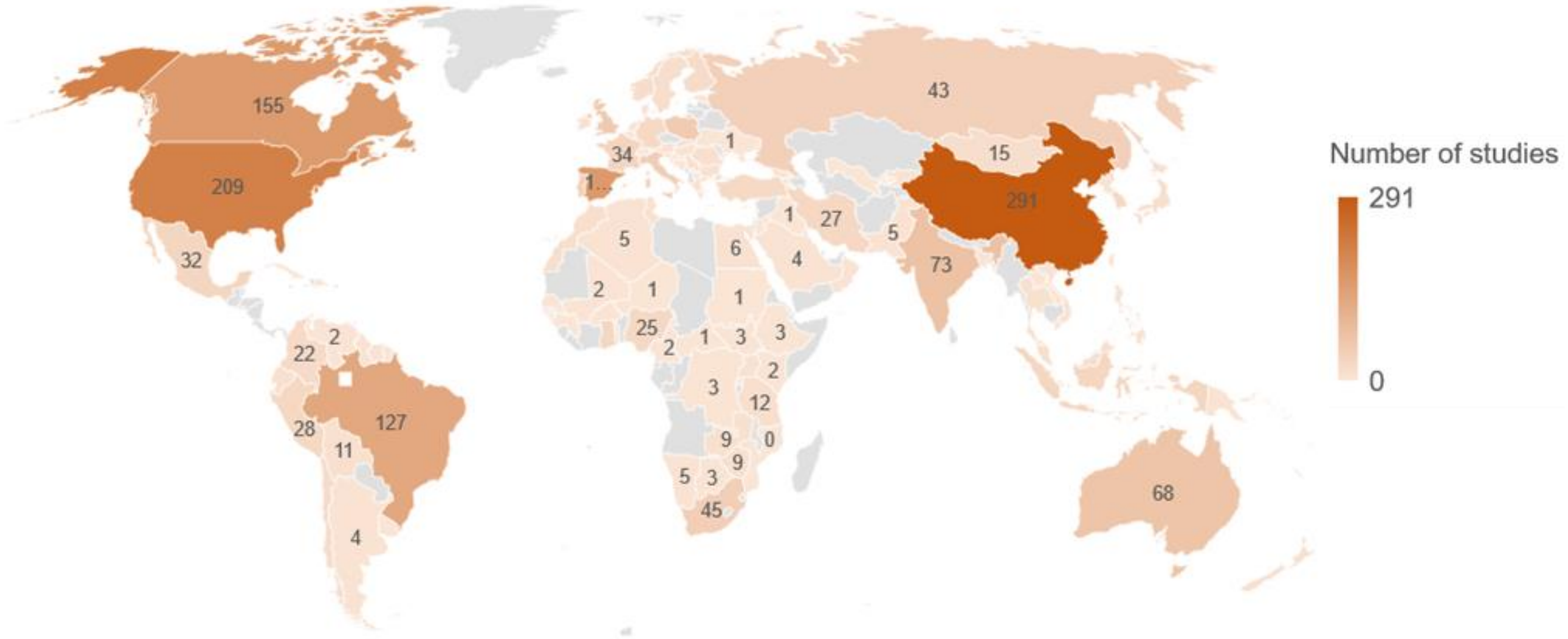

Figure 8: Map showing number of published studies assessing the impacts of mining on biodiversity per country.

3.6.3 Publication and source

Most studies were peer-reviewed articles (99%, *n* = 2081), published in a wide range of journals (*n* = 517). The remaining twelve were conference papers and proceedings. The journals that dominate the literature on this topic are Science of the Total Environment (15.7%, *n* = 329), followed by Environmental Pollution (10.6%, *n* = 222), while Water, Air, and Soil Pollution, Environmental Earth Sciences and Chemosphere contributed (2.5%, *n* = 53), (2.3%. *n* = 47), (2.0%, *n* = 42) respectively. While most of the papers were accessed through university subscription to the specific journals (69%, *n* = 1443), only few papers were open access (31%, *n* = 650). However, all these journals have high impact factors publishing wide range of environmental topics.

3.6.4 Commodity studied

A total of 69 commodities were reported. The top ten reported commodities are gold (13.4%, *n* = 396), copper (12.2%, *n* = 361), lead (12%, *n* = 356) zinc (10.7%, *n* = 316), coal (10.3%, *n* = 305), iron (4.0%, *n* = 117), arsenic (3.8%, *n* = 114), silver (3.2%, *n* = 94), uranium (2.7%, *n* = 81) and nickel (2.5%, *n* = 75); (Figure 8, 9). 7.2%, *n* = 214 of the studies did not report the type of commodity studied.

High number of reported commodities is associated with current high demand for these commodities which escalated their extraction. For example, high gold demand is linked to increase in jewellery consumption (Alvarez-Berríos and Aide, 2015), and global economic uncertainties (Depren et al., 2021); innovation of modern electric cars increases the demand for copper and nickel (Martins et al., 2021); reliance on coal for electricity generation in some countries such as India and China (Bijl et al., 2018), escalated coal extraction for the past decade (Bai et al., 2018); while increasing share of nuclear power increased the demand for uranium (Monnet et al., 2017). While improved technologies and infrastructure is vital to halt climate change, extraction of more metals will be escalated and the knock-on impacts on biodiversity (Sonter et al., 2020). This will also increase research efforts on high demanded metals to understand their potential impacts on biodiversity and wider environment.

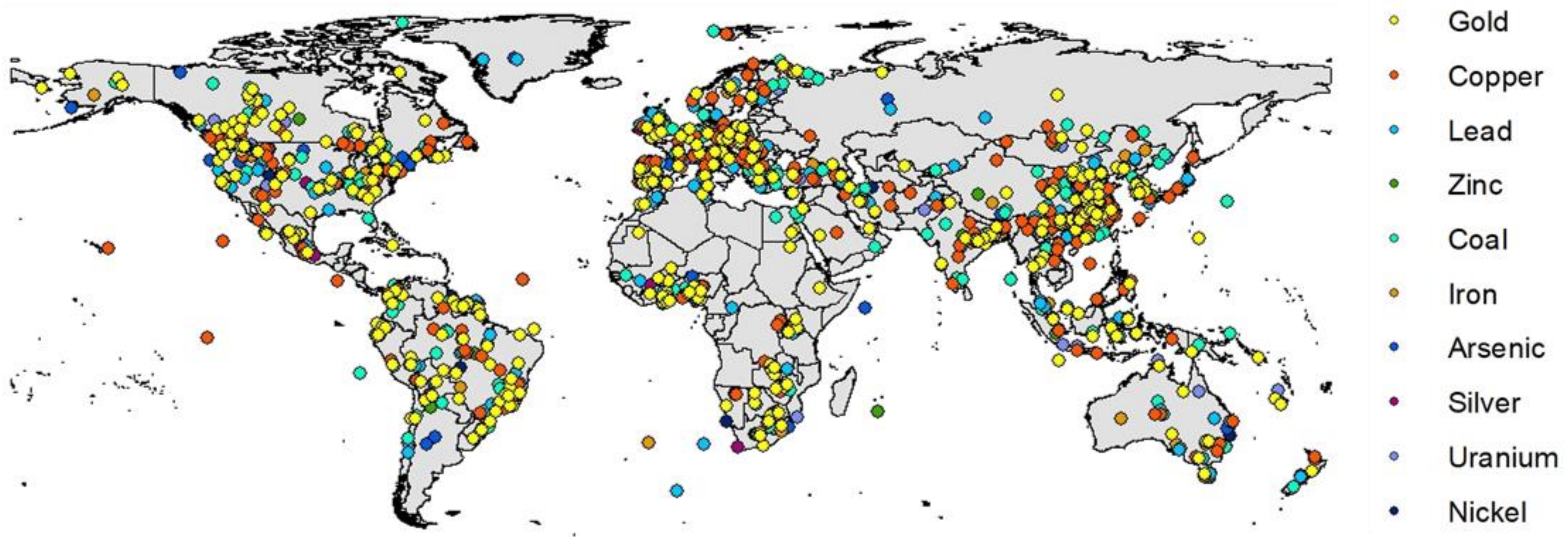

Figure 9: Global distribution of the ten most mined commodities among studies reviewed for biodiversity impacts.

3.6.5 Ecosystems reported

Most of the studies were conducted on terrestrial ecosystems (51.3%, *n* = 1073), followed by freshwater and riparian ecosystems (45.7%, *n* = 957). Only few studies reported impacts of mining on marine ecosystems (3.0%, *n* = 63) as shown in Figure 10.

While considerable research efforts have been put into evaluating the impacts of mining on terrestrial, freshwater, and riparian ecosystems, we lack the same pace of research in marine ecosystems. Marine ecosystem is highly vulnerable to mining as it receives mining pressure from both terrestrial (Fernandes et al., 2016) and marine ecosystem itself (Kaikkonen et al., 2018). This can eliminate irreplaceable biodiversity components and disrupt fisheries that supports adjacent livelihoods (Fernandes et al., 2016). There is a need to extend research efforts on mining impacts to marine ecosystems to recommend strong environmental performance to halt biodiversity loss in marine ecosystems.

3.6.6 Mining scale and biodiversity indicator reported

Most of the studies reported on impacts from large scale mining (48.6%, *n* = 1017), and only a few studies reported on artisanal and small-scale mining (5.5%, *n* = 116). The remaining studies (45.9%, *n* = 960), did not specify the scale of mining. Of all the studies, 27.1%, *n* = 568, reported mining impacts using general term “biodiversity”, while most of the remaining studies reported on plants (27.2%, *n* = 570), fish (11.0, *n* = 229), mammals (5.6%, *n* = 119), terrestrial invertebrates (4.7%, *n* = 99), birds (4.0, *n* = 83), benthic invertebrates (3.7%, *n* = 78), macrophytes (3.2%, *n* = 66), and fungi (3.0%, *n* = 62). Few studies reported on general micro-organisms (2.5%, *n* = 52), phytoplankton (2.3%, *n* = 48), zooplankton (1.8%, *n* = 37), aquatic invertebrates (1.1%, *n* = 22), bivalvia (0.8%, *n* = 17), amphibians (0.8%, *n* =16), reptiles (0.5%, *n* = 11), algae (0.4, *n* = 8), crabs (0.1%, *n* = 3) and sea urchins (0.05%, *n* = 1).

Despite the high recognition of the impacts of artisanal and small-scale mining on the environment (Ofosu et al., 2020), we still lack evidence of this mining scale on biodiversity. Although large number of studies did not specify the scale of mining (45.9%, n = 960), only 5.5% (n = 116), reported on artisanal and small-scale mining. This calls for increased efforts on mining research to evaluate the ecological impacts of artisanal and small-scale mining (Dethier et al., 2019).

While large number of the studies used plants and fish as indicators of biodiversity on evaluating mining impacts, most of these evaluated the potential bioaccumulation of heavy metals on either fish or plants. Only few of them evaluated change in community structure, diversity, or composition about mining impacts. There is still lack of evidence on how mining impacts different biodiversity indicators. Since mining impacts vary greatly between biodiversity indicators (Kujala et al., 2015), evaluation of mining impacts should focus on ecological impacts and not relying on generic indicators.

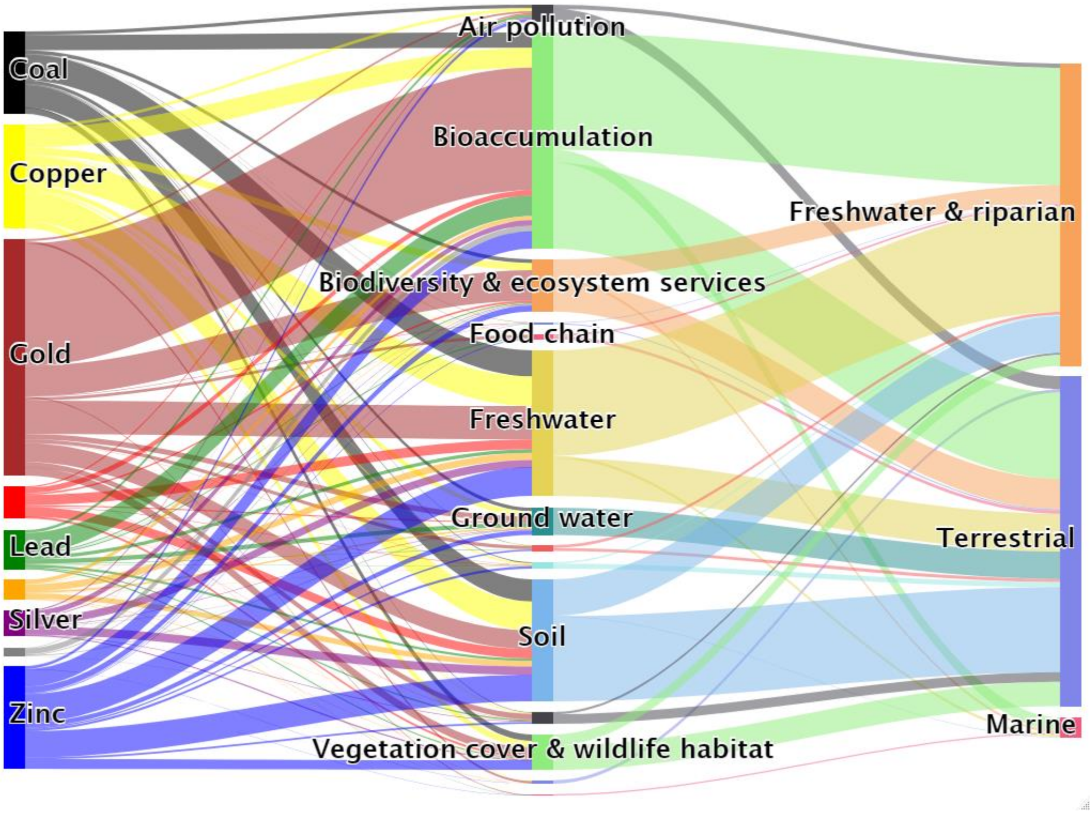

Figure 10: Ecosystems (right) that are impacted by the mining of extracted commodities (left), determined by consolidating alternative terms used by 2093 articles reviewed (centre). The middle axis presents specific impacts of mining across different ecosystems. The size of the axis represents the number of studies per specific reported aspect.

3.6.7 Direct and indirect impacts

Of the 2093 studies that reported mining impacts on biodiversity, 95%, *n* = 1986 reported on the direct impacts, while only 5%, *n* = 107 reported on the indirect impacts. While, mining has the potential to impact biodiversity either directly through habitat destruction, deforestation and soil and water contamination (de Castro Pena et al., 2017; Murguía et al., 2016), or indirectly by escalating landscape alteration and biodiversity loss through infrastructure development (de Castro Pena et al., 2017) and expansion of settlements by attracted migrants to reside adjacent mining areas (Sonter et al., 2018), indirect impacts of mining on biodiversity and wider environment have largely been overlooked. Mostly, studies reporting on the indirect impacts, focus on socio-economic spill over to the adjacent communities (Mancini and Sala, 2018), but not on biodiversity. Thus, the existing scientific literature is minimizing the over-all impact of mining activities by leaving out the indirect impacts of mining, while the over-all impact of mining on biodiversity can be elucidated by considering the indirect impacts for proper management.

3.6.8 Sink and source impacts

Sink impacts occurs when materials from mining operations are added to terrestrial, freshwater, riparian, marine ecosystems, and the atmosphere, such as greenhouse gases emissions (Thomashausen et al., 2018), heavy metals (Karn et al., 2021), and chemicals (Lyu et al., 2019). *Source* impacts arise from the extraction of materials from the environment, such as extracting underground or surface water, and clearing vegetation to establish mine infrastructure (Agboola et al., 2020). Most studies (87%, n = 1816) reported on *sink* impacts, while only 13%, n = 276 of the studies reported on *source* impacts (Figure 9).

The greater attention paid to sink impacts can be attributed to the enthusiasm to define critical thresholds of impacted ecosystems (Franks et al., 2010), and the high interest in determining consequences of mining pollution on public health (Ogola et al., 2002), through contamination of different levels of food chain (Sonone et al., 2020).

3.6.9 Sink impacts

Surface water contamination

The impact of mining activities on water (51.0%, n = 1068) has been intensively studied across the globe. Contamination of fresh water, riparian and marine ecosystems jeopardize long-term population viability and diversity of biodiversity components. Studies reported that, contamination of water ecosystems has caused impacts on spawning areas (Carmo et al., 2017; Stubblefield et al., 2005), reducing fish habitat and changes fish assemblages (Allard et al., 2016; Mol and Ouboter, 2004; Pouilly et al., 2013; Schorr and Backer, 2006), or increasing genotoxic effects in aquatic birds jeopardizing their long-term population (Baos et al., 2006). Contamination of water ecosystems can also impact fresh water and marine by impacting life of benthic invertebrates (Kilgour et al., 2018), lowering diversity of zooplanktons and phytoplankton (Fernandes et al., 2020; Levings et al., 2005), decline of amphibians population (Zocche et al., 2014), decline of crab population (Jonah et al., 2015), disruption of population and diversity of aquatic macro-invertebrates (Ali et al., 2018; Wright and Ryan, 2016) and limiting growth and population of the phylum Mollusca (Rogers et al., 2018). Water contamination is mostly driven by failure of the tailing storage facilities (Carmo et al., 2017; Fernandes et al., 2020; Meharg et al., 1999), acid mine drainage (Frelich, 2019; Williams et al., 2020), riverbank erosion and diverting river channels (Dethier et al., 2019; Lusiagustin and Kusratmoko, 2017; Macháček, 2020), and sedimentation (Kerfoot et al., 2018; Stubblefield et al., 2005).

Soil contamination

Like water contamination, high number of studies reported on soil contamination (48.1%, *n* = 1007). Where mining has resulted in high concentration of heavy metals in soils, plant growth is limited and restoration possibility is impaired (García-Gómez et al., 2014; Ogola et al., 2002), native floristic quality is affected (Struckhoff et al., 2013), soil microbiological balance is affected which can also affect soil health (Chibuike and Obiora, 2014; Fazekašová and Fazekaš, 2020). Such contamination further impacts ecosystem services such as nutrient cycling (Dinis et al., 2021), agricultural soil fertility (Abbaslou et al., 2018; Mileusnić et al., 2014) and livestock fodder production (Coimbra et al., 2021).

Bioaccumulation by aquatic and terrestrial flora and fauna

Reports of 35.0%, *n* = 731 studies from this systematic review revealed significant impacts of bioaccumulation of toxic metals on aquatic and terrestrial flora and fauna (Castro-Bedriñana et al., 2021; Dragun et al., 2019; Marshall et al., 2020). Bioaccumulation caused significant impacts on fish reproductive capacity there by reducing their population size (Driessnack et al., 2011; Franssen, 2009), aquatic invertebrates (Weithoff et al., 2019), sea urchins (Kobayashi and Okamura, 2005), earth worms (García-Gómez et al., 2014; Lourenço et al., 2012), wild birds (Berglund et al., 2010) and herpetofauna (Fuentes et al., 2020; Sasaki et al., 2016). Bioaccumulation can also reduce gonadosomatic index, fecundity, hatching rate, fertilization success and abnormal and can cause abnormal shape of reproductive organs (Taslima et al., 2022), resulting into embryo mortality and development difficulties (Fuentes et al., 2020).

High bioaccumulation can also produce behavioural abnormalities in amphibian species (Hayden et al., 2015), and small mammals (Hernández-Plata et al., 2020), thereof affecting their survival rates leading to population decline. Alteration of grassland and woodland ecosystems by reducing species richness for lesser tolerant species (Hernández and Pastor, 2008; Mapaure et al., 2011), and affecting primary productivity of phytoplankton (Levings et al., 2005), are also reported impacts of bioaccumulation on biodiversity.

Generally, most bioaccumulation studies focused on assessing permissible limits of heavy metal uptakes on fish and edible plants, above which can cause public health problems (Battsengel et al., 2020; Lee and Lee, 2020).

Tailing contamination in high biodiversity and conservation areas

A total of 40 studies (2 %) looked at negative externality of tailings dam accidents on high biodiversity and conservation areas. These accidents spilled large amount of mine tailings causing irreversible biodiversity loss on protected areas, high biodiversity conservation areas, biosphere reserves, key biodiversity conservation areas, important bird areas, World Heritage Sites, and riparian ecosystems (Carmo et al., 2017; Coimbra et al., 2021; Fernandes et al., 2020; Garris et al., 2018; Meharg et al., 1999; Santos et al., 2019; Teramoto et al., 2021; Turner et al., 2008). These huge impacts also travelled across spatial scales. For example, 17 days after Fundão Dam collapse, mine tailings arrived at the Atlantic Ocean about 600 km downstream via Doce River (Carmo et al., 2017; Marta-Almeida et al., 2016). This one event impacted array of aquatic ecosystems, burying aquatic and riparian vegetation and negatively impacted vegetation regenerative capacity (Rocha et al., 2022) which can create persistent impacts on biodiversity years after the impacts leading to long-term changes in ecosystem structure and functions (Coimbra et al., 2021; Fuentes et al., 2020; UN Environment, 2017).

Although this systematic review has identified 40 peer reviewed studies as of 01 March 2021 that reports on failure of the TSF, there have been over 300 failures of the TSF since 1985 (Lyu et al., 2019; UN Environment, 2017). Our results can be attributed by the focus of our study. Our study focused on all drivers of mining impacts on biodiversity which extended the search beyond negative externality of tailings dam accidents. However, they provided narratives on how tailings dam accidents are still a problem to biodiversity conservation and wide range of ecosystem services.

Air pollution

Mined air pollutants come in the form of dust, smoke, odours, fumes, mists, and gases. Since there is little understanding of air pollution as *sink* impact of mining in the existing literature (4.6%, *n*= 96), we lack evidence of the consequences of air pollution from mining activities on biodiversity (3.5%, *n* =73). These limited research evaluated the impacts of air pollution on the population dynamics of Lepidoptera (Koricheva and Haukioja, 1995; Zvereva and Kozlov, 2006), long-term population viability of threatened mammal species due to adverse impacts on their reproductive capacity (Amir Abdul Nasir et al., 2018), alterations of embryonic development and embryo mortality in fish and other aquatic vertebrates (Guerrero-Castilla et al., 2019), genetic damage in plant species (Li et al., 2016), and increased in phytotoxicity resulting into change in vegetation structure (Hutchinson and Whitby, 1977; Mighall et al., 2004), and increase in genotoxic effects in wild rodents (León et al., 2007).

3.6.10 Source impacts

Impact on vegetation cover

This systematic review has found 12.1%, *n* = 253 studies that reported on *source* impacts of mining on vegetation cover. Our results suggests that vegetation cover is the most studied indicator of biodiversity loss in mining landscapes (Kuzevic et al., 2022; Qin et al., 2020; Sonter et al., 2017). In mining landscapes, vegetation is cleared for establishing access roads, tailings storage facilities, process plants, waste rock dumps and mining camps (Agboola et al., 2020). This is associated with negative alterations in plant communities and loss of Critically Endangered plant species (Salles et al., 2019), shift in plant species composition and spread of invasive alien species (Kumi et al., 2021).

One of the current challenges in mining research, is a lack of baseline information and/or data on mining landscapes before mining activities (McIntyre et al., 2018, 2016), to establish the actual relationships on biodiversity and individual species before and after the mining operation (Andrades et al., 2020; Attuquayefio et al., 2017). Only few attempts have been made to establish the actual relationships of mining impacts before and after mining operations (Attuquayefio et al., 2017), and most efforts focused on evaluating mining impacted sites using reference controls (Giam et al., 2018; Vuori and Joensuu, 1996). This has led to difficulties in understanding the underlying drivers behind changes in individual species and other biodiversity indicators in mining impacted sites.

In the efforts to understand the actual impacts of mining on biodiversity before and after mining impacts, vegetation cover has been the most targeted indicator of biodiversity loss in mining landscapes (Kuzevic et al., 2022; Qin et al., 2020; Sonter et al., 2017), because land clearance leave the most identifiable impacts with the application of GIS and remote sensing (Werner et al., 2019), thus becoming the most used indicator to identify *source* impacts of mining (Kujala et al., 2015).

Impact on land use change

Existence of mining activities opens the window for infrastructure development, urbanization, and agricultural expansion (Sonter et al., 2014; Takam Tiamgne et al., 2021), of which acts as main drivers of landscape alteration (Schmäck et al., 2022), as evidenced by 54 studies (2.6%) in this review. Landscape alteration is associated with loss of forest cover (Takam Tiamgne et al., 2021), increase in soil erosion, sedimentation in freshwater and marine ecosystems (Fernandes et al., 2016) and loss of catchments (Kusena et al., 2022). This has direct and indirect impacts on various components of biodiversity (Sonter et al., 2014).

While surface mining is often considered the most underlying driver in land use dynamics, that cannot exempt underground mining from doing the same (Xiao et al., 2018). Thus, the issue of land use change in mining landscape is contributed by all types of mining activities. With increasing global demand for minerals (Sonter et al., 2020), mining will continue to threaten vulnerable ecosystems in mining landscape (Luckeneder et al., 2021).

Impact on wildlife habitat

Loss of vegetation cover in mining landscapes denies wild animals with habitats (Owusu et al., 2018), causing loss and or decline of species/species diversity (Krauss et al., 2010). Only 2%, $n = 38$ studies directly reported on mining impacts on wildlife habitat destruction. For example, mining has negatively altered temperate mountainous habitat for giant panda (*Ailuropoda melanoleuca*) (Wanghe et al., 2020), riverine habitat for elephants (*Elephas maximus*) (Singh and Chowdhury, 1999), conifer forest for grizzly bears (*Ursus arctos*) (Cristescu et al., 2016), potential natural vegetation for herpetofauna (Mayani-Parás et al., 2019), aquatic and stream habitats for aquatic invertebrates (Gangloff et al., 2015) and fish and diatom assemblages (Dedieu et al., 2014). Interestingly, few studies have reported on the positive impacts of mining on the provision of suitable habitats for wildlife. However, only 0.01%, *n* = 2 have reported on the increase in bird species richness and diversity in artificial wetlands created for mining purposes (Salovarov and Kuznetsova, 2006) and in subsidence wetlands (Li et al., 2019). Nevertheless, the negative impacts surpass positive impacts, thus putting flora and fauna living in aquatic and terrestrial ecosystems in jeopardy (Menzies et al., 2021).

While mining actors can contribute towards biodiversity conservation goals outside mining areas (Simmonds et al., 2020), there is little efforts directed on understanding how this can be achieved by creating suitable habitats for wildlife in mining landscapes. Since there is inconsistent pattern of wildlife habitat use between inside (Seki et al in review) and outside (Cristescu et al., 2016) mining leases during active mining, long-term collaboration among actors in conservation and mining sector can increase effectiveness of protecting potential wildlife habitats in mining landscapes (Sonter et al., 2018).

Impact on threatened and endemic species

Threatened species are those vulnerable to extinction and are categorised by IUCN red list of threatened species as near threatened, vulnerable, endangered, and critically endangered. They include endemic species that exclusively occurs to a specific geographic area (Foggi et al., 2015), with restricted ranges of environmental conditions (Gereau et al., 2016).

Few studies (1.5%, *n* = 32) have reported on the impact of mining on threatened species. These studies reported mining impacts on 32 anuran (tailless amphibians) and eight bird species endemic to the eastern Brazil mountaintops (de Castro Pena et al., 2017), critically endangered Iberian lynx (*Lynx pardinus*) with a population of less than 200 in the wild of Southern Spain (Millán et al., 2008), Blue Mountains water skink (*Eulamprus leuraensis*) of the Temperate Highland Peat Swamps on Sandstone (Gorissen et al., 2017), endangered black-throated finch (*Poephila cincta cincta*) in central Queensland, Australia

(Vanderduys et al., 2016), and endemic earthworm communities in New Zealand (Boyer et al., 2011).

The few mentioned examples are vital indication that threatened species are more vulnerable to mining activities, therefore, hold a higher extinction risk (Coelho et al., 2020). However, lack of scientific studies on threatened species prevents accurate quantification of extent, and magnitude of mining impacts (Koehnken et al., 2020). Therefore, mining remains to be a major threat to threatened species.

Loss of protected areas through PADDD

One of the biggest challenges facing the legalized conservation areas is the existing mineral concessions in their boundary. Key biodiversity areas are prone to deforestation (Durán et al., 2013), and PADDD (protected areas downgrading, downsizing, or de-gazettement). (Qin et al., 2019) because of the existing metals and mineral concessions in their boundary.

Although this review picked few studies (1.4%, *n* = 28) that looked at the implication of PADDD on protected areas, they reported higher rates of loss in protected areas. For example, Batang Gadis National Park in Indonesia was reduced by 38500 ha to allow mining and Selous game reserve by then (before part of it became Nyerere National Park) was downsized by 20000 ha game reserve to allow uranium mining (Qin et al., 2019). More examples are shown in (Mascia and Pailler, 2011; Qin et al., 2019), and for much more examples are found on https://www.padddtracker.org/.

Protected areas vulnerability to PADDD events from mining point of view is growing fast than expected. Protected areas are more likely to have their status diluted, their areas shrunk, or their legal protection completely withdrawn (Qin et al., 2019). While increase in population is reported to increase PADDD events (Symes et al., 2016), mining can escalate these events and puts more pressure on threatened species (Roy et al., 2018; Wanghe et al., 2020) and key biodiversity areas (Armendáriz-Villegas et al., 2015; Durán et al., 2013; Sonter et al., 2020).

3.6.11 Other less reported vital impacts

Some other impacts of mining are less reported despite their vital importance in maintaining continuous flow of ecosystem services and global climate. There is little evidence on the existing literature on the impact of mining on aquifer, coral reef, forest carbon emission and climate change.

Impacts on aquifers

We found few studies that reported mining impacts on aquifers (0.7%, *n* =14), even though mining operations have significant impacts on aquifers, which are and can jeopardize supply of water to various ecosystems (Ma et al., 2021).

Aquifers are important hydrological components which can contain or transmit groundwater. They are essential in sustaining spring discharge and river base flow, and other aquatic ecosystems such as lakes, lagoons, and wetlands, which in turn supports various terrestrial habitat and human livelihoods (Custodio, 2002). When dewatering is applied to remove water of the disrupted aquifers to prevent flooding of the active underground mining (Younger et al., 2002), such pumped water can be contaminated and can contaminate wide range of surface aquatic and marine ecosystems (Younger, 2016).

Impacts on coral reefs

Although, other non-mining pressures on coral reefs are widely studied (Fine et al., 2019), there is little evidence on how mining impacts coral reef ecosystems - despite their widely recognized importance to sustain life underwater (e.g., the Great Barrier Reef world heritage site with high diversity of coral species, fish species, mollusc species (Brodie et al., 2012) and six of the world's seven sea turtle species) and protecting coastal ecosystems from storm surges. Of the few studies that linked mining pressure on the coral reefs (0.2%, n = 5), looked at the biomagnification of the trophic levels (Fey et al., 2019), branching corals and calcareous encrusting organisms (Martinez-Escobar and Mallela, 2019) and coral reef lagoons (Fernandez et al., 2006).

Impacts on forest carbon emissions

Another significant impact of mining for solid metals and minerals that has been given little attention is forest carbon emissions. Of 253 studies that looked at the impact of mining on vegetation cover change only 5 (2%) were found to link that with forest carbon emission and the focus has mostly been in the Amazon (Asner et al., 2010; Csillik and Asner, 2020) and Asia (Kartikasari et al., 2019; Qin et al., 2020; Yang et al., 2019). This poses a major threat to forest carbon stocks (Asner and Tupayachi, 2017), with climate change implications. This is only 0.2% of all reviewed studies.

Our results indicate that, only few studies have linked changes in vegetation cover with emission of carbon stocks in mining landscapes. Similarly, much focus has been on above ground tree carbon, leaving other carbon pools under researched. Only few studies (0.1%, *n* = 3) have focused on soil carbon (Qin et al., 2020; Xu et al., 2019; Yang et al., 2019). Although release of carbon by mining activities is difficult to measure especially from indirect impacts (Huang et al., 2015; Sonter et al., 2018), there is a need to increase efforts of carbon accounting in mining landscapes across various carbon pools.

3.6.12 Impacts on ecosystems services

Ecosystem services can be defined as the benefits that people obtain from ecosystems (MEA, 2005), or the direct and indirect contributions of ecosystems to human well-being (TEEB, 2010), or contributions of ecosystem structure and function to human well-being (Burkhard et al., 2012). Ecosystem services can be categorised into provisioning services, regulating services, supporting services and cultural services (MEA, 2005; TEEB, 2011).

Ecosystem services can be severely destroyed through direct and direct impacts of operations (Qian et al., 2018; Seki et al., 2022). However, few studies have assessed impacts of mining on ecosystem services (Boldy et al., 2021), despite the fast growing mining sector and the knock-on impacts on different ecosystems (Durán et al., 2013), that provide these ecosystems services and contribution to human well-being (TEEB, 2011).

In this review we found relatively few studies (37%, *n* = 777) that reported on ecosystems services. Additionally, these studies were not directly designed to study the relationship between mining impacts and ecosystems services but rather reported impacts on ecosystems services as a secondary aspect.

Most of the studies reported on the impacts of mining on fresh water (56%, *n* = 433) and soil quality (51%, *n* = 399). Other reported ecosystem services are quality air (6%, *n* = 47), nutrient cycling (5.5%, *n* = 43), wildlife habitat (5%, *n* = 40), carbon sequestration (1.2%, *n* = 9), detoxification (0.1%, *n* = 1) and fish (0.1, *n* = 1). The reported ecosystem services were categorised as provisioning services (60%, *n* = 464), regulating services (60%, *n* = 465) and supporting services (11%, *n* = 83).

Our results indicate that ecosystem services are highly neglected in mining sector despite the tremendous impacts caused by mining operations (Neves et al., 2016). Thus there is a need to understand the relationship between mining impacts and specific ecosystem services (Boldy et al., 2021). This will support the global efforts to maintain resilient ecosystems that will continuously provide ecosystem services that contribute to human wellbeing (TEEB, 2011). Additionally, all ecosystem services reported in this review were associated with negative impacts of mining operations and while positive impacts were not reported as they are related to restoration activities (Boldy et al., 2021).

3.6.13 Convergences of biodiversity hotspots with mining

Biodiversity hotspots are areas of high concentrations of endemic species (contain at least 1,500 endemic species of vascular plants), experiencing at least 70 % loss of its native habitat (Lee et al., 2011) and high species extinction (Le Roux et al., 2019) driven by anthropogenic activities (Weinzettel et al., 2018), despite being given high conservation priority (Poynton et al., 1998).

Point analysis revealed that 15 out of 36 globally recognized biodiversity hotspots are vulnerable from mining expansion (Luckeneder et al., 2021). Although all commodities studied in this systematic review were distributed across areas of high biodiversity, biodiversity hotspots were observed to be more vulnerable to the extraction of gold, copper, lead, zinc, coal, iron, silver, uranium, and nickel. Similar observations were reported for other biodiversity areas (Durán et al., 2013; Luckeneder et al., 2021).

High convergency were observed in the Atlantic Forest, Guinea forest of west Africa, Eastern Afromontane, Coastal Forest of Eastern Africa, Mediterranean basin, Madagascar and the Indian Ocean islands, Irano-Anatolian, Horn of Africa, Mesoamerica, North America Coastal Plain, New Zealand, Forest of Eastern Australia, Southwest Australia, and Western Ghats and Sri Lanka (Figure 11).

Most global spatial analyses of mining pressure on biodiversity have been on diversity of vascular plants (Murguía et al., 2016), protected areas, and watersheds (Durán et al., 2013; Luckeneder et al., 2021). Yet, our results highlight biodiversity hotspots receive pressures from the growing mining sector across the globe. Given many areas lack protection status, and research efforts have been directed to determine vulnerability of these biodiversity hotspots from other non-mining activities, but not mining – this is clear area for future work.

Figure 11: Showing convergency of mining activities and biodiversity hotspots

3.7 Research priorities and future directions

3.7.1 Mineral price inflation during pandemics

A global pandemic can affect the global economy with the knock-on impacts on the society and the environment (Akinsorotan et al., 2021). During the recent covid-19 pandemic, the lockdown measures affected supplies of metals and minerals from smelters and mines (Anser et al., 2022). This has resulted in the price inflation of gold (Depren et al., 2021), copper (Govreau, 2021) and other high demanded metals (Akcil et al., 2020).

Price inflation for minerals and metals was associated with high biodiversity degradation. For example, there was increase in illegal mining during covid-19 pandemic in Zimbabwe (Ndlovu et al., 2021), Nigeria (Attah et al., 2021), Brazil (Vale et al., 2021), Ecuador (Mestanza-Ramón et al., 2021), and Indonesia (Cahyadi and Newsome, 2021). This escalated rate of biodiversity loss and the situation could be worsened by the prolonged pandemic (Ndlovu et al., 2021). High rates of deforestation were also intensified during the pandemic (Siqueira-Gay and Sánchez, 2021). For example, deforestation rates increased by 55% in the Amazon rain forest (Bang and Khadakkar, 2020). This highlights the vulnerability of key biodiversity areas in the wake of the current and future pandemics (Thurstan et al., 2021).

With limited research efforts during pandemic to identify drivers and determine the impacts of the pandemic on biodiversity and wider environment (Ndlovu et al., 2021). There is a need to establish global conservation policies to tackle the issues of biodiversity and conservation to prepare for similar crisis in the future.

3.8 Conclusions

Our results indicate increasing research efforts on evaluating mining impacts on biodiversity and ecosystems services. However, the focus has been much on sink and direct impacts than source and indirect mining impacts. Most studies reported on negative impacts, while positive impacts were associated with artificial establishment of water dams and subsidence.

While there is great understanding of how *sink* impacts affect different components of terrestrial and aquatic ecosystems, there is also a need to determine the consequences of *sink* impacts on large fauna especially wild animals, birds, and reptiles, as reflected from this review, only few studies have focused on assessing *sink* impacts on the mentioned biological components.

Understanding mining impacts on specific indicators of biological components in mining research will enhance global efforts to manage threats and achieving a no net loss of biodiversity (Sonter et al., 2018), thus contributing to sustainable mining that sustain natural ecosystems and ensures the continuous flow of ecosystem services.

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3.10 Supplementary material

3.10.1 Systematic review eligibility criteria in relation to questions key elements.

Key elements of questions	**Eligibility criteria**
Population (P) .	**Included** • We will include all ecosystems worldwide according to (Kottek et al., 2006), including terrestrial and aquatic systems. • Natural and non-natural ecosystems will be included. **Excluded** • Social, political, economic, and technical systems.
Intervention (I)	**Included** • All primary studies that reported on the ecological, environmental and ecosystem services impact of mining for solid metals and minerals (including iron and ferro-alloy metals, non-ferrous metals, precious metals, industrial minerals, and mineral fuels) on biodiversity and ecosystem services (positive, negative, both, direct, indirect) from source to sink. • We focus on solid metals and minerals as they largely contribute to surface mining, therefore poses significant impacts to ecological systems (Lima et al., 2016; Phillips, 2016). • Research pertaining to all stages of mining, from prospecting onwards, i.e., prospecting, exploration, construction, operation (including extraction, crushing, milling, smelting, furnacing, burning, and other processes), maintenance, expansion, abandonment, decommissioning, reopening and repurposing. • Deep sea mining for relevant minerals and metals, such as silver, gold, copper, manganese, cobalt, and zinc amongst others. • Studies which include the impact of artificial acid mine drainage and other sink impacts caused by mining extraction. **Excluded** • All studies that reported on social-economic impacts of mining. • All studies that describe the use of the above listed solid metals and minerals in stages after the mining (e.g., in

Key elements of questions	**Eligibility criteria**
	impact of coal-fired power plants, manufacturing of products, the use of products in industrial complexes). - Studies which describe the impact of products made from listed mined materials (e.g., cement or steel). - Fracking is not included, nor is deep sea trawling. - Natural acid mine drainage. - Studies that describe the geochemistry.
Comparator (C)	**Included** - The absence of subterranean solid metal or minerals mining activities or mitigation measures - either prior to an activity or in an independent, controlled location outside a mined area lacking such impacts. **Excluded** - Studies without comparator.
Outcome (O)	**Included** - Effectiveness of restoration in mining landscapes. - All terms used for different restoration objectives will be included i.e., remediation, restoration, reclamation, and rehabilitation (R4) as described in (Lima et al., 2016). - All outcomes (i.e., measurable impacts) observed in environmental/ecological systems during or after mining (e.g., water pollution, habitat destruction, increase or decrease of wild animals). - Effectives of the Restoration, remediation, rehabilitation, and reclamation methods. **Excluded** - Social, technological, political, or institutional outcomes. - All studies focusing *only* on geomorphology, geology, human impacts, agricultural production, infrastructural studies, energy development studies, land cover change studies (e.g., impact of land use change on habitat quality), or ecological studies without consideration of mining impacts on ecosystem services and biodiversity.
Commodity types	**Included** - Iron, gold, copper, nickel, lead, zinc, diamond, tanzanite, coal, bauxite, uranium, titanium, silver, quartz, lead, gypsum, cobalt, phosphate, aluminium, helium, graphite, platinum, potash, chromium, sand,

Key elements of questions	**Eligibility criteria**
	ruby, antimony, arsenic, beryllium, bismuth, cadmium, gallium, germanium, indium, lithium, mercury, rhenium, selenium, tellurium, tin, manganese, molybdenum, niobium, tantalum, tungsten, vanadium, palladium, platinum, rhodium, asbestos, baryte, bentonite, boron minerals, diatomite, feldspar, fluorspar, anhydrite, kaolin, magnesite, perlite, sulphur, steatite, pyrophyllite, vermiculite and zircon. **Excluded** • All studies that reported on impacts of marine salt, natural gas, petroleum, diesel, marble, groundwater extraction, oil, peat, algae, lime, lignite, tantalite, among others.
Biodiversity	**Included** • This may include, for example, reference to impacts on components of biodiversity, such as *inter alia* impacts on plants, birds, animals, forests, protected areas, wildlife, land use land cover change, amphibians, reptiles, flora, fauna, avifauna, herpetofauna, fish, forest carbon, catchments, watersheds, species composition, wildlife habitat, vegetation cover, aquatic ecosystems, species diversity, species richness, plant communities, threatened species, endemic species, biodiversity hotspots, key biodiversity areas, important bird areas, world heritage sites, mountains, top soil, ecological zones, spawning areas, key stone species, ecological fragile areas, invertebrates, butterflies and riparian areas.
Type of ecosystem services, goods and functions	**Included** • All ecosystem services as described in (Millenium Ecosystem Assessment, 2005). This includes the following • Provisioning services, such as food, fibre, fresh water, natural medicine resources • Regulating services, such as air quality regulation, water regulation, erosion regulation, water purification and waste treatment, disease regulation, paste control, pollination, natural hazard regulation • Cultural services, such as spiritual and religious values, aesthetic values, recreation, and ecotourism • Supporting services, such as nutrient cycling, soil formation and primary production

Key elements of questions	Eligibility criteria
Data type	**Included:** Quantitative, qualitative**,** both
Geographic location	**Included:** Global (No geographical limitation)
Time period	No limitation on publication date
Language	Bibliographic database searches were performed in English only, since the selected databases catalogue research using English titles and abstracts. Although this may introduce bias against studies conducted in in non-English language, it widely applicable under limited time and resources (Thorn et al., 2016)
Study type	**Included:** • Empirical research • Studies that model the impacts of mining on biodiversity and ecosystems services, e.g. (Luan et al., 2020) • Experimental and, studies that used existed data to assess impacts of mining • Both scientific and grey literature. **Excluded**: • Review studies, studies that have predictions solely, non-experimental studies, commentaries. • Studies that focus on methodological advancements.

3.10.2 Test library

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3.10.3 Searches in websites and journals

	DATABASE	RESULTS	RECORDS EXPORTED	DATE	SEARCH TERMS	LINKS
BIBLIOGRAPHIC DATABASE	Web of Science	4108	4108	19/01/2021	TITLE: (((“mine*” OR “mined*” OR “mining*” OR “mines*” OR (“extract*” AND “resource*”) OR (“extract*” AND “industry*”) OR (“extract*” AND “mineral*”) OR “mining regions*” OR “mining areas*” OR “artisan*” OR “galamsey*” OR “large scale mining*” OR ("processes*" AND "mining regions*")))) AND TITLE: (((“impact*” OR "effect*" OR "activity*" OR "restor*" OR "rehabilitat*" OR “evaluat*” OR “downgrad*” OR “downsize*” OR “degazet*” OR “gazet*” OR “expand*” OR “outcom*” OR “prospect*” OR “explor*” OR “construct*” OR “operat*” OR “maint*” OR “expan*” OR “abandon*” OR “decommission*” OR “repurpose*” OR “mitigate*” OR “overlap”* OR “contaminat*” OR “regenerat*”))) AND TOPIC: (((“biodiversity*” OR “plant*” OR “bird*” OR “animal*” OR “water*” OR "forest*" OR "protected area*" OR "wildlife*" OR "community*" OR "climate change*" OR "land cover change*" OR "infrastructure*" OR "erosion*" OR "amphibian*" OR "reptile*” OR "flora*" OR "fauna*" OR "avifauna*" OR "herpetofauna*" OR "ecosystem service*" OR "fish*" OR “forest carbon*” OR “land use*” OR “catchment*” OR “watershed*” OR “species composition*” OR “wildlife habitat*” OR “vegetation*” OR “vegetation cover*” OR “aquatic ecosystems*” OR “species diversity*” OR “species richness*” OR “plant communities*” OR “threatened species*” OR “endemic species”* OR “biodiversity hotspot*” OR “key biodiversity area*” OR “important bird area*” OR “world heritage site*” OR “forest*” OR “mountains*” OR “top soil*” OR “ecological zones*” OR “spawning areas*” OR “key stone*” OR “pollination*” OR “ecological fragile*” OR “recreation*” OR “aesthetic*” OR “invertebrates*” OR “butterfly*” OR "riparian*"))) AND TITLE: ((("metal*" OR "iron*" OR "gold*" OR "copper*" OR "nickel*" OR "lead*" OR "zinc*" OR "diamond*" OR "tanzanite*" OR "coal*" OR "bauxite*" OR "Uranium*" OR "Titanium*" OR "Silver*" OR "Quartz*" OR "Lead*" OR "Gypsum*" OR "Cobalt*" OR "Phosphate rock*" OR "aluminum*" OR "helium*" OR "graphite*" OR "platinum*" OR "potash*" OR "Chromium*" OR "sand*" OR "ruby*" OR "Antimony*" OR "Arsenic*" OR "Beryllium*" OR "Bismuth*" OR "Cadmium*" OR "Gallium*" OR "Germanium*" OR "Indium*" OR "Lithium*" OR "Mercury*" OR "Rare Earth Minerals*" OR "Rhenium*" OR "Selenium*" OR "Tellurium*" OR "Tin*" OR "Manganese*" OR "Molybdenum*" OR "Niobium*" OR "Tantalum*" OR "Tungsten*" OR "Vanadium*" OR "Palladium*" OR "Platinum*" OR "Rhodium*" OR "Asbestos*" OR "Baryte*" OR "Bentonite*" OR "Boron Minerals*" OR "Diatomite*" OR "Feldspar*" OR "Fluorspar*" OR "Anhydrite*" OR "Kaolin*" OR "Magnesite*" OR "Perlite*" OR "Sulfur*" OR "Steatite*" OR "Pyrophyllite*" OR "Vermiculite*" OR "Zircon*"))) Refined by: DOCUMENT TYPES: (ARTICLE OR DATA PAPER OR PROCEEDINGS PAPER OR LETTER) AND LANGUAGES: (ENGLISH) Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI.	http://apps.webofknowledge.com/
	Scopus	3526	3526	20/01/2021	(TITLE (impact OR effect OR activity OR restore OR rehabilitate OR evaluate OR downgrade OR downsize OR degazette OR gazette OR expand OR outcome OR prospect OR exploration OR construct OR operation OR maintenance OR expand OR abandon OR decommission OR repurpose) AND TITLE-ABS-KEY (mine) OR TITLE-ABS-KEY (mined) OR TITLE-ABS-KEY (mining) OR TITLE-ABS-KEY (artisan) AND TITLE-ABS-KEY (biodiversity) OR TITLE-ABS-KEY (plants) OR TITLE-ABS-KEY (vegetation) OR TITLE-ABS-KEY (birds) OR TITLE-ABS-KEY (invertebrates) OR TITLE-ABS-KEY (spawning AND areas) OR TITLE-ABS-KEY (protected AND areas) OR TITLE-ABS-KEY (pollination) OR TITLE-ABS-KEY (watershed) OR TITLE-ABS-KEY (catchment AND areas) OR TITLE-ABS-KEY (wildlife) OR TITLE-ABS-KEY (wildlife AND habitat) OR TITLE-ABS-KEY (endemic AND species) OR TITLE-ABS-KEY (threatened AND species)) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "EART") OR LIMIT-TO (SUBJAREA , "AGRI") OR LIMIT-TO (SUBJAREA , "MATE") OR LIMIT-TO (SUBJAREA , "SOCI"))	https://www.scopus.com/
	AGRIS	260	260	25/01/2021	(mining AND impact) OR (mining AND biodiversity)OR(miningANDrestoration) OR (mining AND environment) OR (mining andmetals)OR(mining AND minerals) OR (mining AND watershed) OR(miningANDcatchment) OR (mining AND forest) OR (mining AND wetland) OR(miningANDinvertebrates) OR (mining and overlap) OR (mining AND concession) catchment) OR (mining AND forest) OR (mining AND wetland) OR (mining AND invertebrates) OR (mining and overlap) OR (mining AND concession): journal_article +publicationDate:[1965 TO 2021] +language:(English)	https://agricola.nal.usda.gov/
	ProQuest	4213	4213	20/01/2021	mainsubject(: ("mine*" OR "mined*" OR "mining*" OR "mines*" OR ("extract*" AND "resource*") OR ("extract*" AND "industry*") OR ("extract*" AND "mineral*") OR "mining regions*" OR "mining areas*" OR "artisan*" OR "galamsey*" OR "large scale mining*")) AND noft(impact OR effect OR activity OR restor OR rehabilitat OR evaluat OR downgrad OR downsize OR degazette OR gazet OR expand OR outcom OR prospect OR explor OR construct OR operat OR maint OR expan OR abandon OR decommission OR repurpose OR mitigate OR overlap OR contaminat OR regenerat) AND (biodiversity OR plant OR bird OR animal OR water OR forest OR protected area OR wildlife OR community OR climate change OR land cover change OR infrastructure OR erosion OR amphibian OR reptile OR flora OR fauna OR avifauna OR herpetofauna OR ecosystem service OR fish OR forest carbon OR land use OR catchment OR watershed OR species composition OR wildlife habitat OR vegetation OR vegetation cover OR aquatic ecosystems OR species diversity OR species richness OR plant communities OR threatened species OR endemic species OR biodiversity hotspot OR key biodiversity area OR important bird area OR world heritage site OR forest OR mountains OR top soil OR ecological zones OR spawning areas OR key stone OR pollination OR ecological fragile OR recreation OR aesthetic OR invertebrates OR butterfly OR riparian) AND mainsubject(metal OR iron OR gold OR copper OR nickel OR lead OR zinc OR diamond OR tanzanite OR coal OR bauxite OR Uranium OR Titanium OR Silver OR Quartz OR Lead OR Gypsum OR Cobalt OR Phosphate rock OR aluminium OR helium OR graphite OR platinum OR potash OR Chromium OR sand OR ruby OR Antimony OR Arsenic OR Beryllium OR Bismuth OR Cadmium OR Gallium OR Germanium OR Indium OR Lithium OR Mercury OR Rare Earth Minerals OR Rhenium OR Selenium OR Tellurium OR Tin OR Manganese OR Molybdenum OR Niobium OR Tantalum OR Tungsten OR Vanadium OR Palladium OR Platinum OR Rhodium OR Asbestos OR Baryte OR Bentonite OR Boron Minerals OR Diatomite OR Feldspar OR Fluorspar OR Anhydrite OR Kaolin OR Magnesite OR Perlite OR Sulfur OR Steatite OR Pyrophyllite OR Vermiculite OR Zircon) Refined by: DOCUMENT TYPES: (ARTICLE) AND LANGUAGES: (ENGLISH): Timespan: All years	https://www.proquest.com/
ONLINE SEARCH	YorSearch	2292	2292	31/12/2020	Title contains impact OR effect OR activity OR restore OR rehabilitate OR evaluate OR downgrade OR downsize OR degazette OR gazette OR expand OR outcome OR prospect OR exploration OR construct OR operation OR maintenance OR expand OR abandon OR decommission OR repurpose OR mitigate OR overlap OR contaminant OR regenerate AND Title contains mine OR mined OR mining OR mines OR extract OR mineral artisan OR galamsey OR processes AND Subject contains biodiversity OR plant OR bird OR animal OR water OR forest OR protected area OR wildlife OR community OR erosion OR amphibian OR reptile OR flora OR fauna OR avifauna OR herpetofauna OR fish OR catchment OR watershed OR forest OR mountains OR pollination OR recreation OR aesthetic OR invertebrates OR butterfly OR riparian AND Title contains (metal OR iron OR gold OR copper OR nickel OR lead OR zinc OR diamond OR tanzanite OR coal OR bauxite OR Uranium OR Titanium OR Silver OR Quartz OR Lead OR Gypsum OR Cobalt OR aluminium OR helium OR graphite OR platinum OR potash OR Chromium OR sand OR ruby OR Antimony OR Arsenic OR Beryllium OR Bismuth OR Cadmium OR Gallium OR Germanium OR Indium OR Lithium OR Mercury OR Rhenium OR Selenium OR Tellurium OR Tin OR Manganese OR Molybdenum OR Niobium OR Tantalum OR Tungsten OR Vanadium OR Palladium OR Platinum OR Rhodium OR Asbestos OR Baryte OR Bentonite OR Boron Minerals OR Diatomite OR Feldspar OR Fluorspar OR Anhydrite OR Kaolin OR Magnesite OR Perlite OR Sulfur OR Steatite OR Pyrophyllite OR Vermiculite OR Zircon)	https://yorsearch.york.ac.uk/
	Google Scholar	648	648	24/01/2021	Impact of metal mining on biodiversity Impact of metal mining on wildlife habitats Impact of metal mining on ecosystem services Impact of metal mining on protected areas Impact of mining on land use and vegetation cover change Restorationand rehabilitiation in mining regions	https://scholar.google.com/
KEY INTERNATIONAL JOURNALS	Restoration ecology	136	136	21/01/2021	"(impact OR effect OR activity OR restore OR rehabilitate OR evaluate OR downgrade OR downsize OR degazette OR gazette OR expand OR outcome OR prospect OR exploration OR construct OR operation OR maintenance OR expand OR abandon OR decommission OR repurpose OR mitigate OR overlap OR contaminant OR regenerate)" anywhere and "(mine OR mined OR mining OR mines OR (extract AND resource) OR (extract AND industry) OR mineral OR (mining AND regions) OR (mining AND areas) OR artisan OR galamsey OR (large AND scale AND mining) OR (processes AND of AND landuse))" in Title and "(biodiversity OR plant OR bird OR animal OR water OR forest OR protected area OR wildlife OR community OR erosion OR amphibian OR reptile OR flora OR fauna OR avifauna OR herpetofauna OR fish OR catchment OR watershed OR forest OR mountains OR pollination OR recreation OR aesthetic OR invertebrates OR butterfly OR riparian)" anywhere	https://onlinelibrary.wiley.com/journal/1526100x
	Biological Conservation	609	609	20/01/2021	(mining AND impact) OR (mining AND biodiversity) OR (mining AND restoration) OR (mining AND ecosystem services) OR (mining and metals)	https://www.journals.elsevier.com/biological-conservation
	Environmental Pollution	1870	1870	19/01/2021	(mining AND impact) OR (mining AND biodiversity) OR (mining AND restoration) OR (mining AND ecosystem services) OR (mining and metals)	https://www.journals.elsevier.com/environmental-pollution
	Science of the Total Environment	4636	4636	19/01/2021	(mining AND impact) OR (mining AND biodiversity) OR (mining AND restoration) OR (mining AND ecosystem services) OR (mining and metals)	https://www.journals.elsevier.com/science-of-the-total-environment
	Journal of Environmental Management	1326	1326	20/01/2021	(mining AND impact) OR (mining AND biodiversity) OR (mining AND restoration) OR (mining AND ecosystem services) OR (mining and metals)	https://www.journals.elsevier.com/journal-of-environmental-management
SPECIALIST INTERNATIONAL ORGANIZATION	The World Bank	1174	1	01/02/2021	mining impacts on biodiversity, impacts of metal mining, impacts of mining, mining	https://www.worldbank.org/
	International Union for Conservation of Nature	90	2	26/01/2021	mining impacts on biodiversity, impacts of metal mining, impacts of mining, mining	http://www.iucn.org
	Africa Biodiversity Collaborative Group	24	4	01/02/2021	mining impacts on biodiversity, impacts of metal mining, impacts of mining, mining	http://www.abcg.org/bbop
	World Gold Council	44	1	01/02/2021	mining impacts on biodiversity, impacts of metal mining, impacts of mining, mining	https://www.gold.org/
	NGO Mining Working Group	0	0	01/02/2021	mining impacts on biodiversity, impacts of metal mining, impacts of mining, mining	https://miningwg.com/
	International Council on Mining and Metals	184	0	01/02/2021	mining impacts on biodiversity, impacts of metal mining, impacts of mining, mining	https://www.icmm.com/
	The Extractive Industries Transparency Initiative	1200	0	01/02/2021	mining impacts on biodiversity, impacts of metal mining, impacts of mining, mining	https://eiti.org/
	UN Environment World Conservation Monitoring Centre	23	0	01/02/2021	mining impacts on biodiversity, impacts of metal mining, impacts of mining, mining	https://www.cambridgeconservation.org/organisation/unep-wcmc/
	BirdLife International	1410	3	01/02/2021	mining impacts on biodiversity, impacts of metal mining, impacts of mining, mining	https://www.birdlife.org/
	World Wide Fund for Nature	19	0	01/02/2021	mining impacts on biodiversity, impacts of metal mining, impacts of mining, mining	https://www.wwf.org.uk/
	The Nature Conservancy	234	0	01/02/2021	mining impacts on biodiversity, impacts of metal mining, impacts of mining, mining	https://www.nature.org/en-us/
	Global Reporting Initiative	0	0	01/02/2021	mining impacts on biodiversity, impacts of metal mining, impacts of mining, mining	https://www.globalreporting.org/
	Key Biodiversity Areas	0	0	01/02/2021	mining impacts on biodiversity, impacts of metal mining, impacts of mining, mining	http://www.keybiodiversityareas.org/home

3.10.4 Search string used during the systematic search if relevant studies

String 1

“mine*” OR “mining*” OR (“extract*” AND “resource*”) OR (“extract*” AND “industry*”) OR (“extract*” AND “mineral*”) OR “artisan*” OR “galamsey*” OR “large scale mining*” OR ("process*" AND "mining region*")

String 2

“impact*” OR "effect*" OR "activity*" OR "restor*" OR "rehabilitat*" OR “evaluat*” OR “downgrad*” OR “downsize*” OR “degazet*” OR “gazet*” OR “expand*” OR “outcom*” OR “prospect*” OR “explor*” OR “construct*” OR “operat*” OR “maint*” OR “expan*” OR “abandon*” OR “decommission*” OR “repurpose*” OR “mitigate*” OR “overlap*” OR “contaminat*” OR “regenerat*”

String 3

“biodiversity*” OR “plant*” OR “bird*” OR “animal*” OR “water*" OR "forest*" OR "protected area*" OR "wildlife*" OR "community*" OR "climate change*" OR "land cover change*" OR "infrastructure*" OR "erosion*" OR "amphibian*" OR "reptile*” OR "flora*" OR "fauna*" OR "avifauna*" OR "herpetofauna*" OR "ecosystem service*" OR “fish*” OR “forest carbon*” OR “land use*” OR “catchment*” OR “watershed*” OR “species composition*” OR “wildlife habitat*” OR “vegetation*” OR “vegetation cover*” OR “aquatic ecosystems*” OR “species diversity*” OR “species richness*” OR “plant communities*” OR “threatened species*” OR “endemic species”* OR “biodiversity hotspot*” OR “key biodiversity area*” OR “important bird area*” OR “world heritage site*” OR “mountains*” OR “top soil*” OR “ecological zones*” OR “spawning areas*” OR “key stone” OR “pollination” OR “recreation*” OR “aesthetic*” OR “invertebrates*” OR “butterfly*” OR "riparian*"

String 4

"metal*" OR "iron*" OR "gold*" OR "copper*" OR "nickel*" OR "lead*" OR "zinc*" OR "diamond*" OR "tanzanite*" OR "coal*" OR "bauxite*" OR "uranium*" OR "titanium*" OR "silver*" OR "quartz*" OR "lead*" OR "gypsum*" OR "cobalt*" OR "phosphate rock*" OR "aluminum*" OR "helium*" OR "graphite*" OR "platinum*" OR "potash*" OR "chromium*" OR "sand*" OR "ruby*" OR "antimony*" OR "arsenic*" OR "beryllium*" OR "bismuth*" OR "cadmium*" OR "gallium*" OR "germanium*" OR "indium*" OR "lithium*" OR "mercury*" OR "rare earth minerals*" OR "rhenium*" OR "selenium*" OR "tellurium*" OR "tin*" OR "manganese*" OR "molybdenum*" OR "niobium*" OR "tantalum*" OR "tungsten*" OR "vanadium*" OR "palladium*" OR "platinum*" OR "rhodium*" OR "asbestos*" OR "baryte*" OR "bentonite*" OR "boron minerals*" OR "diatomite*" OR "feldspar*" OR "fluorspar*" OR "anhydrite*" OR "kaolin*" OR "magnesite*" OR "perlite*" OR "sulfur*" OR "steatite*" OR "pyrophyllite*" OR "vermiculite*" OR "zircon*"

3.10.5 Codebook. Variables that were extracted descriptive information and codes during systematic review.

Variable or code name	Description	Data
Title	Title of the journal article	Text
Authors	List authors (Name, Initials)	Text
Abstract	Copy and paste the abstract	Text
Journal name	List the name of the journal.	Text
Country of funders	The country where the funder (see acknowledgements) is affiliated.	Text
Country(s) of authors	Insert the name of the country where the author's primary institution (or first institution listed to be affiliate to their name,	Text
Scale of the study	(Local/National/Regional/Global)	Category
Country(s) of study	The country(s) where the study is located	Text
Town / city of study	Country in which study was undertaken	Coding
Latitude	Study location latitude as quoted in the report - or nearest town	Coding
Longitude	Study location longitude quoted in the report – or nearest town	Coding
Climatic zone	Equatorial (rainforest, monsoon, savannah), arid (steppe and desert), warm temperate, snow climate, polar climate (tundra and frost), Don't know, Other (please describe)	Coding
Solid metal type	Gold, Platinum, Silver, Iron, Cobalt, Nickel, Titanium, Aluminium, Arsenic, Bauxite, Copper, Lead, Mercury, Tin, Zinc, Other (please describe)	Coding
Mineral type	Diamond, Asbestos, Graphite, Gypsum, Phosphates, Rock salt, Uranium, Oil sands, Other (please describe)	Coding
Scale of the mining operation	Large, Medium, Small/artisanal	Coding
Legality of mining operation	Legal, Illegal, Unknown	Coding
Mine type	Surface mining, Underground mining, Highwall mining; Other (please describe)	Coding

Variable or code name	**Description**	**Data**
Mine status	Prospecting, exploration, construction, operation, maintenance, expansion, abandonment, decommissioning, reopening, repurposing	Coding
Mine description	Short textual description (possibly a quotation, identified as such) of the type of mine investigated	Coding
Ecosystem reported	Terrestrial, Forest, Grassland or pasture, Desert, Tundra, Freshwater, Marine, Mangrove, Rangeland, Mountain, Riparian, Other (please describe)	Coding
Biodiversity indicator taxa	Plant, Fish, Avifauna, Invertebrate, Reptile, Mammal, Other (please describe)	Coding
Ecosystem service studied/reported	All ecosystem services as described in (Millenium Ecosystem Assessment, 2005). This includes Provisioning services such as Food, Fibre, Fresh water, natural medicine Regulating services such as air quality regulation, water regulation, erosion regulation, water purification and waste treatment, disease regulation, paste regulation, pollination, natural hazard regulation Cultural Services such as spiritual and religious values, aesthetic values, recreation, and ecotourism Supporting services such as nutrient cycling, soil formation, primary production	Coding
Category of ecosystem services	Provisioning, regulating, cultural, supporting	Coding
Environmental/ecological change	Loss of wildlife, vegetation cover change, soil erosion, loss of endemic species, water contamination/pollution, vegetation cover change, land use change, destruction of wildlife habitats, degradation of flora and fauna, climate change, carbon emission, degradation of spawning areas and restored mining areas, degradation of protects area and key biodiversity areas, degradation of amphibian, reptile, avifauna, herpetofauna, ecosystem service, fish, forest carbon, catchment, watershed, species composition, vegetation, vegetation cover, aquatic ecosystems, species diversity, species richness, plant communities, threatened species, endemic species, biodiversity hotspot, important bird area, world heritage site,	Coding

Variable or code name	Description	Data
	forest, mountains, top soil, ecological zones, spawning areas, key stone species, pollination, ecological fragile, recreation, aesthetic, invertebrates, butterfly, riparian	
Drivers of Change/degradation	Vegetation clearance, soil or water contamination, sedimentation, degradation, hunting, downsizing, downgrading, de-gazettement, dredging, fire, hunting, logging, poisoning, soil stockpile, subsidence, river diversion, soil compaction, restoration by seeding	Coding
Predicted, potential, theoretical or observed impacts	Predicted, potential, theoretical, observed, Other (please describe)	Coding
Type of outcome	Direct (mining impacts that are caused by the proposed/ongoing mining operation occurring on site), indirect (impacts that do not result directly from mining operations, and are often produced by other entities at a different location and time)	Coding
Negative and positive impacts	Positive, negative, both	Coding
Source or sink impacts	Sink impact results from the addition of material to a receiving environment as described in (Franks et al., 2010). This includes vibration, noise, dust, pollutants, mine water, heavy metals. Source impact results from changes to existing socio-ecological system, this includes changes to surface and groundwater, biodiversity, vegetation, land use/land cover.	Coding
Mining impacts	Short textual description (possibly a quotation, identified as such) of the mining or mitigation impact investigated	Coding
Outcome measurement method (used for assessment)	GIS and remote sensing, transects, camera traps, plots, experiment, sweep nets, pitfall traps, bait lamina sticks, key informant interviews, focus groups, scenario planning, participant observation, participant mapping, household surveys, expert and practitioner knowledge	Coding
Outcome measurement method	Short textual description (possibly a quotation, identified as such) of the method of outcome measurement	Coding

Variable or code name	**Description**	**Data**
Timeframe of mining / mitigation impacts	Time since investigated activity began at the time of the study was completed (years)	Coding
Type of restoration/rehabilitation	Passive (natural succession), Active	Coding
Time of restoration/rehabilitation (years)	Insert number of years	Coding
Time of restoration/rehabilitation	Before mining, During mining, After mining	Coding
Effectiveness of restoration/rehabilitation	Successful, Unsuccessful, Unsure	Coding
How was success defined	Text description	Text
Effectiveness of restoration/rehabilitation	Text description	Text

CHAPTER FOUR

4 A global systematic review on the restoration outcomes in mining landscapes

4.1 Abstract

Restoration of degraded mining landscapes has been a top priority in recent research agenda. This chapter is built from the previous chapter (Chapter three). After looking on the impacts of mining on biodiversity and ecosystem services, this chapter was designed to understand the global efforts and effectiveness of restoration of biodiversity and ecosystem services in post-mining landscapes.

We systematically reviewed the findings of 830 publications studying restoration of the mining landscapes. Results revealed slower pace of research in restoration studies as compared to that of studying mining impacts with low average numbers of papers published per annum before and after 2000. There was a gap of at least six decades between studies on the mining impacts and restoration studies, leaving important biodiversity areas with mining legacy without scientific intervention on their recovery potential.

A total of 38 commodities were reported, with coal mining (23.5%, *n* = 195), being the most targeted commodity in restoration studies. Most studies focused on remediation experiments (43.9%, *n* = 364) to (i) identify species suitable for phytoremediation (43.7%, *n* = 159), (ii) evaluate biological components suitable for bioremediation (11.2%, *n* = 41), and other organic amendments applicable for remediation (45,1%, *n* = 164), while 26.3%, (*n* = 216) focused on reclamation, 14.9%, *n* = 124 focused on rehabilitation and 14.9%, *n* = 124 focused on restoration, with most experiments (62.4%, *n* = 479) being conducted in the greenhouse/laboratory (ex-situ), while only 37.6%, *n* = 289 reported on studies from field observation (in-situ).

The success of restoration in mining landscapes was mostly evaluated using structural diversity indicators (41.6%, *n* = 585), followed by species composition (17.1%, *n* = 195), while ecosystem functions indicators were the least studied (9.4%, *n* = 107).

To achieve effective restoration projects in mining landscapes, it is vital to develop common indicators which consider heterogeneity in geological substrates, ecosystems, and climatic conditions of the mining landscapes, to provide

consistent evaluation of the effectiveness of restoration project across the globe. In addition, standard policies should be developed and enforced to guide restoration in mining landscapes to effectively achieve the restoration targets.

4.2 Introduction

Mining plays a vital role in global economic development (World Gold Council, 2021), and in generating required minerals and materials for green technologies and sustainable infrastructure to halt climate change (Bradley, 2020; Sonter et al., 2020). However, mining landscapes across the globe are severely altered during extraction of various commodities contrary to the restoration efforts (Chen et al., 2022; Festin et al., 2019). Yet, few studies have addressed restoration in mining areas. Most studies focused on drivers of landscape degradation and forest loss, notably agricultural expansion, livestock keeping, and urban expansion (Alvarez-Berríos and Aide, 2015; Hosonuma et al., 2012), as mining is considered a less prominent driver (Kissinger et al., 2012).

Restoration interventions in mining landscape is necessary (Mansourian et al., 2017), to return the degraded ecosystems to their original state (Yao et al., 2019), and to slow down with the ongoing degradation processes (Montanarella, 2016). However, the objectives and outcomes for ecological restoration in mining landscapes are still debatable (Ehrenfeld, 2000; Macdonald et al., 2015). Thus, there is unclear defined terminology to be used when dealing with alteration caused by mining activities, instead terminologies such as remediation, reclamation, restoration, and rehabilitation (Table 4), are commonly used (Lima et al., 2016a). While the expected goal of restoration is to return a mined site to its original landscape or to a condition similar with the pre-mining condition (Rocha-Nicoleite et al., 2018), most implemented restoration technique do not achieve that, instead, the focus has been either to deal with contaminants, returning the site to more human use (Lima et al., 2016b) or returning the site to its original functions but not necessarily the original vegetation, landscape or ecological functions (Powter et al., 2012). This trend puts existence of natural ecosystems into jeopardy as more are transformed and replaced by either monoculture or exotic species.

In response to global issues of land degradation affecting over 1.5 billion people and over 23% of the globe's terrestrial area (Stavi and Lal, 2015), various international Landscape Restoration Initiatives have been launched to restore degraded areas across the globe, with much emphasis on returning the ecological integrity of the degraded ecosystems to support biodiversity, enhance human wellbeing and mitigate climate change (McLain et al., 2021; Stanturf et al., 2017). One of the initiatives is The Bonn Challenge which aims to restore 350 million hectares of degraded landscape by 2030 (https://www.bonnchallenge.org). The Bonn Challenge is aligned with other global initiatives, including Sustainable Development Goals (SDGs), the Land Degradation Neutrality (LDN) goal, and the Paris Climate Change Agreement. Other local initiatives targeting specific regions including The World Resources Institute's 20 × 20 Initiative for Latin America, and the AFR100 initiative for Africa (McLain et al., 2021). All the initiatives focus on forest landscape restoration (FLR) approach to achieve both conservation objectives and sustainable management (Stanturf and Mansourian, 2020).

While mining landscapes restoration attempts has been influenced by global restoration initiatives (Mansourian et al., 2017) such as the ambitions to achieve net zero carbon emission by 2050 through avoiding destruction of natural ecosystems or restoration of the degraded ecosystems in mining landscapes, such initiative requires clear restoration objectives on the ground. Restoration practices attempted by mining companies are often carried out only for compliance with legal requirements (Martins et al., 2022), lacking detailed restoration objectives and methods as described in the UN Decade on Ecosystem Restoration (FAO et al., 2021), leading to unsuccessful restoration projects (Martins et al., 2022). Hence, mining companies must be both technical and financially responsible for these restoration projects (Chen et al., 2022; Martins et al., 2022).

While the literature on restoration success in mining landscapes has grown in recent years, there have been few global syntheses on the potential for restoration in mining landscapes. We used systematic review approach to investigate the four specific questions: -

i. What is the effectiveness of restoration measures in mining landscapes?
ii. To what extent do restoration projects in mining landscapes adhere to the principles for ecosystem restoration as defined by UN Decade 2021-2030?
iii. What are the variations of restoration projects in mining landscapes across the globe?
iv. What are future research priorities to overcome gaps in knowledge for restoration in mining areas?

4.3 Materials and Methods

4.3.1 Data collection

Our review process followed systematic review of the Collaboration for Environmental Evidence Guidelines and Standards for Evidence Synthesis in Environmental Management (Collaboration for Environmental Evidence, 2018). We used the highly recommended PICO tool (Methley et al., 2014). Thus, the review question has elements of Population, Intervention, Comparator, Outcome (PICO). Detailed method is described in the previous chapter.

4.3.2 Data analysis

Each compiled data was coded in Microsoft Excel and for those with multiple response, a binary data was created. We conducted descriptive analysis to produce trends, tables, figures, and maps. We extracted coordinates of each studied location using google maps to create point locations to produce distribution maps per extracted commodity.

4.4 Results and discussion

4.4.1 Temporal evolution

The number of studied evaluating the potential for restoration in mining landscapes has been increasing over the years, from an average of 4 papers published per annum before 2000 to 36 papers per annum after year 2000 (Figure 12). In addition, there were fewer studies on restoration studies compared to studies focusing on mining impacts as indicated by low average numbers of papers published per annum before and after 2000.

Studies evaluating mining impacts on biodiversity (started in 1922 see the previous chapter) compared to studied evaluating the potentials for restoration in mining landscape which started in 1981. For nearly six decades, biodiversity in mining landscapes has been left without scientific intervention on their potential recovery (Batty, 2005; Burke, 2008a; Thornton, 1996), This has attracted accumulation of enormous mining wastes for decades, with increased costs of restoration by impairing selection of the scope and objectives of restoration (Burke, 2008b). However, restoration efforts started to emerge in 1981 across the globe and since then as mining activities across the globe increased, so is the number of restoration research in mining landscapes (Navarro-Ramos et al., 2022).

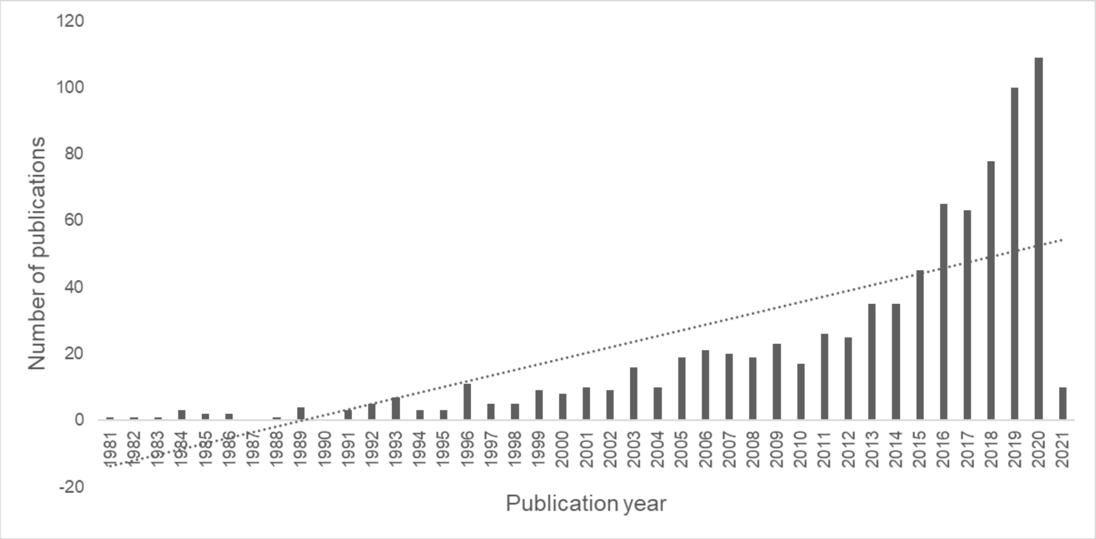

Figure 12: Growth in the number of restoration studies in mining impacted areas per annum between 1981 and March 2021.

4.4.2 Geographic distribution

Studies focusing on restoration of mining landscapes were distributed across five continents (Figure 13). Asia (32.2%, *n* = 267) and Europe (24.8%, *n* = 206) were most studied, followed by North America (21.1*%, n* = 175), Oceania (10%, *n* = 80), South America (7.5%, *n* = 62) and Africa (4.5%, *n* = 40). These studies were distributed across 68 different countries (Figure 12), but the majority (19.1%, *n* = 160) were reported in China, followed by USA (13.5%, *n* = 113), Australia (8.7%, *n* = 173), and Spain (7.6%, *n* = 64).

Most of the studies were conducted at specific sites (67.1%, *n* = 557), followed by national scale (30.1%, *n* = 250) and regional scale (2.1%, *n* = 18), while only (0.5%, *n* =4) studies were conducted at global scale.

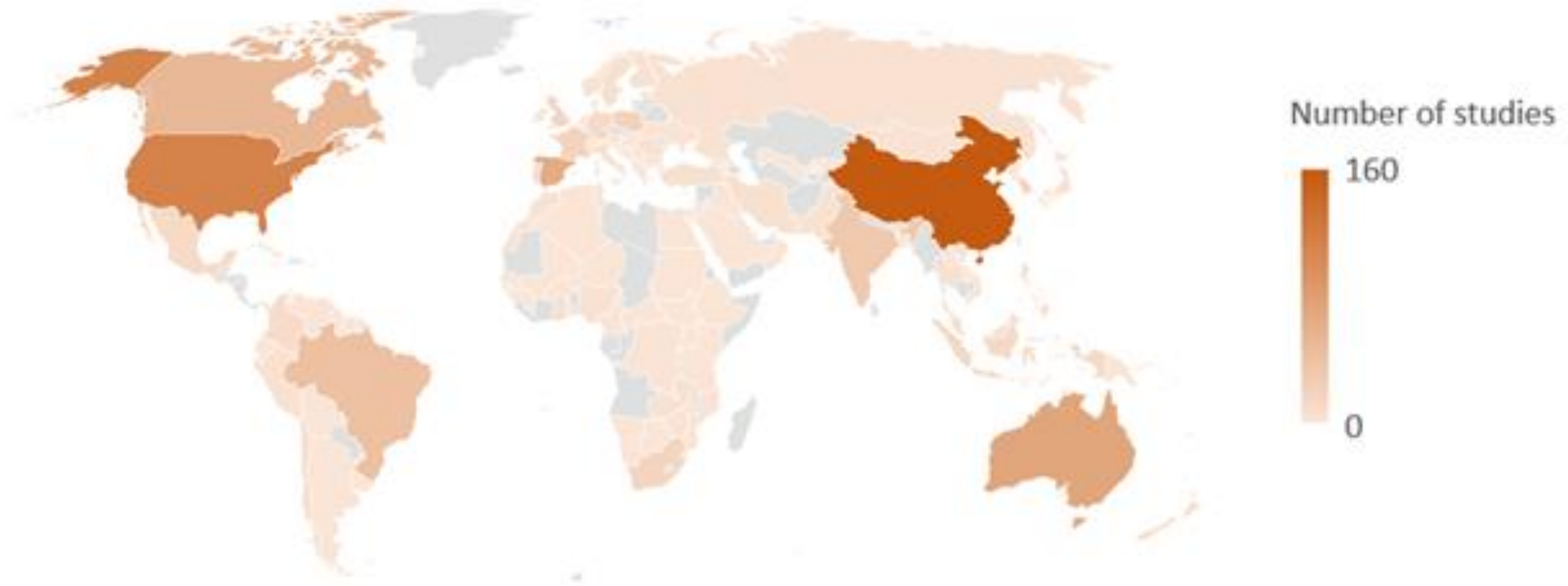

Figure 13: Map showing number of published restoration studies per country.

4.4.3 Publication

Most studies were peer-reviewed articles (97.2%, *n* = 807), published in a wide range of journals (*n* = 350). The remaining 2.8%, *n* = 23 were conference papers and proceedings. The journals that dominate the literature on this topic are Restoration Ecology (16.3%, *n* = 135), Science of the Total Environment (5%, *n* = 41), followed by Chemosphere and Water, Air, and Soil Pollution, both with (2.7%, *n* = 22). While most of the papers were accessed through university subscription to the specific journals (70.6%, *n* = 586), only few papers were open access (29.3%, *n* = 244). However, all these journals are highly reputed with high impact factors publishing wide range of environmental topics.

4.4.4 Commodity studied

A total of 38 commodities were reported. The top ten reported commodities are coal (23.5%, *n* = 195), lead (12%, *n* = 99), copper (10.6%, *n* = 88), zinc (10.6%, *n* = 88), gold (7.7%, *n* = 64), bauxite (6.1%, *n* = 51), silver (4%, *n* = 33), oil sand (3.6%, *n* = 30), iron (3.5%, *n* = 39) and sand (3%, *n* = 25); (Figure 14). 15.6%, *n* = 130 of the studies did not report the type of commodity studied. There was a big variation between selected commodities for studying mining impacts and those selected for restoration studies.

While high number studies on mining impacts were on gold, areas of coal mining were highly studies for restoration potential. There is no clear explanation for what is causing high number of researchers to direct their restoration studies to coal mining and not gold mining despite the high number of studies evaluating impacts of gold mining as opposed to coal mining. However, this can be attributed by the enthusiasm of the success of their restoration projects as most restoration in gold mining areas has proven failures. Gold mining sector is dominated by large scale and artisanal and small-scale mining (Patel et al., 2016; Pedersen et al., 2019), as opposed to few existing evidence of artisanal and small-scale coal mining (Blahwar et al., 2012; Lahiri-Dutt, 2003). In addition, methods applied by artisanal and small-scale gold mining induce depletion of soil nutrients (Timsina et al., 2022), and can contaminate wide range of soil by mercury thereby limiting regeneration and plant growth (Ogola et al., 2002), causing complex recovery of mining landscapes (Chambi-Legoas et al., 2021). For example, forest regeneration following small-scale gold mining was slow or close to zero in the Suriname (Peterson and Heemskerk, 2001), and Guyana (Kalamandeen et al., 2020) in the Amazon compared to regeneration following other land uses.

For gold mining landscapes to show successful restoration performance, there should be backfilling of mined pits, topsoil conservation, and the preservation of local seed sources (Timsina et al., 2022), and remediation of contaminated soil (Norris et al., 2022). These activities have cost implications and researchers may want to avoid that and opt for more cheaper restoration projects such as in coal mines.

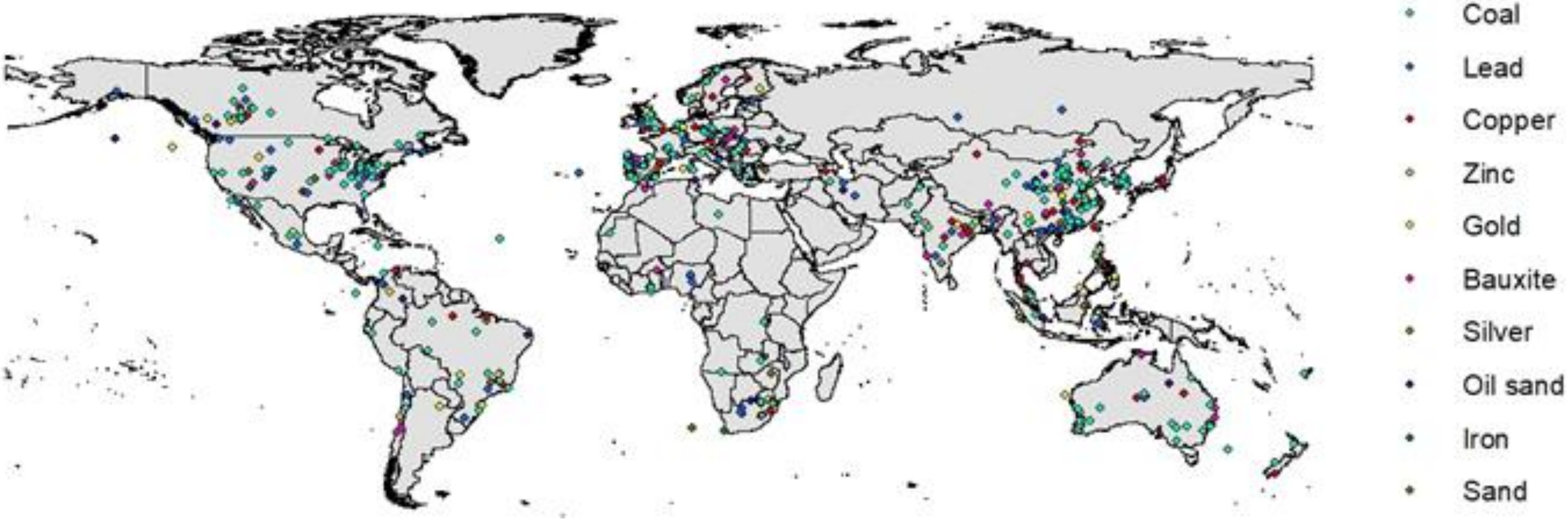

Figure 14: Distribution commodities studied across the globe delineated by studies on restoration

4.4.5 Terminologies used to describe restoration progress in mining landscapes

It is important to understand the different terms that are used when dealing with mining disturbed landscapes. These are remediation, reclamation, restoration, and rehabilitation. These terminologies can be used interchangeably, and their expatiations varies between actors (Festin et al., 2019; Lima et al., 2016). The following table provides definition of all terminologies as defined by (FAO et al., 2021).

Table 4: Major categories of restorative activities in mining landscapes

Restorative category	Restorative category defined	Result
Reclamation	Reduction of negative environmental and societal impacts, such as pollution and unsustainable resource use and management. The aim is to stabilise land via a series of integrated operations (Lima et al., 2016).	Full recovered ecosystem
Remediation	Removal of contaminants, pollutants and other threats, Remediation aims at using physical, chemical, or biological action on removing pollution or contamination from water or soil (Beames et al., 2014).	Decontaminated water or soil
Rehabilitation	Rehabilitation of ecosystem functions and services in highly modified areas such as former mining sites and degraded production systems. Its focus resembles that of restoration on using pre-existing ecosystems as references (Rosa et al., 2020).	Original ecosystem or a more human use ecosystem
Restoration	Ecological restoration, which aims to remove degradation and assists in recovering an ecosystem to the trajectory it would be on if degradation had not occurred, accounting for environmental change (Morrison and Lindell, 2011).	Full restored original ecosystem

4.4.6 State of evidence of the existing restoration progress in mining landscapes across the globe

There has been substantial increase in number of studies reporting various restorative activities across the globe (Figure 12). However, the focus has mostly been on remediation experiments (43.9%, *n* = 364) to (i) identify species suitable for phytoremediation (43.7%, *n* = 159), (ii) evaluate biological components suitable for bioremediation (11.2%, *n* = 41), and other organic amendments applicable for remediation (45,1%, *n* = 164), while 26.3%, *n* = 216 focused on reclamation, 14.9%, *n* = 124 focused on rehabilitation and 14.9%, *n* = 124 focused on restoration.

Most studies (92.5%, *n* = 768) evaluated the potential of restoring mining landscapes by active restoration while only 7.5%, (*n* = 62) evaluated the potential for passive restoration. Most of the studies (62.4%, *n* = 479) that evaluated the potential of active restoration to recover the degraded mining landscapes were conducted in the greenhouse/laboratory (ex-situ), while only 37.6%, *n* = 289 reported on studies from field observation (in-situ). In addition, most studies (57.6%, *n* = 478) evaluated the potential to restore mining impacted soil, 8.4%, *n* = 70, evaluated the potential to recover mining impacted aquatic ecosystems and the rest of the studies (34.0%, *n* = 282) evaluated the potential for vegetation recovery in mining impacted landscapes. Additionally, all studies that reported in-situ restoration activities (i.e., 37%) did not specify scales of the reported projects (i.e., number of hectors covered by specific restoration projects), which pose uncertainties for the effectiveness of restoration in mining landscapes.

Restorative activities differ in approach and end target (Table 4). The end goals ranges from long-term stabilization of landforms and soil (Díaz-García et al., 2020), partial or full restoration of the original ecosystem to sustain wildlife and human wellbeing (Hendrychová et al., 2020), to elimination and or prevention of pollution in adjacent ecosystems (Gil-Jiménez et al., 2021). While most studies reported on the potential for active restoration of mining landscapes, the few existing evidence on passive restoration reported on substantial recovery of degraded landscapes. However, passive restoration in mining landscape shows little recovery progress of the degraded mining landscape (Gomez-Ros et al., 2013; Ruggles et al., 2021), or can take very long time up to 35 years to start showing results (Koch and Hobbs, 2007; Nichols and Grant, 2007; Ruggles et al., 2021)

To achieve successful restoration of mined landscapes, active restoration to assist the ecosystem recovery is highly recommended (Sandell et al., 2018). Intervention should include, backfilling of mined pits, tailing storage facilities and all contaminated areas (Brown, 2005; Timsina et al., 2022), management of topsoil as a crucial component for vegetation restoration (Amir et al., 2022; Bizuti et al., 2021; Sheoran, 2010), and most importantly is the preservation of local seed sources (Timsina et al., 2022). However, the fact that large numbers of studies were experiments in the greenhouse or laboratory, implies fewer restoration projects exists in the actual degraded mining landscape, and if they do exist there is lack of monitoring and reporting to provide lessons for other projects to learn.

4.4.7 Selection of indicators to measure restoration effectiveness in mining landscapes

A total of 58 indicators were identified in this systematic review, and further grouped into 5 categories following (Martins et al., 2022: Cadier et al., 2020) (Table 5). The number of selected indicators per study to evaluate restoration success varied between 1 and 12. The most selected indicators were in structural diversity (41.6%, *n* = 585), followed by species composition (17.1%, *n* = 195), absence of threats (11.7%, *n* = 134), physical-chemical condition (10.5%, *n* = 120), and ecosystem functions (9.4%, *n* = 107). The most selected sub-categories of indicators were plant diversity (11.1%, *n* = 126), reduced pollution (10.5%, *n* = 120), plant biomass (10.3%, *n* = 118), vegetation coverage (9.6%, *n* = 110), tree height (9.1%, *n* = 103), and water quality (7.9%, *n* = 90).

While restoration is a vital approach to recover degraded mining landscapes (Koch, 2007), it requires systematic evaluation through selected key indicators to measure the effectiveness of the restoration projects (Browne et al., 2018; Cadier et al., 2020). Restoration indicators provide the basis for the desired outcomes of the ecosystem recovery (Martins et al., 2022) which can be compared with reference sites (Wortley et al., 2013) or to a hypothetical restored habitat, or other habitats of conservation concern (Brewer and Menzel, 2009). However, there is a lack of common indicators to measure restoration success in mining landscapes (Cadier et al., 2020), which hinders the understanding of the ecosystem restoration process (Barbosa et al., 2022).

Most of the restoration projects selected structural diversity and species composition indicators to evaluate restoration success because they recover fast (Listopad et al., 2018; Teixeira et al., 2020) and they are easy to measure (Cadier et al., 2020; Sun and Zhou, 2018) as opposed to ecosystem function indicators (Gibbons and Freudenberger, 2006). In this study, indicators on ecosystem functions were the least evaluated group, with most focus on water retention capacity (2.7%, *n* = 31), nutrient cycling (2.6%, *n* = 29) and carbon sequestration (0.9%, *n* = 10). Although they are much ignored, they are more important indicators to assess the recovery of ecosystem services (Bullock et al., 2011;

Shimamoto et al., 2018), as a primary objective of restoration (Cadier et al., 2020). Thus, for restoration projects to be successful, a stepwise evaluation of ecosystems functions is recommended (Pander and Geist, 2013).

Nevertheless, increased structural diversity and species composition are commonly considered as indicators of restoration success (Koch, 2015; Navarro-Ramos et al., 2022), evaluating ecosystem function indicators can be a significant way to measure restoration effectiveness (Cadier et al., 2020), for which it signifies the resilience of the restored ecosystem from its underlying stressors (Wolff et al., 2019). For example, it was found that ecosystems recovering from metal pollution have lower resilience to other non-metal stressors (Wolff et al., 2019). Thus, ecosystem function indicators are significant determinant of restoration targets (Dey and Schweitzer, 2014). In addition, by considering ecosystem function indicators among others, will be vital path towards achieving the goals set forth by UN Decade on Ecosystem Restoration by restoring ecosystems that supports biodiversity, provide ecosystem services to support human wellbeing and increasing the efficacy of climate change mitigation (FAO et al., 2021).

Table 5: List of selected indicators in evaluating restoration success in mining landscapes

Indicator category	Indicator subcategory	Number of studies	Overall %
Structural diversity	Plant biomass	10.3%, *n* = 118	41.6%, *n* = 585
	Vegetation coverage	9.6%, *n* = 110	
	Tree height	9.1%, *n* = 103	
	Bacterial structure	7.3%, *n* = 83	
	Fauna structure	5.5%, *n* = 63	
	Vegetation structure	4.1%, *n* = 48	
	Macroorganisms biomass	2.8%, *n* = 32	
	Basal area	0.5%, *n* = 6	
	Food web	0.4%, *n* = 5	
	Microbial structure	0.4%, *n* = 5	
	Algal structure	0.3%, *n* = 4	
	Leaf area index	0.3%, *n* = 5	
	Macroinvertebrate biomass	0.2%, *n* = 2	

Indicator category	Indicator subcategory	Number of studies	Overall %
	Ant structure	0.1%, *n* = 1	
	Phytoplankton biomass	0.1%, *n* = 2	
Species composition	Plant diversity	11.1%, *n* = 126	17.1%, n = 195
	Presence of soil microfauna	2.1%, n = 23	
	Richness of native plant species	0.7%, *n* = 8	
	Presence of birds	0.6%, *n* = 7	
	Presence and diversity of plant forms other than trees	0.3%, *n* = 4	
	Benthic invertebrates	0.26%, *n* = 3	
	Invertebrate community	0.26%, *n* = 3	
	Vertebrate communities	0.26%, *n* = 3	
	Bacterial communities	0.2%, *n* = 2	
	Epilithic communities	0.2%, *n* = 2	
	Fish communities	0.2%, *n* = 2	
	Fungi community	0.2%, *n* = 2	
	Herbaceous Species Composition	0.2%, *n* = 2	
	Presence of mammals	0.2%, *n* = 2	
	Earth worm	0.1%, *n* = 1	
	Macroinvertebrates density, diversity, and richness	0.1%, *n* = 1	
	Presence of insects	0.1%, *n* = 1	
	Presence of plant species from different successional groups	0.1%, *n* = 1	
	Presence of reptiles	0.1%, *n* = 1	
	Presence of soil mesofauna	0.1%, *n* = 1	
Absence of threats	Reduced pollution	10.5%, *n* = 120	11.7%, *n* = 134
	Reduced Soil erosion	0.8%, *n* = 9	
	Absence of biological threats	0.3%, *n* = 3	

Indicator category	Indicator subcategory	Number of studies	Overall %
	Reduced Plant metal uptake	0.2%, *n* = 2	
Physical-chemical condition	Water quality	7.9%, *n* = 90	10.5%, *n* = 120
	Organic matter content	2.1%, *n* = 23	
	Soil structure	0.3%, *n* = 3	
	Soil fertility	0.2%, *n* = 2	
	Soil nutrient	0.1%, *n* = 1	
	Soil quality	0.1%, *n* = 1	
Ecosystem function	Water retention capacity	2.7%, *n* = 31	9.4%, *n* = 107
	Nutrient cycling	2.6%, *n* = 29	
	Carbon stock sequestration	0.9%, *n* = 10	
	Germination rate	0.9%, *n* = 10	
	Protection from soil erosion or sedimentation processes in rivers and streams	0.9%, *n* = 10	
	Regulation of water regimes	0.7%, *n* = 8	
	Avifaunal recolonisation	0.2%, n = 2	
	Mite communities' colonization	0.2%, n = 2	
	Air quality regulation	0.1%, *n* = 1	
	Plant regeneration	0.1%, *n* = 1	
	Succession for natural forest communities	0.1%, *n* = 1	
	Water yield	0.1%, *n* = 1	
	Toxic element sorption	0.1%, *n* = 1	

4.4.8 State of evidence of the adherence to the principles for ecosystem restoration as defined by UN Decade 2021-2030 in mining landscapes.

The process of halting and reversing degradation through various restorative activities can yield improved ecosystem services and biodiversity in mining landscapes (Kolar et al., 2021). However, restoration efforts in mining landscapes have been ineffective due to lack of proper restoration design (Lindenmayer, 2020), and monitoring principles (Baldera et al., 2018) to quantify restoration success. Well-designed restoration can contribute to the UN sustainable development goals, the goals of the Rio conventions and can support human well-being (Edwards et al., 2021; FAO et al., 2021). To achieve that, adoption of the principles that underpin the full set of ecosystem restorative activities applicable across all sectors, biomes and regions put forward by the UN Decade (FAO et al., 2021), is inevitable. UN Decade principles referred here is that produced by FAO, IUCN CEM & SER. 2021.

The following is the list of UN Decade principles for ecosystem restoration. The

i. Ecosystem restoration contributes to the UN Sustainable Development Goals and the goals of the Rio Conventions;
ii. Ecosystem restoration promotes inclusive and participatory governance, social fairness and equity from the start and throughout the process and outcomes;
iii. Ecosystem restoration includes a continuum of restorative activities;
iv. Ecosystem restoration aims to achieve the highest level of recovery for biodiversity, ecosystem health and integrity, and human well-being;
v. Ecosystem restoration addresses the direct and indirect causes of ecosystem degradation;
vi. Ecosystem restoration incorporates all types of knowledge and promotes their exchange and integration throughout the process;
vii. Ecosystem restoration is based on well-defined short-, medium- and long-term ecological, cultural and socio-economic objectives and goals;
viii. Ecosystem restoration is tailored to the local ecological, cultural and socioeconomic contexts, while considering the larger landscape or seascape;
ix. Ecosystem restoration includes monitoring, evaluation and adaptive management throughout and beyond the lifetime of the project or programme;
x. Ecosystem restoration is enabled by policies and measures that promote its long-term progress, fostering replication and scaling-up.

Here we discuss how different restoration attempts in mining landscapes have adhered to the principles for ecosystem restoration as defined by UN Decade 2021-2030

Principle 1 of the UN Decade put an emphasis for ecosystem restoration to contribute to the UN sustainable development goals and the goals of the Rio conventions. While 62.4%, (*n* = 479) of the restorative activities were conducted at experimental green house or in the lab, only 37.6%, n = 289 were looking at the restoration success on the impacted mining areas. However, these studies were conducted at a small scale, and they were yet to take landscape restoration approach. Thus, these studies looked on how to restore the pre-mining ecosystems and increase the productivity of the mined landscapes, by establishing conditions for successful restoration such as improving soil properties (Lwin et al., 2018). Other studies looked on the best ways to clean mine impacted soil and water using phytoremediation (Gebru, 2019) or bioremediation (Afonso et al., 2020). Therefore, these large group of studies did not contribute to any of restorative activities but rather experimenting on proper restoration approaches on mining landscapes. The other remaining studies (37.6%, *n* = 289) that looked at the field performance were conducted in small scale but adhered to the principle 1 of the UN decade by contributing to UN SDGs.

There was variation of the contribution of these restorative activities to the UN sustainable goals. While restoration, rehabilitation and reclamation contributed much to Climate Action (SDG 13) and Life on Land (SDG 15), remediation contributed much to Clean Water and Sanitation (SDG 6). All restorative activities were aligned to improving different mined ecosystems to achieve Zero Hunger (SDG 2) and provision of Good Health and Wellbeing (SDG 3) as shown in Figure 15. There were some few peculiar cases such as the Jarrah Forest of Western Australia, which focused on restoring the landscape after bauxite mining to establish a self-sustaining ecosystem (Grant, 2006; Tibbett et al., 2020) setting a good example of long-term restoration practices that covers relatively large area. (Gould, 2011).

Generally, effective restoration projects are the vital paths to achieve other global goals and initiatives such Rio Conventions, United Nations Convention to Combat Desertification (UNCCD) and United Nations Framework Convention on Climate Change (UNFCCC) through improvement of biodiversity, increasing carbon sequestration and climate mitigation, and improving land stability by avoiding land degradation.

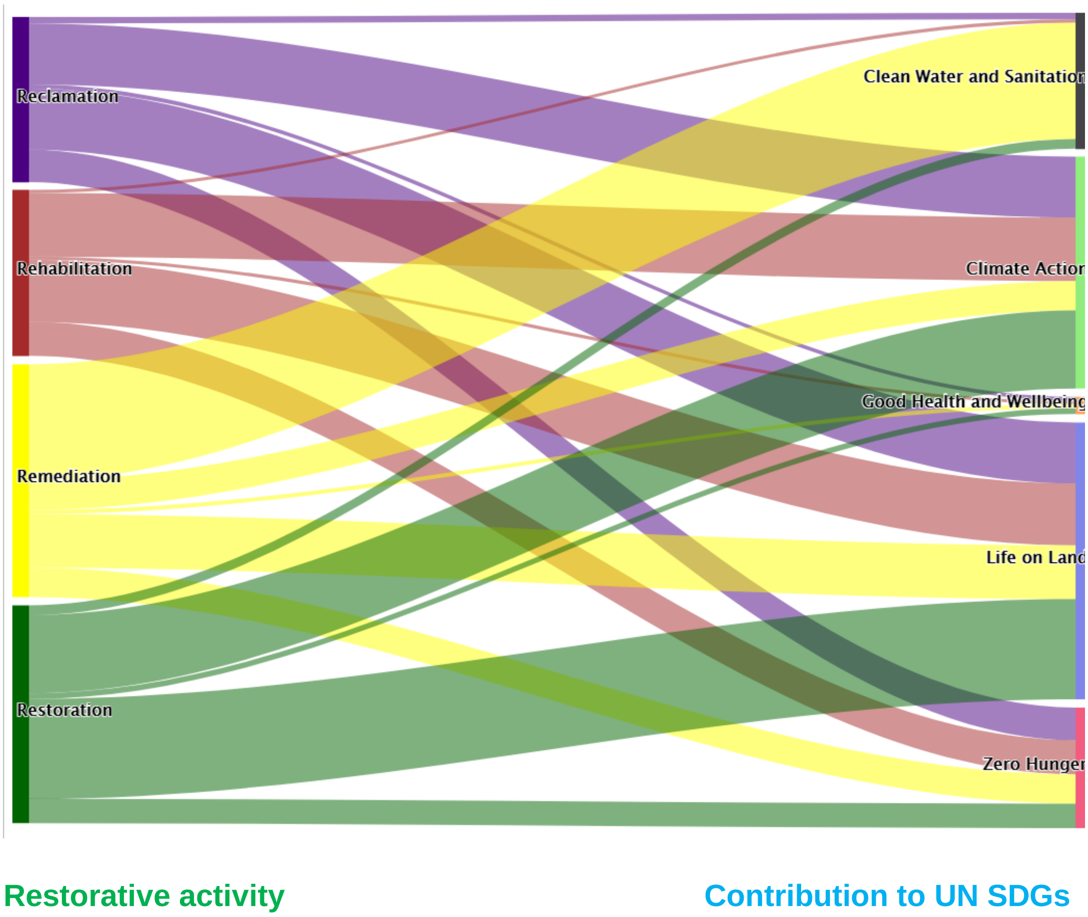

Figure 15: Individual contribution of restorative activities to the achievement of UN SDGs.

Principle 2 of the UN decade put an emphasis on the stakeholder's engagement during the whole restoration process of the mined landscape from planning to monitoring, to ensure inclusive participation for achieving the desired outcomes of restoration (FAO et al., 2021). Of all reviewed studies, only 4% indicated the engagement of the stakeholders in the rehabilitation planning stages, which could be explained by the nature of the studies, most of which were research based. Overall, in the reviewed literature there is little evidence of ongoing restoration project that aim to restore the original ecosystems, rising concerns on the future natural wilderness as most of the mined landscapes are not restored to their original ecosystems or their original composition is changed to other monocultural ecosystems. Ignoring the principle 2 of the UN decade could impair restoration projects by creating mismatch between community desires and restoration projects (Höhl et al., 2020), which can also lead to failures of the restoration projects and continued degradation to targeted ecosystems (Gornish et al., 2021). There is an overlap of targets between principle 2 and **principle 6**, as they both emphasise on stakeholders' engagement while the only highlight in the principle 6 is an element of knowledge sharing among stakeholders.

Principle 3 put much emphasis on including a continuum restorative activity while **principle 4** emphasizes on achieving the highest level of recovery for biodiversity, ecosystem health and integrity, and human well-being. The two principles are discussed together because they are interdependent. Although some of the restorative activities may overlap in their approaches and end goals such as reclamation and rehabilitation (Lima et al., 2016a), as discussed in section 4.4.5, there is lack of evidence on the combination of more than one restorative activity to achieve wide range of restoration from remediation of pollutants to full recovery of the original ecosystem (Lima et al., 2016a). Thus, there is lack of evidence on how restoration projects can deal with long-term mining legacies whose impacts extend far beyond mining leases and can be felt by the surrounding communities and ecosystems for a long time after the mining operations. While progressive rehabilitation projects by large scale companies only focuses onsite and are conducted to fulfil legal requirements to environmental compliance and mostly do not aim to achieve the principle 4 of the UN decade, there is lack of evidence on how artisanal mined landscape are put into long term restoration plans due to the scattered nature of the artisanal mines (Byizigiro et al., 2015) and lack of effective regulation (Adu-Baffour et al., 2021; Edwards et al., 2014; Hilson, 2002). Consequently, we are in the verge of losing nature in the wake of mining operations because (i) only direct impacted areas are considered by large scale companies leaving out large area of the altered landscape by indirect impacts and (ii) there is lack of restoration plans to restore landscapes altered by artisanal and small-scale mining activities.

There is also a huge discrepancy between restoration efforts in mining landscapes and the goal to adhere to principle 5, to address the direct and indirect drivers of ecosystem degradation. We found all 36.7% of the restoration studies were driven by direct impacts of mining (Figure 16). Although indirect impacts of mining are somewhat recognized (Sonter et al., 2017, 2014), the lack of evidence on how these impacts are dealt in restoration plans of the mining landscapes is leaving loopholes for further ecosystem degradation (FAO et al., 2021). Wide range of indirect impacts occurs beyond mining leases due increase in population that increase dependency on the natural ecosystems (Edwards et al., 2014). To execute successful landscape restoration in these areas, indirect drivers should also be dealt by provision of incentives to restrict activities that may drive further degradation (Wainaina et al., 2021). Currently, there is lack of inclusion of this element in restoration attempts of the mining areas which can lead to failures of these efforts to achieve the main goal of restoration.

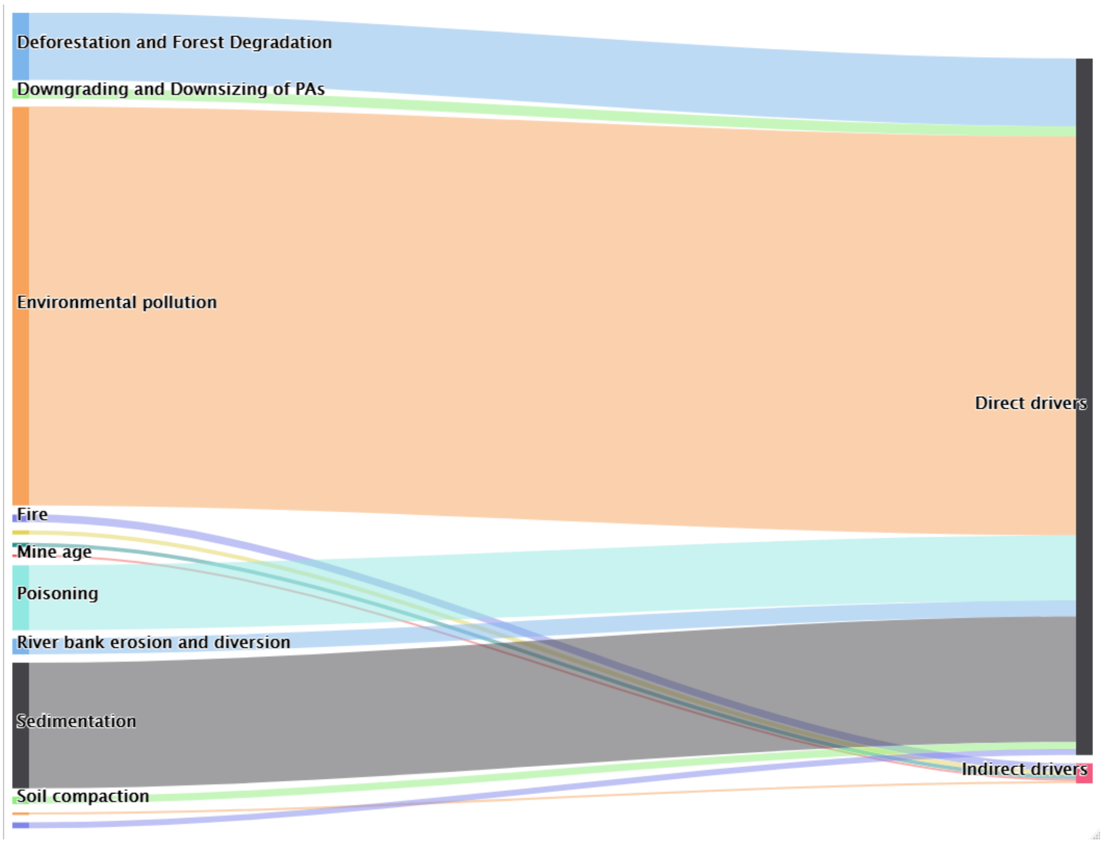

Figure 16: Showing direct and indirect drivers of change in mining landscapes. There were more studies on direct impacts of mining on the environment, with pollution being ranked as the most important driver of ecosystem change affecting terrestrial, freshwater, marine habitats, and the atmosphere.

In adhering to principle 7 of the UN decade, mining restoration projects and programmes, should encompass realistic and achievable short, medium, and long-term restoration goals. There is little evidence in the literature on how mining companies establish long term restoration goals. Although, short and medium restorative activities are implemented through progressive rehabilitation in mining impacted areas by mining companies, lack of proper restoration plans before the actual mining is undermining progressive restoration projects leading to complete waste of money and time. Successful restoration requires a long-term plan accompanied with scientific research and monitoring (Commonwealth of Australia, 2006). This will also enable restoration projects in mining landscapes to successfully adhere to principle 9 of the UN decade.

Meanwhile, the lack of evidence on how long-term restoration projects are guided and regulated (Kragt and Manero, 2021) as per principle 10 of the UN decade, and the increasing advocacy for mining companies to rehabilitate mine sites to different land uses and not the original ecosystems (Manero et al., 2020) is creating global future with lack of native ecosystems. Restoration attempts in mining landscapes must be strictly mainstreamed and implemented in national and international research strategies (Festin et al., 2019; Macdonald et al., 2015). Although returning the mined landscapes into pre-disturbance conditions may seem unrealistic (Hernandez-Santin et al., 2020; Kragt and Manero, 2021), proper planning, designing, high investment and high coordination among stakeholders in restoration projects can create desirable outcomes (Lamb et al., 2015). One example that gives hope that returning of the original ecosystems is possible is the restoration of Jarrah Forest (Koch, 2007). The focus on restoration in mining areas should also adhere to principle 8 by expanding their ambitious restoration projects to landscape level. This is currently lacking as only site level restoration is being practiced as discussed in the previous sections.

4.4.9 Variation of restoration studies across the globe

While studies of mining impacts are fairly represented across the globe, restoration studies had uneven representation. Most restoration studies were reported among developed countries, whereas less studies were observed from developing countries. 19% of all restoration studies were reported from China, 13.5 from USA, 9% from Australia and 8% from Spain. Restoration studies in developing countries are represented by Brazil (5%) and South Africa (2%). Although, good landscape restoration projects in mining impacted areas may exist on the less studied countries, and they are not known because they are not reported; we infer that restoration studies are attributed by existing restoration projects in specific countries.

One of the big reasons for the uneven distribution of restoration studies which implies lack of restoration projects in mining landscapes, is existence of stricter environmental regulations for restoration programmes after mining projects in developed countries, while there is lack of the same in developing countries (Cao, 2007), and if they exist there is lack of strict enforcement (Festin et al., 2019). For example, according to the World Gold Council (2018), Tanzania is one among high gold producers after South Africa and Ghana, accounting for approximately 1.3% of total global production. However, no evaluation of any restoration success has been conducted yet (Theonest Shwekelela, 2022), while more investment in mining sector have been observed for the past decade adding more pressure to biodiversity and wider environment (Muhanga and Urassa, 2018). Despite the existing regulations in Tanzania, such as *Environmental Management Act, 2004 (No. 20 of 2004)*, there is lack of enforcement and follow up for rehabilitation and restoration programmes. Apart from that, effective restoration programmes need strong collaboration between mining companies and the government, but the government on *Environmental Management Act, 2004 (No. 20 of 2004)* is detaching to collaborate in these projects by stating "*Upon expiry of a project or undertaking stipulated under the Second Schedule to this Act, the proponent or operator shall, at his own cost undertake safe decommissioning, site rehabilitation and ecosystem restoration before the closure of the project or undertaking*". Regulations should be made to strengthen the collaboration among stakeholders as per principles of the UN decade to execute effective restoration projects in mining landscapes.

4.5 Conclusion

This study has found limited attention given to degraded mining landscapes. Most of the studies were looking on the ways to restore, rehabilitate, remediate or reclamate mining landscapes through conducting ex-situ experiments, leaving the actual degraded mining landscape unattended. While there is increasing global studies on mapping the current and future threats of mining on various ecosystems (Durán et al., 2013; Sonter et al., 2020; Wanghe et al., 2020), there has been few similar studies to prioritise restoration in mining landscapes. Mapping of priority areas degraded by mining for restoration is highly needed to halt degraded landscapes (Festin et al., 2019).

Future restoration studies should also move from experiments in the lab and start to focus on experimenting the actual degraded landscapes for which it can define trajectories of restoration targets (Wolff et al., 2019). Restoration projects in mining areas should also adhere to principles of ecosystem restoration when planning for restoration projects (FAO et al., 2021), which are largely ignored. These principles for ecosystem reforestation are comprehensive guidelines on integrating carbon stocking, biodiversity conservation, human well-being (Brancalion and Chazdon, 2017). Global initiatives on restoration of degraded mining landscapes should also prioritise degraded mining landscapes as vital ecosystems to be restored by identifying biodiversity hotspots.

Ecosystem restoration requires long term monitoring of the selected indictors to predict the time required for degraded ecosystem to be restored (Leps et al., 2016). However, when selecting indicators to assess restoration effectiveness, ecosystem function indicators must be one among the key selected indicators on evaluating restoration success (Cadier et al., 2020; Wolff et al., 2019). In addition, there is a need to develop common indicators which considers heterogeneity in geological substrates, ecosystems, and climatic conditions of the mining landscapes (Gwenzi, 2021). This can provide consistent evaluation of the effectiveness of restoration project across the globe.

To achieve all the above, it is vital to develop standard policy to guide restoration in mining landscapes (Zedler et al., 2012). This goes inline to making sure that, the developed policies are enforced to effectively achieve the restoration targets (Bradley, 2020). While, developing countries are known either for weak legislation or poor enforcement to guide restoration projects in mining areas (Bradley, 2020), initiation of global restoration policy, just like other restoration initiative such as the Bonn Challenge, will provide a steppingstone towards achieving the goal of restoration in mining landscapes.

4.6 References

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CHAPTER FIVE

5 Evaluating the environmental impacts of commercial gold mining from 1990-2019 for six districts in Tanzania

5.1 Abstract

Mining is important for economic development but can cause significant impacts such as changes in land use. Quantifying land use change dynamics in mining landscapes is critical in documenting and tackling aspects such as biodiversity loss and impact on ecosystem service delivery, particularly in areas undergoing rapid land use change due to gold mining. Here, we use a mixed method approach to analyse the dynamics of land use change in six districts with commercial gold mines and six districts without commercial gold mines across north Tanzania using Landsat images from 1990 to 2019. We further investigate changes in ecosystem service provisioning and availability, and possible future impacts of these changes.

We show how commercial gold mines have escalated the rate of forest loss, impacted aquatic ecosystems, increased cropland, and settlements, and attracted artisanal and small-scale mining adjacent to mine leases. The highest rate of land use change was recorded between 2000 and 2010 in the districts with commercial gold mines. Land use change was significantly higher after opening of commercial gold mines than before. Communities adjacent to commercial gold mines report the decline of important wildlife and plant species and increased degradation following mining operations. However, local communities report that wildlife populations are often found in mining leases to avoid being hunted outside mining leases.

Results could be used to support a range of stakeholders, such as government officials, conservation NGOs and mining companies, to manage the mining landscapes by tackling the issues of deforestation, biodiversity loss and growth of urban centres and artisanal operations adjacent to mining sites. Results can further support more comprehensive and participatory land use planning, adaptive co-management, and designing effective approaches to limit environmental degradation in Tanzania and other landscapes of sub-Saharan Africa.

Keywords: Forest loss; biodiversity; land use, Landsat, commercial gold mines, urbanization

5.2 Introduction

Mining is important for economic development (Azubuike et al., 2022; Sulista and Rosyid, 2022), supplies essential raw materials to society (Carvalho, 2017; Worlanyo and Jiangfeng, 2021), and strengthens the industrial development of many countries (Emuze and Hauptfleisch, 2014). For example, in 2020, gold mining contributed about US$37.9bn to the GDP of the 38 countries (World Gold Council, 2021). However, globally mining causes significant changes in land use (Basommi et al., 2016), directly though mining operations (Sonter et al., 2017) and indirectly through socio-economic developments such as the expansion of human settlement, infrastructure development and agriculture in the vicinity of mining project (Sonter et al., 2014). Mining can also escalate urbanization through inward migration for trade opportunities and employment (Ericsson and Löf, 2019), which can further lead to intensive change in land use putting more pressure on natural resources (Davison et al., 2021).

Both surface mining (e.g., Schueler et al., 2011), and underground mining (e.g., Mi et al., 2019) induce land use change and can both be manifested by rapid natural vegetation loss (Espejo et al., 2018), soil erosion (Mensah et al., 2015), and changes in river direction and ensuing sedimentation (Barasa et al., 2016), amongst other impacts. Such processes lead to the loss of biodiversity (Sonter et al., 2018), erosion of ecosystem service availability (Boldy et al., 2021; Tost et al., 2020) and can escalate the impacts of climate change (Kahhat et al., 2019). For example, mining induced land use change has altered critical wildlife habitat in a biodiversity rich hotspot of Nimba nature reserve in Liberia (Enaruvbe et al., 2019), and the Peruvian Amazon (Sánchez-Cuervo et al., 2020). Mining induced land use change has also impacted insectivorous tropical bat populations in Thailand (Costantini et al., 2019), primates and other medium to large mammals in Ghana (Owusu et al., 2018), and the movement of grizzly bears (*Ursus arctos*) in Canada (Cristescu et al., 2016). Other studies have shown how mining has caused aboveground carbon emissions in the Peruvian Amazon (Asner et al., 2010; Csillik and Asner, 2020), Kutai Kartanegara (Kartikasari et al., 2019) and China (Qin et al., 2020; Yang et al., 2019) and negatively impacted vegetation cover in the Peruvian (Espejo et al., 2018) and Brazilian (Sonter et al., 2017) Amazon.

Studies on mining induced land use change are crucial to anticipate potential impacts on vulnerable biodiversity areas where changes could occur in the future (Pereira et al., 2004; Simkin et al., 2022). Such research provides essential information on effective strategies to implement environmental policies that mitigate biodiversity impacts (Houet et al., 2010; Simkin et al., 2022). Similarly, international agreements on biodiversity conservation, such as the Convention on Biological Diversity had an oversight on the management of biodiversity in areas with high rate of human population growth and only integrated the issue of mining and biodiversity conservation in the post-2020 global biodiversity framework (OECD, 2019; Sonter et al., 2018). Therefore, temporal studies provide scientific information to shape and feed into relevant policies such as the United Nations Human Settlement Program's (UN-Habitat's), New Urban Agenda, that works parallel with the Sustainable Development Goals (Simkin et al., 2022) or the Africa Union's Agenda 2063. These international strategies can support national and subnational governments to enact conservation policies within their jurisdiction to mitigate the impacts on biodiversity of high population growth in mining landscapes and support sustainable land management (Kumi et al., 2021).

Previous studies on the impacts of mining on land use change are not equally distributed across the globe. Many studies have been conducted in South America (e.g., Brazil (Rudke et al., 2020; Sonter et al., 2017, 2014), Peru (Asner et al., 2013; Asner and Tupayachi, 2017) and Ecuador (Mestanza-Ramón et al., 2022, 2021)). There remains a lack of evidence on the impact of mining on land use change across Africa, with most attention paid in West Africa (Gbedzi et al., 2022; Obodai et al., 2019; Owolabi, 2020; Schueler et al., 2011), and Central Africa (e.g., Rwanda (Pierre et al., 2021), Democratic Republic of Congo (Mwitwa et al., 2012)) with relatively few studies conducted in East Africa. Evidence of the impact of gold mining on land use change in Tanzania is lacking despite its long history of large-scale mining since 1920s when gold was discovered in the Lupa and Lake Victoria gold fields (Pedersen et al., 2019), which by then shifted the dependence away from agriculture as the main driver for Tanzania economy to gold mining (Bryceson et al., 2012).

Similarly, there is a lack of studies that look at environmental and social change. Most applications of remote sensing do not combine with socio-economic insights; thereby inhibiting our understanding of the contextual drivers of change. Studies charting mining induced land use change are crucial to anticipate potential impacts on vulnerable biodiversity areas (Pereira et al., 2004; Simkin et al., 2022). Such research can provide essential information that can be used to design effective land management strategies (Kumi et al., 2021) to implement environmental policies that can mitigate biodiversity loss (Houet et al., 2010; Simkin et al., 2022) and aid more adaptive co-management (Jew et al., 2019).

This study assesses the direct and indirect impacts of commercial gold mining on land use change in six districts of Tanzania with active mines between 1990 to 2019. Key objectives were to: (1) chart the change in land cover from 1990 to 2019, (2) assess the direct and indirect drivers of mining on land use and land cover change; (3) determine perceptions of historic drivers of land use change before and after mines were leased and off-site impacts between 1990 and 2019, and (4) compare observed and perceived data of land use data to inform future co-adaptive sustainable land management and policies.

5.3 Material and methods

5.3.1 Study area

The study areas are in the six districts of Geita, Tarime, Kahama, Biharamlo, Nzega and Chunya, which have commercial gold mines (Figure 17). To provide a comparative control we also analysed land use change for other districts without commercial gold mining; these include Chato, Mbeya, Urambo, Rorya, Shinyanga and Uyui (Figure 17). There is a variation of time from when commercial gold mine was opened and began to operate in each selected district that provides a temporal element to the analysis. Opening of commercial gold mine was earliest in Nzega district (1999), followed by Geita (2000), Tarime (2002), Biharamlo (2005), Kahama (2009) and Chunya (2012).

Tanzania has experienced rapid demographic growth: between 1967 and 2016 the population increased from 12.3 to 50.1 million (United Republic of Tanzania, 2016), and based on the current population growth rate of 3.1%/yr^{-1} Tanzania currently has 61.2 million people living in the country (United Republic of Tanzania, 2016, 2018). Population growth continues to put pressure on natural ecosystems. For example, Tanzania lost 165kha of natural forest, equivalent to 59.9Mt of CO_2 emissions between 2010 and 2021 (Global Forest Watch, 2022).

In the 1970s, the value of gold increased (Jønsson and Bryceson, 2009; Bryceson et al., 2012; Pedersen et al., 2019), catalyzing production, and associated rapid population expansion in and around Tanzanian gold mining areas (Edwards et al., 2014).

The study districts were selected for three reasons. Firstly, study districts represent areas of high gold reserves in the Lupa and Lake Victoria gold fields

(Henckel et al., 2016) and are characterized by large investments by commercial mining companies (Mwalyosi, 2004). In 2019, these districts contributed more than 90% of the country’s total mineral exports, representing revenue of US$ 2.2 billion. All together, these district employs up to 18,000 workers. Geita Gold Mine has maximum number of employees (6401) including permanent workers and contractors compared to all study districts. Secondly, annual gold production from these districts has increased significantly in recent years. Between 2008-2018, gold annual production increased from less than 1 to 40-50 tonnes (TEITI, 2018). Annual gold production per commercial gold mine is between 0.4 tonnes and 18 tonnes. Geita Gold Mine (GGM) can produce up to 18 tonnes per year, followed by North Mara Gold Mine (14.2) and Buzwagi (5.6). Thirdly, these areas are recognized as key biodiversity areas (van Soesbergen et al., 2018), predominantly covered with miombo woodlands (Shirima et al., 2015, 2011), characterized by the genera *Brachystegia* and *Julbernardia* (Shirima et al., 2015, 2011) which are under threat (Jew et al., 2016); and unique open woodlands that harbors high diverse of birds (Manyanda et al., 2020; Tøttrup et al., 2005).

The study area has a tropical climate with an average rainfall ranging from 600-800 mm per annum (Duguma et al., 2014). These districts have a unimodal weather pattern experiencing high rainfall during wet season (November – April). The study districts have a diverse range of economic activities, including commercial and small-scale agriculture, which contributes to 26.7% of the national GDP followed by livestock (7.4%), forestry (4%), fishing (1.4% of GDP, or 35% rural employment) (Food and Agriculture Organization, 2021). However, mining is the second economic activity after agriculture, and most of the people adjacent to mining practice both mining and agriculture (Kitula, 2006). Annual population growth rates in study districts range from 3.0 to 7.1 with an average of 4.0 % growth rate per annum in mining districts, and 1.8 to 3.8 with an average of 2.7 growth rate per annum in districts without mining.

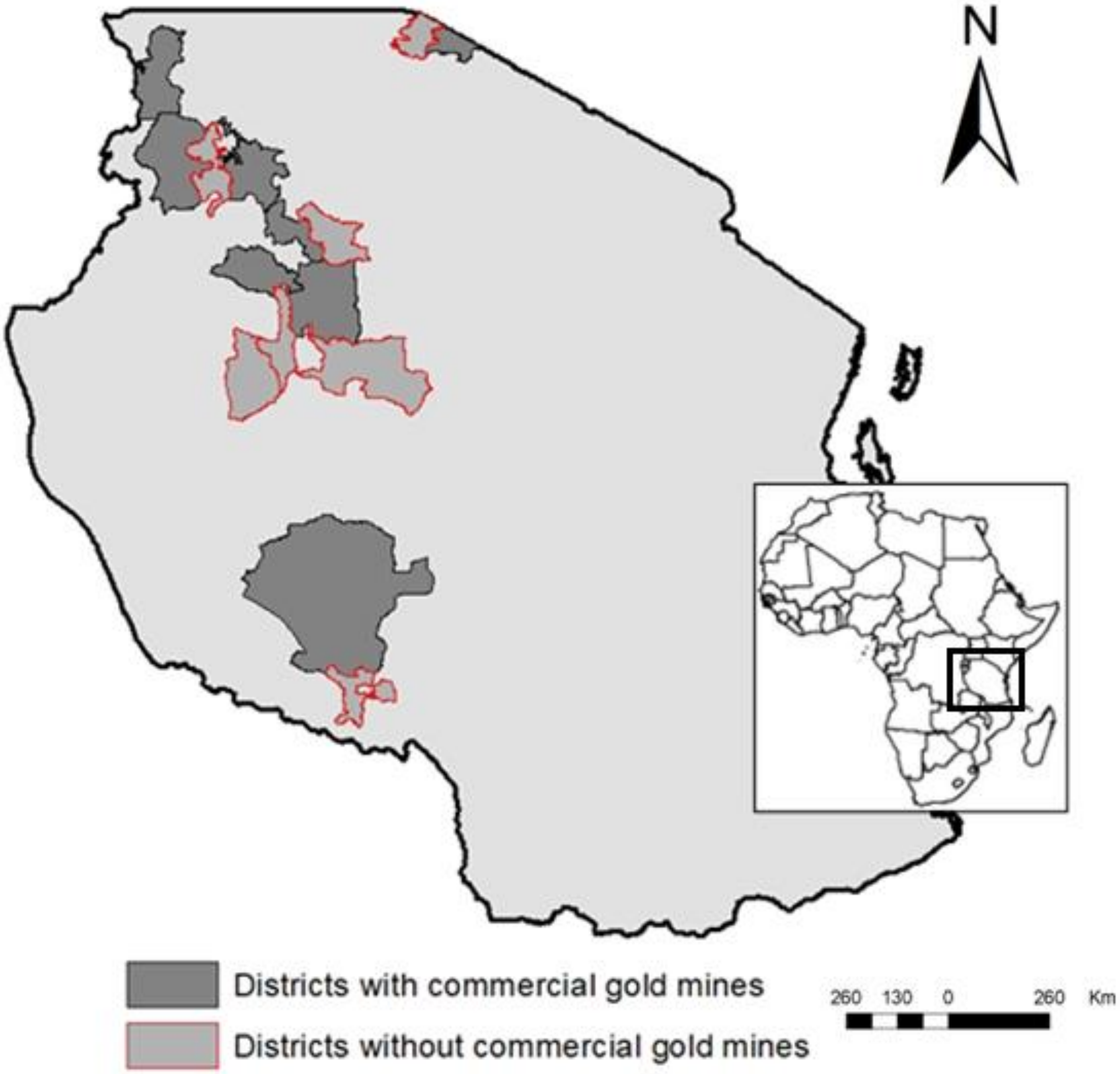

Figure 17: Map showing study districts in Tanzania.

5.3.2 Data collection

To identify the direct and indirect impacts of commercial gold mining on land use change, a mixed methods approach combining land use change detection and social surveys was used. Field work for the socio-economic survey was conducted between July and September 2019. Fieldwork for ground truthing was conducted in between July and September 2019, July 2020, and April 2022.

5.3.3 Imagery data acquisition and processing

Landsat image mosaics for each year was created from three different sensors (i.e., Landsat Thematic Mapper ™ 1990 and 2010, Landsat Enhanced Thematic mapper ETM 2000, and Landsat Operational Land Imagery (OLI) 2019). Satellite imageries were acquired from the dry season (July-September) to enhance spectral separability and compatibility across the Landsat images. Cloud contaminated pixels were corrected by screening cloud algorithm using quality assessment bands. Surface reflectance data was computed by Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS).

5.3.4 Supervised classification

Six land cover classes (Table 1) were identified for supervised classification following Agariga et al., (2021). Fifty training samples per land cover type were created using field visits between 2019 and 2022, and an additional 50 training samples were created using historical Google Earth imagery (Gbedzi et al., 2022) for study area. Thus, a total of 1200 training data for each land cover type in all districts were used to generate spectral signatures to perform image classification in Google Earth Engine. We used Random Forest Classifier, a widely used algorithm for land cover classification (Kelley et al., 2018), that comprises a combination of tree classifiers that operates in an ensemble decision to determine the most popular class (Horning, 2010; Pal, 2005). Random Forest Classifier was selected due to its high ability of handling outliers (Noi Phan et al., 2020), and has high classification accuracy for land cover classification (Mahdianpari et al., 2017). However, spectral differentiation between built areas and mining areas in districts with commercial gold mining was not resolved. Thus, historical mining areas were digitized from high resolution Google Earth imagery and overlaid on specific Landsat imagery to differentiate its cover form that of built areas classification.

Table 6: Description of the land cover classes.

Land use categories	**Description**
Forest	An area of land with at least 0.5 ha, with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ (FAO, 2020).
Water bodies	Include inland water (dams and rivers) and inundated areas include (swamps or marshes) (Schourup-Kristensen et al., 2021)
Bare soils	Land which includes bare land and beach sands
Cropland with scattered settlements	Land actively used for agriculture crops including wooded crops, herbaceous crops, and grain crops with scattered settlements (Akinci et al., 2013; Fichera et al., 2012).
Built up areas	The union of all spatial units containing buildings or part of it especially urban areas (Pesaresi et al., 2016).
Mine	Cleared land for mining purposes, including pits and offices (ICMM, 2010).

5.3.5 Accuracy assessment

Accuracy assessment was performed by comparing the classified LULC map with validation data obtained from field observations and Google Earth. The error matrices were prepared and 1200 validation points for each land cover were used during accuracy assessment. This was done to evaluate the classification approach, and to determine the error that might be involved during image classification (Abbas and Jaber, 2020). User’s accuracy (UA) and producer’s accuracy (PA) for each land cover was also generated.

5.3.6 Land use change detection

Post change detection analysis was performed to determine the dynamics of land use and land cover for the period 1990 - 2019. The change matrix was generated by cross tabulation and analysis conducted on pixel-by-pixel basis following Munsi et al. (2010). Attribute tables resulted from the change detection analysis through overlay of classified maps were exported to Microsoft Excel to compute area change and rate of change for 1990 – 2019. Change in percentage (%), was obtained by comparing initial and final LULC areal coverage using the following equation after Garai and Narayana (2018).

$$\text{Percentage of change (\%)} = \frac{(\text{present LULC area} - \text{previous LULC area})}{\text{previous LULC area}} \text{x } 100$$

Rate of change were computed form the LULC change data for the period 1990–2019 using the formular by Puyravaud (2003).

$$r = {}^{1}/_{t2} - t1 \, x \, \frac{ln_{2}^{\wedge}}{A1} \, x \, 100$$

where, A_1 and A_2 are the areas of land cover classes correspond to year t_2 and t_1 respectively.

5.3.7 Statistical analysis

All statistical analysis was carried out using R version 3.6.2 (R Core Team, 2019). We used simple generalized linear models (GLMs) with a Gaussian error function to determine the influence of mining on the rate of change for different land covers. In this case presence or absence of largescale mining in specific districts was used as predictor variable while rate of change for different land covers was used as response variable. Variation on the rate of change for different land uses before and after opening of mines in districts with commercial gold mines was tested using t-test.

5.3.8 Socio-economic survey

Socio-economic surveys were conducted to get insights from the adjacent communities on the direct and indirect drivers of historical land use change before and after the mining investments, and the rate of biodiversity loss inside versus outside mining leases. To do this, three districts that were surveyed for indirect ecological impacts of commercial gold mining (see chapter six), were also selected for socio-economic surveys. The aim was to make a proper explanation from ecological, satellite and socio-economic data. The selected districts were from the same study regions. These districts were Geita, Songwe (Chunya) and Ikungwi in Singida.

Nine villages (three in each district) were selected for socioeconomic surveys based on their proximity to commercial gold mines of varying ages. This allowed to compare perceptions from acquired spatial data from satellite imagery for the period 1990 – 2019 and between mining sites of varying ages.

Closed structured interviews using a questionnaire (Appendix 1) were conducted between July and September 2019. 180 respondents who had lived in the area for more than 25 years (60 per selected district) surrounding villages for the three targeted sites namely Geita, Songwe and Ikungi districts were selected because they were knowledgeable to have a good understanding of historical events that had significant contribution to the landscape dynamics and could ascertain degradation events of the study areas following Bhuyan et al., (2020) (SM 5.9.1). We chose villages in Geita, Songwe and Ikungi districts because plots for indirect impacts assessment were conducted in the same districts. Interviews were conducted in Swahili in a village hall and lasted for approximately thirty minutes each. Responses were recorded by three interviewers using the questionnaire (Appendix 1) which were translated into English by the main author.

Semi-structured interviews were also administered to 60 key informants including villagers, village officials, resource users, decision makers, and residents. Interviews was used to get in-depth information on land use change driven by existing commercial gold mining and were recorded using voice recorder. Snowballing and door knock sampling techniques were used to identify eligible respondents by asking the interviewees.

Consultations with mining companies, government departments, non-government organizations, university researchers, traditional authorities, and community leaders to get their insights on mining related socio-economic, natural, and cultural resource management needs and preferences were also conducted. In addition, three dedicated workshops were conducted involving 60 people (20 in each district) to get their insights on the current and future perspectives of the mining sector.

5.3.9 Socio-economic data analysis

Qualitative data from the adjacent community consultations included field notes, meeting notes, photos, and voice recordings. Data were subject to manual content and thematic analysis, following (Annandale et al., 2021). Quantitative data collected in the surveys was transcribed and coded in MS Excel. After cleaning the data, preliminary descriptive statistics were conducted. Then the data was coded and analysis in SPSS. Post hoc analyses were carried out where necessary using analysis of variance (ANOVA), compared means were considered statistically significant when p-values less than 0.05.

Perceived land use changes and the underlying drivers driving the changes were analysed by categorizing response of the respondents by: - (i) past land cover and dominant land uses 25 years back from the time of data collection (i.e., 1994), (ii) then just before opening of the mining sites and, (iii) after opening of the mine sites. This approach enabled us to compare perceived land cover and dominant land use at different time periods. Independently, socio-economic data enabled us to compare perceived and remote sensing changes in land use to recommend appropriate conservation strategies in mining landscape (Ahrends et al., 2021).

5.4 Results and discussion

5.4.1 Accuracy assessment of land cover classification

The overall accuracy of the land cover classification for four-time step ranged between 85.1% and 93.1%, with kappa agreement indices ranging from 0.79 to 0.85. User's accuracy and producer's accuracy for each land cover is shown in a SM2. Land sat images acquired in 1990 depicted less user and producers' accuracy. The obtained accuracy values imply very good to excellent agreement for the classified maps (Monserud, 1990).

5.4.2 Trends in land cover

In the districts with commercial gold mining between 1990 and 2019, there was a considerable decline in forest cover and water bodies. Conversely, cropland and scattered settlements, built up areas, mining areas and bare lands increased within the same period (Figure 18). Forests occupied an average of 293,714.7 ha (48.7%) in 1990 but reduced to an average of 77,920.5 ha (12.1%) in 2019, water bodies covered an average of 58,383.5 ha (9.7%) in 1990 and reduced to an average of 21,875.4 ha (3.4%) in 2019; while cropland and scattered settlements covered an average of 206,483.5 ha (34.2%) but increased to an average of 461,916.1 ha (71.6%) in 2019, built-up areas covered an average of 1655 ha (0.3%) in 2019 but increased to 69306 ha (10.7%) in 2019, mining areas covered an average of 677.2 ha (0.1%) but increased to an average of 11217.8 ha (1.7%) in 2019, and bare soil increased to an average of 488.2 ha (0.1%) in 2019 from zero coverage in 1990.

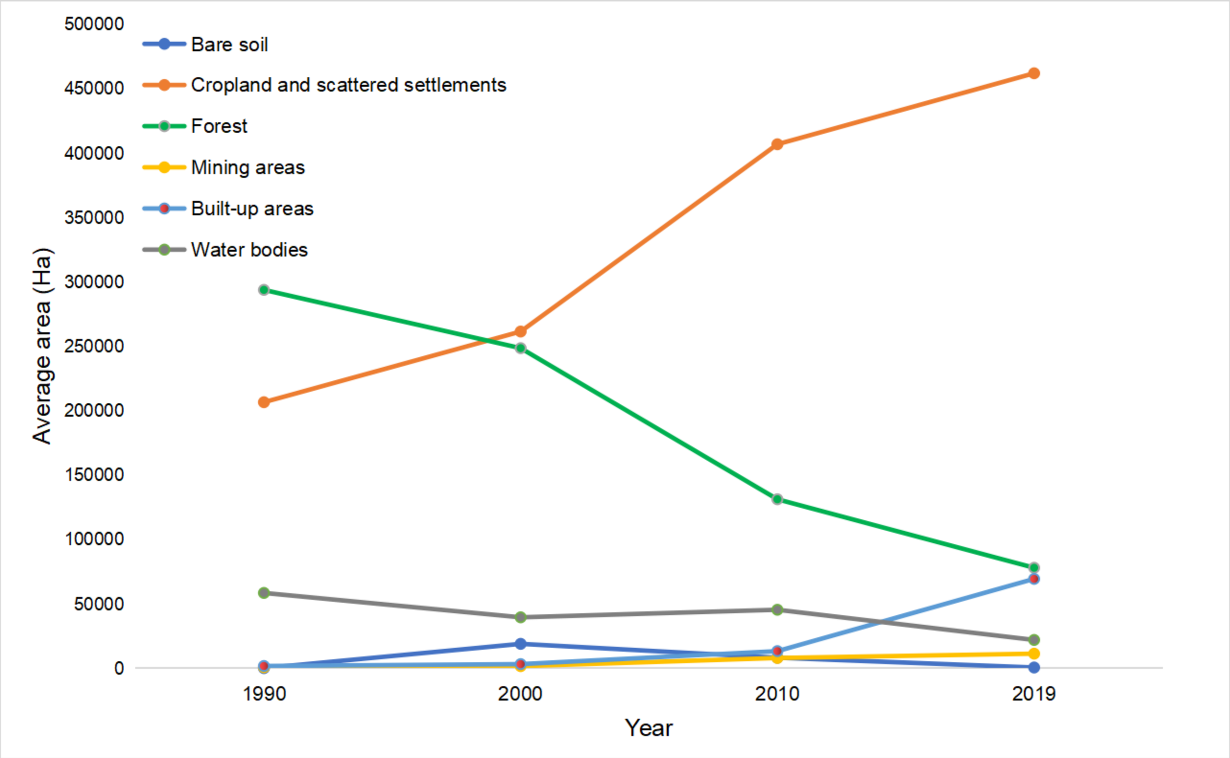

Figure 18: Trends in land cover area of the districts with gold mining investments (1990–2019).

In the control districts (districts without gold mining investments) a similar trend was found between 1990 and 2019 (Figure 19). Forests occupied an average of 255,644.8 ha (44.4%) in 1990 but reduced to an average of 153,430.3 ha (24.4%) in 2019, water bodies covered an average of 80,971.1 ha (14.1%) in 1990 and reduced to an average of 77,385.1 ha (12.3%) in 2019; while cropland and scattered settlements covered an average of 238,084.1 ha (41.3%) but increased to an average of 374,203.6 ha (59.5%) in 2019, built-up areas covered an average of 1514.2 ha (0.3%) but increased to an average of 19879.8 ha (3.2%) in 2019, and bare soil increased to an average of 4368.4 ha (0.7%) in 2019 from zero coverage in 1990.

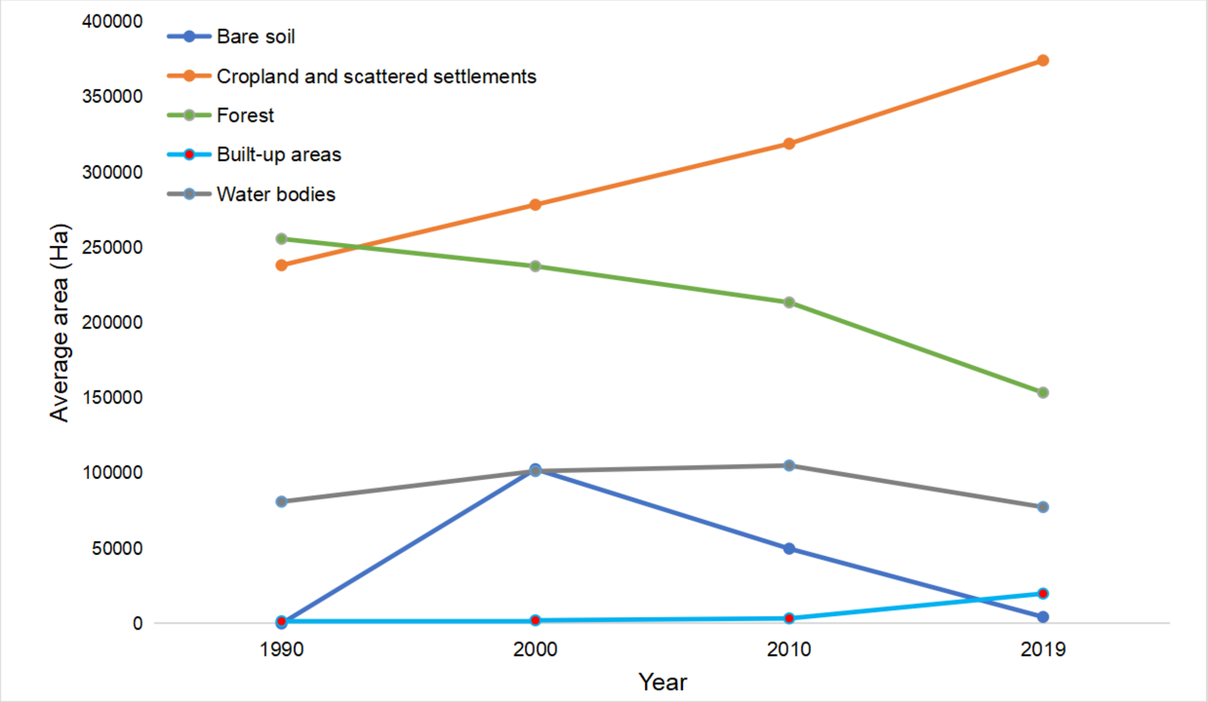

Figure 19: Trends in land cover area of the districts without gold mining investments (1990–2019)

Figures 18 and 19 shows decline of forest covers in expense of the increase in cropland and scattered settlements and built-up areas for both districts with and without commercial gold mining investment. Increase in mining areas has also contributed to loss of forest covers in districts with commercial gold mining. However, there is a significant variation in the rate of change for forest cover (t = 11.9, p = 0.001), cropland and scattered settlement (t =7.5, p =0.001) and built-up areas (t = 5.7, p =0.001) between districts with and without commercial gold mining. The rate of change for areas occupied by water bodies and bare land was not significant. GLMs further revealed high rate of annual decline in forest covers (%D = 49), high annual rate of increase in cropland and scattered settlement (%D = 52) and built-up areas (%D = 54) in districts with commercial gold mines than districts without commercial gold mines (Figure 21).

High rates of forest cover change and cropland and scattered settlements in districts with commercial gold mining investments occurred between 2000 and 2010. Most of the commercial gold mining was opened between 2000 and 2002. Thus, 2000 and 2010 was the period of major economic development in these districts (Edwards et al., 2014), which attracted significant number of people and caused extensive land alteration. Similar cases were reported in northern Ghana (Gbedzi et al., 2022). High levels of annual forest decline occurred after the opening of commercial gold mining in Geita (9,612 ha), Chunya (68,573 ha), Kahama (14,039 ha), Biharamulo (16,744 ha), and Nzega (9600 ha), while cropland and scattered settlement increased in Geita (13,467 ha), Chunya (70,550 ha), Kahama (13,911 ha), Biharamulo (17,698), and Nzega (10,694 ha).

Although the trend in decline of forest covers, increase in cropland and scattered settlement and built-up areas also occurred before opening of commercial gold mining, there was a significant variation in annual rate of change for forest cover ($t = 4.5$, $p = 0.001$), cropland with scattered settlement ($t = 4.7$, $p = 0.002$) and in built-up areas ($t = 2.6$, $p = 0.005$) before and after opening of commercial gold mines. However, annual rate of change of water bodies and bare land was not significant.

These results are attributed by the increasing population’s need for economic development in mining regions – as reported in other studies (Arifeen et al., 2021; Mwitwa et al., 2012; Sonter et al., 2014; Xu et al., 2016), along with crop production (Gbedzi et al., 2022), increased charcoal production (Tolksdorf et al., 2015), and eventual degradation of specific tree species for timber (Mwitwa et al., 2012). The accelerated need for energy consumption, timber for furniture and areas for crop production is largely influenced by high migration flows (Girard, 2002), which has knock-on impacts on biodiversity (Kouami et al., 2009; Sedano et al., 2016). Similar observations have also evidenced by other studies in Ghana (Gbedzi et al., 2022), Congo DRC and Zambia (Mwitwa et al., 2012), Peru (Espejo et al., 2018) and Brazil (Sonter et al., 2017, 2014).

Although there was significant variation in annual rate of change between districts within and beyond commercial gold mines, our results revealed a high rate of change in land cover between 2010 and 2019 for all areas. For example, between 2010 and 2019, forest declined in Urambo and Uyui districts without commercial gold mining was 12768 ha/a and 14127 ha/a respectively, whilst cropland and scattered settlements increased in Urambo and Uyui by 12883 ha/a and 16184 ha/a respectively. These results could be attributed to migration by large-scale agro pastoralists from the cleared landscapes of Mwanza and Shinyanga Regions into relatively intact ecosystems in Urambo and Uyui in search for fertile soil and unoccupied land (Masanja, 2017). This escalated rate of deforestation and increase in scattered settlements due to livestock keeping and tobacco cultivation (Yamat, 2021). Tobacco cultivation is recognized as the significant driver of land use change and can drive extensive deforestation in miombo woodlands (Jew et al., 2019, 2017).

Results of the land cover analyses for 1990, 2000, 2010 and 2019 are presented in Figure 20.

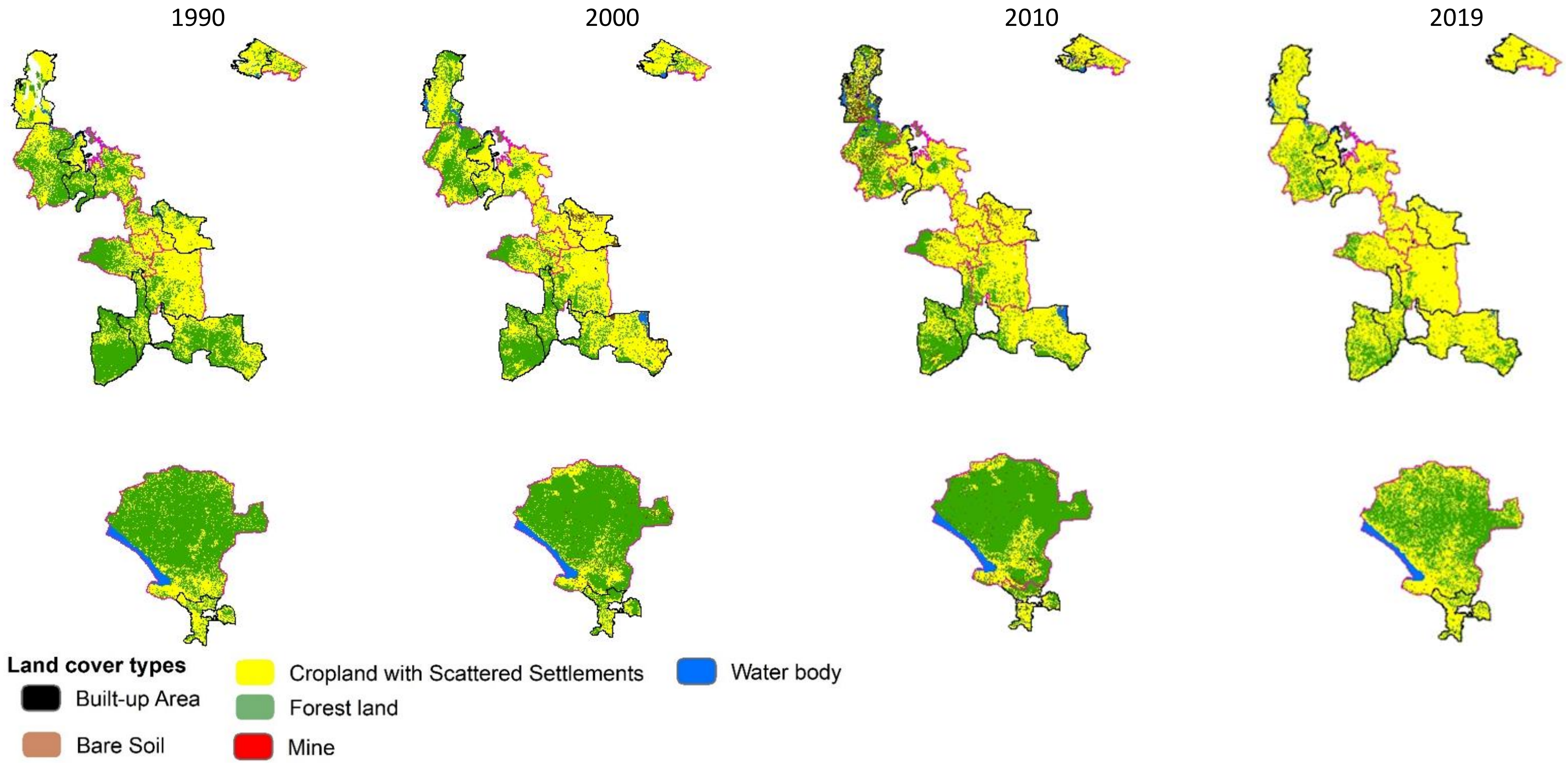

Figure 20: Land cover maps for all studied districts. Pink boundaries represent districts with commercial gold mining while black boundaries represent districts without commercial gold mining. Figure shows that there was a high annual rate of forest decline after opening of large-scale mining.

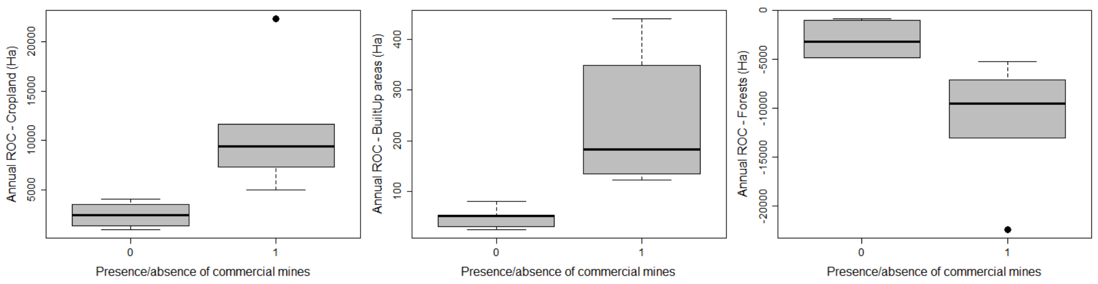

Figure 21: Annual rate of change for cropland with scattered settlements, built up areas, and forests in districts with large scale gold mining and districts without large scale gold mining.

5.5 Perspectives of mining induced land use change from adjacent communities of selected mining districts

5.5.1 Demographic characteristics of respondents

Most of the respondents (61.6%) were male (SM1), and (81.2%) practice agriculture, followed by business (61.1%) and small-scale mining (40%). This bias could be due to male being heads of a given household (Mabey et al., 2020) although we do have good representation from females across the study area. Communities within active mine districts (i.e., Geita 19 years, Songwe 8 years), were involved more in business and small-scale mining, while communities without active mines (i.e., Ikungi 0 years) were more involved in livestock keeping. In addition, communities in Songwe district were engaged in fishing (45%), due to the proximity with Lake Rukwa, especially in Maleza and Mbangala villages.

5.5.2 Land use change

Based on information provided by different respondents living adjacent to mining, district officials, and staff from mining companies collectively determined historical events pertaining to land use land cover changes in mining landscapes of Tanzania. The information provided corresponds with the results from GIS and remote sensing on the rate of land use change in mining regions. Since the selected mining sites for socio-economic surveys varied in age, information on the previous land use and how they have transformed was simplified to three-time steps (i.e., 25 years ago, just before opening of the mine and for the year 2019) for the respondents to easily respond and describe the pertaining land use transformation. Respondents residing adjacent to active mines report the increasing rate of land use and land cover since the opening of the commercial gold mines in their areas.

Most of the respondents reported that 25 years ago (1994) there was high coverage of indigenous forest in Songwe (93.3%, *n* = 56), Geita (68.9%, *n* = 40) and Ikungwi (100%, *n* = 60), aquatic ecosystems in Songwe (96.6%, *n* = 58), Geita (60%, *n* = 36) and Ikungwi (70%, *n* = 42) and grasslands in Songwe (86.7%, *n* = 52) and Ikungwi (100%, *n* = 60) except for Geita that started to experience loss of grasslands (66.7%, *n* = 40) since 1994 (Table 3). Respondents also reported that, there were less coverage of commercial farmlands in Songwe (75%, *n* = 45), Geita (53.3%, *n* = 32) and Ikungwi (93.3%, *n* = 56), smallholder farmlands in Songwe (83.3% n=50), Geita (60%, *n* = 36) and Ikungwi (90%, *n* = 54), formal settlements in Songwe (80% *n* = 48), Geita (66.7%,*n* = 40) and Ikungwi (85%, *n* = 51), informal settlements in Songwe (76.7%, *n* = 46), Geita (60%, *n* = 36) and Ikungwi (75%, *n* = 45) and artisanal and small scale mining in Songwe (85%, *n* = 51), Geita (76.7%, *n* = 46) and Ikungwi (91.7%, *n* = 55). Different trend of results in Ikungwi district were mostly attributed by few numbers of people and less economic development as the mine was yet to start its operations.

Respondents indicated that there was a declining trend of forest covers, aquatic ecosystems and grasslands and increasing trend of farmlands, formal and informal settlements, and artisanal and small-scale mining even before the opening of the commercial gold mine in Geita (2000), (Songwe, 2012). However, the rate of forest decline was relatively low compared to after opening of the mine (Table 3).

Generally, across districts with active mines, few respondents reported on the decline of the indigenous forest, grasslands i.e., livestock pastures and aquatic areas, and increase in coverage of small hold and commercial farmlands, informal and formal settlements and artisan and small-scale mining before opening of commercial gold mine (Table 3), while others gave the ‘no change’ opinion for any land cover. This implies that there was non-significant land use change before opening of the mines, grasslands, and aquatic areas, while there was low coverage of farmlands, informal and formal settlements and artisan and small-scale mining (Table 3).

By 2019, the commercial gold mine in Geita had been operating for 19 years and in Songwe for 8 years had led to an escalated rate of change for different land covers (Figure 22). Most respondents reported a high rate of decline of the forest cover in Songwe (68.3% *n* = 41) and Geita (96.67%, *n* = 58), aquatic areas in Songwe (93.3%, *n* = 56), Geita (71.7% *n* = 43) and Ikungwi (100%, n = 60), grasslands in Songwe (93.3%, n = 56) and Geita (68.9%, n = 40) but a high rate of increase in coverage of small hold farmlands in Songwe (63.3% *n* = 38), and Geita (100%, *n* = 60), informal settlements in Songwe (75%, *n* = 45), and Geita (100%, *n* = 60), formal settlements in Songwe (76.7%, *n* = 46), and Geita (100%, *n* = 60) and artisan and small-scale mining in Songwe (86.6%, *n* = 52), and Geita (93.33%, *n* = 56). While the rate of change for different land covers was escalated by mining in the districts with active mining sites (Geita and Songwe), in Ikungwi district, the rate of change was similar for all time steps except for grasslands (80%, *n* = 48), small holder farms (73.3%, *n* = 44) and aquatic ecosystems (80%, *n* = 48) that were reported to have high rate of change. However, information from key informants in Ikungwi districts (*n* = 15), especially in areas adjacent to mining site that was yet to be opened, reported that some people returned to their villages to open new farms to get compensation by the mining company once operations began. This practice escalated change in forest cover, increased newly opened farmlands and increased the extent of some informal settlements.

Figure 22: Satellite images 5 years before opening of each mine and in 2019 for Geita and Songwe districts. Red circles indicate areas of high land use transformation due to increased human population.

5.5.3 Perceptions in the decline of biodiversity and ecosystem services

The increased land use change has also been reported by respondents to reduce wildlife population, key miombo species and wider ecosystem service provision.

5.5.3.1 Changes in fauna population

Elephants, lions, and leopards were reported to have declined in Songwe and have disappeared in Geita, while animals such as antelopes and primates and Hyenas have increased in both areas.

When respondents were asked about biodiversity in leased areas versus outside leased areas, most respondents revealed that, inside mining lease there is high biodiversity. This was also highlighted by the environmental department staff of New Luika Gold mine that, there has seen a rapid increase of wildlife in their premises especially antelopes including Bushbuck (*Tragelaphus scriptus*), Waterbuck (*Kobus ellipsiprymnus*) and Common Eland (*Tragelaphus oryx*). They also reported the Common Hippopotamus (*Hippopotamus amphibius*) in their reservoir lake, and they consider the mining leased area a ‘safe heaven’. This is largely driven by high pressure outside mining leases as animals are being hunted by increased human populations adjacent to the mine.

Bushmeat hunting in mining landscapes is common as people practice hunting as an alternative livelihood (Edwards et al., 2014; Spira et al., 2019). It is considered a serious threat wildlife population leading to loss of wildlife species (Reed and Miranda, 2007). Although bushmeat contributes to food security, uncontrolled hunting will can cause severe wildlife declines (Lindsey et al., 2013).

5.5.3.2 Changes in flora composition and increased deforestation

Targeted tree species that are useful for timber including Miyenze (*Brachystegia spiciformis*), Migusu (*Uapaca kirkiana*), Mibanga (*Pericopsis angolensis*), Mininga (*Pterocarpus angolenis*), Mitundu (*Julbernardia globiflora*), Mitimiombo (*Brachystegia* sp), Mikurungu (*Pterocarpus tinctorius*), and Mikola (*Afzelia quanzesis*) have declined in Songwe while they are rare in Geita. High numbers of these species are found within the mining leases.

Communities in Geita also indicated that increasing deforestation outside mining leases have caused valuable tree species to be more abundant within mining leases. This is all because there is high security and regular patrols in mining leases as opposed to outside mining leases where people are not restricted and can conduct deforestation. These events have denied them with important ecosystems services such as trees with edible fruits (*Uapaca kirkiana*), medicinal plants (both *Pterocarpus angolensis* and *Pterocarpus tinctorius*) and valuable timber species including *Afzelia quanzensis* which are very rare to encounter outside mining leases. They also explained on lacking the good quality firewood from mitimiombo (genus *Brachystegia*), mibanga (*Pericopsis angolensis*) and mitundu (*Julbernardia globiflora*) which in most cases are either absent or regenerating. However, the challenge is whenever these species regenerate, they are being cut before becoming mature (Figure 23a). Lack of clean and fresh air is also another problem cause by increased dust presence from mining activities and from expanding bare land that lacks vegetation cover. There is also increased run-off and soil erosion due to lack of vegetation cover that creates massive gullies and increased artisanal mining pits that can lead to reduced farming areas (Figure 23b).

Figure 23: Showing medium sized trees being cut for charcoal (a) and abandoned artisanal mining pits (b).

The major concern of the most respondents (77.8%, *n* = 140) living adjacent to active mines is the rapid increase of migrants who are practicing deforestation to make their new homes, agriculture and engage in timber and charcoal business. One of the key informants who was a farmer in Songwe stated: *"There is rapid increase of artisanal mining to these areas since the opening of the mine. They are destroying environment by digging everywhere in search for gold which is bad for the environment and the use of fire is even worse for livestock pastures*".

The claim that some of the artisanal mining are considering charcoal and timber business as a fast alterative to meet their livelihood needs when they spent longer time in search for gold without success was also mentioned by another four key respondents who were met cutting down approximately 1 ha of forest for charcoal production in a reserved area (Figure 24b): *"We are actually Nyiha people from Mbozi (*approximately 137 km from Songwe district*) not residents in Songwe. We came here in search for job opportunities without success and we ended up engaging ourselves in artisanal gold mining. When we spend longer time without getting any gold, we go to the forest and cut trees to produce charcoal* (Figure 24a) *and timber to get fast money to meet our burning needs, and sometimes we do both mining and charcoal business".*

Figure 24: Showing charcoal kiln in a large, deforested forest area (a) and a man cutting trees with an axe (b).

5.5.3.3 Expansion of villages and growth of towns

Generally, opinions for high rate of change in districts with commercial gold mines from different respondents can be attributed by population “pull” of mining districts as more people are going there to seek employment, business opportunities and some going to seek small scale mining opportunities (Edwards et al., 2014; Mwitwa et al., 2012). For example, the population of Geita in 2002 was four times that of 1999 due to opening of the gold mine (Lange, 2006); in just three years, the adjacent population increased from 30,000 in 1999 to 120,000 in 2002.

In Songwe district, there was booming of some villages such as Makonogorosi, Mkwajuni and Saza driven by migrant workers and investment from artisan and small-scale miners. On the hand, damming of Luika river by New Luika Gold Mine in Songwe district increased the flow period of the river to almost the whole year which was previously becoming dry in July. This event also escalated the growth of artisanal mining camps along Luika river and the knock-on impacts on riverine and adjacent ecosystems.

Globally, mining is recognized in the creation of new towns (Marais et al., 2018), and expansion of the existing ones (Edwards et al., 2014; Jackson, 2018). The rapid expansion of towns is driven by establishment of permanent and non-permanent settlements to accommodate the growing human population (Marais et al., 2018), as a result, forested areas are cleared for settlements, agriculture, and business centres. Similar events that have been escalated by land use change in mining regions of Tanzania has also been reported in Zambia and the DR Congo (Molinario et al., 2020; Mwitwa et al., 2012), Rwanda (Lehmanna et al., 2017), Ghana (Gbedzi et al., 2022; Kumi et al., 2021), India (Garai and Narayana, 2018), Sierra Leone (Wilson et al., 2022), and Brazil (Sonter et al., 2014).

5.5.3.4 Decline of livestock pastures and quality water

It was also reported by respondents that, increased artisanal mining has also degraded livestock pastures which is forcing livestock keepers to move to other regions with their livestock in search for livestock pastures. They also indicated the persistent pollution of water sources by mercury, cyanide, and dust from both large scale and artisan mining which denies them from clean water for drinking. When key respondents were asked about the availability of clean water sources they responded as follows: -

"*We are challenged with the availability of clean water. Most of the water sources, especially rivers and wetlands are filled with sediments and chemicals from artisanal mining. They are searching alluvial gold in water streams and rivers leaving nothing, but degraded rivers filled with sediments. They are also using rivers and other water sources to wash their crushed ore which adds on sediments to the rivers*.

Key respondents in Geita went further by associating the deaths of local livestock with river pollution caused by mining waste that overflowed from its Tailing Storage Facility due to heavy rains. Water pollution in mining landscapes is one of the major challenges in most mining landscapes across the globe. In Tanzania, it was also reported in parts of Kahama (Makene et al., 2012), North Mara (Almås and Manoko, 2012), Geita (Kitula, 2006) and Songwe (Mapenzi et al., 2020). Worse of it, artisanal and small-scale mining are contaminating these important water ecosystems and the associated biota with mercury (Kitula, 2006; Mapenzi et al., 2020), putting public health in jeopardy by contaminating significant food chains (Alvarenga et al., 2014).

5.5.4 Synonymity of results from remote sensing and socio-economic surveys

Results from socio-economic surveys somewhat mirror results from remote sensing data. Remote sensing revealed high rate of change of forest covers, croplands, and built-up areas in district with commercial gold mines. Similar narratives were given by respondents in districts with active commercial gold mines. More importantly the reasons for high rate of land use change were reported by respondents to be (i) high population increase caused by migrants from elsewhere in search for employment and business opportunities, leading to increased settlements and cleared areas for agriculture due to growing food demand (ii) the rapid increase of artisanal and small scale mining in vicinity of large scale mines (iii) increase of business in charcoal and other timber forest products (iv) improvements of infrastructure that facilitates easy transport of raw materials in mining areas and other products outside the mining areas. Moreover, the socio-economic survey helped to identify specific tree species and wild animals that were impacted by increased anthropogenic pressure to forested areas.

Complimenting remote sensing data with socio-economic surveys has given strong narratives of the underlying results in this chapter. The mixed approach in the data analysis enabled to simplify the complex process of land use changes in mining landscapes (Sonter et al., 2014), by evaluating linkages between satellite imagery and narratives from adjacent communities (Nagendra et al., 2004). Communities in landscapes undergoing changes can provide detail on the underlying forces that drives changes in their landscapes. They can resolve contradictions and variables that were not captured by remote sensing analysis (Malek et al., 2014). For example, in this research, respondents were able to resolve the issue of biodiversity variation within and beyond mining leases that was hard to capture by just analysing Landsat imagery.

5.6 Conclusion

This research evaluated the impact of commercial gold mining on land use change in six districts in Tanzania between 1990 and 2019 using Landsat data supported by insights from surveys, workshops, transect walks and interviews in adjacent communities. Findings demonstrated extensive land use change in district with commercial gold mines associated with population “pull” due to increased infrastructure and economic development. Significant impacts were recorded on the loss of forest cover and extent of aquatic ecosystems while there were increases in the coverage of cropland and scattered settlement, built up areas and artisanal and small-scale mining. There was loss of biodiversity and key plant species which impacted adjacent communities with important ecosystem services such as a reduction in clean water for drinking, edible wild fruits, fuel, and commercial timber tree species. Our results suggest the need for relevant stakeholders such as government officials, conservation NGOs and mining companies to manage the mining landscapes by tackling the issues of deforestation, biodiversity loss and emerging new towns adjacent mining sites.

This will be achieved through comprehensive land use planning and designing effective approaches for corporate social responsibility to limit environmental degradation in Tanzania mining landscapes.

Table 7: Perception of land use change (1994 – 2019) associated with mining activities form the communities in the study areas

Year	**Land use/land cover**	**Site 1 (Songwe)**			**Site 2 (Ikungi)**			**Site 3 (Geita)**		
		Decline	**No change**	**Increase**	**Decline**	**No change**	**Increase**	**Decline**	**No change**	**Increase**
25 years ago	Indigenous forest	-	6.7% (n=4)	93.3% (n=56)	-	-	100% (n=60)	15.52% (n=9)	15.52% (n=9)	68.97% (n=40)
	Grassland areas	13.3% (n=8)	-	86.7% (n=52)	-	-	100% (n=60)	66.67% (n=40)	-	33.33% (n=20)
	Farmland commercial	75% (n=45)	-	25% (n=15)	93.3% (n=56)	-	6.7% (n=4)	53.3% (n=32)	-	46.7% (n=28)
	Farmland smallholder	83.3% (n=50)	-	16.7% (n=10)	90% (n=54)	-	10% (n=6)	60% (n=36)	-	40% (n=24)
	Formal settlement	80% (n=48)	-	20% (n=12)	85% (n=51)	-	15% (n=9)	66.7% (n=40)	-	33.3% (n=20)
	Informal settlement	76.7% (n=46)	-	23.3% (n=14)	75% (n=45)	-	25% (n=15)	60% (n=36)	-	40% (n=24)
	Aquatic ecosystems	3.77% (n=2)	-	90.57% (n=58)	30% (n=18)	-	70% (n=42)	40% (n=24)	-	60% (n=36)
	Artisanal small-scale mining	85% (n=51)	-	15% (n=9)	91.7% (n=55)	-	8.3% (n=5)	76.7% (n=46)	-	23.3% (n=14)
Just before opening the mining site	Indigenous forest	25% (n=15)	31.7% (n=19)	43.3% (n=26)	6.7% (n=4)	63.3% (n=38)	30% (n=18)	6.7% (n=4)	28.3% (n=17)	65% (n=39)
	Grassland areas	30% (n=18)	65% (n=39)	5% (n=3)	40% (n=24)	45% (n=27)	15% (n =9)	50% (n=30)	31.7% (n=19)	18.3% (n=11)
	Farmland commercial	25% (n=15)	66.7% (n=40)	8.3% (n=5)	11.7% (n=7)	55% (n = 33)	28.3% (n=17)	23.3% (n=14)	36.7% (n=22)	40% (n=24)
	Farmland smallholder	28.3% (n=17)	31.9% (n=19)	40% (n=24)	16.7% (n=10)	38.3% (n=23)	45% (n=27)	50% (n=30)	23.3% (n=14)	26.67% (n=16)
	Formal settlement	16.7 (n=10)	53.3 (n = 32)	30% (n=18)	53.3 (n=32)	16.7 (n=10)	30% (n=18)	11.7% (n=7)	35% (n=21)	53.3% (n=32)
	Informal settlement	16.7% (n=10)	36.7% (n=22)	46% (n=28)	18.3% (n=11)	33.3% (n= 20)	48.3% (n=29)	68.33% (n=41)	-	31.67% (n=19)
	Aquatic ecosystems	18.3% (n=11)	23.3% (n =14)	58.3% (n=35)	41.6% (n=25)	33.3% (n = 20)	25% (n=15)	38.3% (n=23)	21.7% (n=13)	40% (n=24)
	Artisanal small-scale mining	18.3% (n=11)	28.3% (n=17)	53.3% (n=32)	28.33% (n=17)	33.3% (n=20	21.7% (n=13)	60% (n=36)	-	40% (n=24)
2019	Indigenous forest	68.3% (n=41)	20% (n=12)	11.7% (n=7)	53.3% (n=32)	20% (n=12)	26.7% (n=16)	96.67% (n=58)	0 % (n=0)	3.33% (n=2)
	Grassland areas	82.46% (n=47)	-	17.54% (n=10)	100% (n=60)	0% (n=0)	0% (n=0)	100% (n=60)	0 % (n=0)	-
	Farmland commercial	20% (n=12)	3.3% (n=2)	70% (n=46)	56.7% (n=34)	-	43.3% (n=26	21.7% (n=13)	-	78.3% (n=47)

Year	Land use/land cover	Site 1 (Songwe)			Site 2 (Ikungi)			Site 3 (Geita)		
		Decline	No change	Increase	Decline	No change	Increase	Decline	No change	Increase
	Farmland smallholder	33.3% (n= 20)	4.88% (n=2)	63.3% (n=38)	73.3% (n=44)	-	26.7% (n=16)	-	-	100% (n=60)
	Formal settlement	23.3% (n=14)	-	76.7% (n=46)	45% (n=27)	20% (n=12)	35% (n=21)	-	-	100% (n=60)
	Informal settlement	21.7% (n=13)	3.3% (n=2)	75% (n=45)	73.33% (n=44)	-	26.67% (n=16)	-	-	100% (n=60)
	Aquatic ecosystems	93.3% (n=56)	-	6.7% (n=4)	80% (n=48)	-	20% (n=12)	71.7% (n=43)	21.7% (n=13)	6.7% (n=4)
	Artisanal small-scale mining	13.3% (n=8)	-	86.6% (n=52)	53.33% (n=32)	-	46.67% (n=28)	-	6.67% (n=4)	93.33% (n=56)

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5.8 Appendices A

Appendix 1: Individual community questionnaire with informed consent form

Informed consent form

Title: Environmental impacts of mining on biodiversity and ecosystem services: Identifying past land use transitions and envisioning future trajectories

Researcher: Mr. Hamidu A. Seki, Department of Environment and Geography, University of York, Wentworth Way, Heslington, York YO10 5NG Email: has536@york.ac.uk Tel: +255743215081

Full Name of participant : ______________________________ **Date :** ____________________

Location : (Town /district) : ____________________________ **Contact :** __________________

Please tick each box as you have read and understood it

☐ **Purpose of the research**: The overall aim of this research is to investigate the Environmental Impacts of Mining on Biodiversity and Ecosystem Services.

☐ **What you will be asked to do:** Using semi-structured questionnaires and in-depth interviews, you will be asked a series of questions regarding your perception of the current and future impact of mining on social ecological systems. You will be asked a series of questions relating to the objectives of my research (i) impacts of gold mining on biodiversity and ecosystem services (ii) influence of mining on land use dynamics and other associated socio-economic implication (iii) implications of future locations of gold mining to Key Biodiversity Areas (KBAs). Data may be recorded using audio recorder, and in written form. If photos are taken, we will request your permission to use it in either publication or presentation. The interview lasts about half an hour or one hour and you have the right to skip questions or withdraw at any time.

☐ **Benefits of the research and benefits to you**: The research is targeted to generate decision-relevant evidence and feed it into key decision-making processes to improve sustainable gold mining in Tanzania. Ultimately, we hope the people of Tanzania will benefit from reviewed mining policies, regulations, strategies and guidelines in the mining sector as influenced by the results of this research and key biodiversity areas will be better protected in the future. This research will give a better understanding of the interaction between gold mining and the environment to enhance sustainable management decisions.

☐ **Dissemination:** The report from this research will be converted to paper and published in a peer reviewed journal. We will also present results in presentations at conferences and meetings. We aim to effectively disseminate the research work within and outside the region - including both the existing and ongoing research.

☐ **Voluntary participation and withdrawal**: Your participation in the study is completely voluntary and you may choose to stop participating at any time. Your decision not to volunteer participation, or to refuse to answer questions, will not affect your relationship with the researchers, University of York, or any other group associated with this project either now, or in the future. In the event you withdraw from the study, you do not need to give reasons, all associated data collected will be destroyed. Accepting compensation or inducements does not negate your right to withdraw. This is an independent student project, and I am not affiliated with any government or charity organization.

□ **Confidentiality**: We will secure full security and confidentiality of personal data collected. All data collected will be stored in a locked facility which only research staff will have access to during and after the study. Your name will not appear in any report or publication of the research, unless you specifically indicate your consent. Your location may be using for mapping purposes. For long-term storage, data will be stored in an encrypted external hard drive.

□ **Risks and discomforts**: You have the right to not answer any questions. If you need clarification, full explanation of the research will be given in Swahili or the local dialect. Anonymity will ensure no potential in infringements of privacy or property rights. This research has been reviewed and approved by the Department of Environment and Geography Ethics Research Committee on behalf of the University of York.

Do you agree to be interviewed now? Do you have any questions about the interview or about the research project before we proceed? By taking part in this interview, you confirm that you have understood and agree to participation in this survey. Thank you for your time.

Legal rights and signatures:

I, ____ have understood the nature of the project, and consent to participate in this study conducted by Hamidu Seki from the University of York.

Signature________________________   **Date____________________**

Participant

Signature________________________   **Date____________________**

Principal Investigator

Partners and funders: Commonwealth Scholarship

Questions about the research? I will remain available to answer any questions or listen to feedback regarding the study, and you can contact my supervisors Prof. Robert Marchant by e-mail (robert.marchant@york.ac.uk), Dr Jessica Thorn (Jessica.thorn@york.ac.uk) or Prof. Andy Marshall (andy.marshall@york.ac.uk).

Individual community questionnaire

Socioeconomic information

Name of respondent_____________________ Date

____

Main livelihood activities ____

Time lived in the community (years)_____Village name: _____________________

District _________________________ Region: _________________________

GPS: Lat ______________________________ Long ___________________________

Sector ________________________________

Gender__________________________

Age__________________________________

Tribe___________________________

No of inhabitants now (approx.): ____

Changes in vegetation, biodiversity and other land uses (mainly surface)

Please describe changes in the environment you have observed in the last twenty-five years.
Imagine the area before the mine around the mine and in the district in general (see Satellite image)

1. How does mining activities influence change in land use? Compared with now, how much vegetation and other types of land use were there before they opened the mining site?

(Increases: ++; Increases slightly +; Unmodified: 0; Decreases slightly: -; Decreases: --)

Land uses	**2019**	**Just before opening the mining site**	**25 years ago,**	**Comments**
Indigenous forest				
Exotic forest				
Grassland and grazing areas				
Farmland (commercial)				
Farmland (smallholder)				

Formal settlement				
Informal settlement				
Wetlands, lakes and rivers				
Mine (Artisanal, small-scale miners)				
Other land uses (specify)				

2. In the current state, do you think any vegetation type has become particularly degraded? Yes/no
3. Please explain.

Land use	**Degraded/ Not degraded**	**Comments**
Indigenous forest		
Exotic forest		
Grassland and grazing areas		
Farmland (commercial)		
Farmland (smallholder)		
Formal settlement		
Informal settlement		
Wetlands, lakes and rivers		
Mine (Artisanal, small-scale miners)		
Other land uses (specify)		

4. Between **inside mining lease** and **outside mining lease** areas, where there is high biodiversity? Give reasons to support your answer.

Inside mining lease	**Outside mining lease**	**Comments**

5. What are the impacts/expected impacts of gold mining on the following?

Resource	**Impacts/expected impacts**	**Comments**
Water sources		
Mammals		
Avifauna		
Aquatic organisms		
Soil		
Vegetation		
Adjacent ecosystem		
Other (specify)		

6. Please provide some details of animals and plants which have become ‘difficult to find’. Name species in local language if not known scientific name

(Increases: ++; Increases slightly +; Unmodified: 0; Decreases slightly: -; Decreases: --)

S/n	**Name**	**Change**	**Comments**

Animal			
Animal			
Animal			
Animal			
Plant			
Plant			
Plant			
Plant			

7. In your opinion, do the mining companies **sufficiently/effectively** support biodiversity conservation? Yes/No

8. If yes in (vii) above, what support are they giving?

Activities	**Tick (√)**	**Comment**
Provide biodiversity monitoring fund		
Initiate restoration and rehabilitation on impacted areas		
Biodiversity offsets		
Provision of anti-poaching funds		
Recruitment of biodiversity managers onsite		
Recruitment of Environmental officers onsite		
Others (Specify)		

9. Are there any restoration/rehabilitation efforts done by mining companies on the impacted areas? Yes/No

10. If yes, please explain what they are doing.

11. Which are the consequences of mining on the following ecosystem services? Please provide some details.

Supporting services	**Tick (√)**	**Comments**
Soil formation		
Nutrient cycling		
Water cycling		
Provisioning services		
Water		
Food		
Energy (fuelwood)		
Building material		
Fodder / Pasture for cows		
Local medicine		
Non-timber forest products incl. Wild fruits and honey		
Regulating service		
Carbon sequestration and climate regulation		
Detoxification		
Purification of water		
Pest and disease control		

Cultural services		
Recreational activities		
Spiritual (space for ceremonies)		
Aesthetic beauty		
Tourism		

12. Between **inside mining lease** and **outside mining lease** areas, where there is high degradation? Give reasons to support your answer in (v) above

Inside mining lease	**Outside mining lease**

<u>Socio-economic impacts of mining</u>

13. Are there any changes or shifts of social-economic activities brought by mining activities in your village in the last 25 years? Yes/no.

14. If yes, what are these changes?

Changes in socio-economic activities	Reference of change

15. How does mining operation impact (benefits/tradeoffs) the adjacent communities? (Tick where appropriate)

Factor	**Benefits (opportunities)**	**Tradeoffs (risks)**	**Comments**
Employment			
Income			
Health and mental wellbeing			
Safety			
Gender equality			
Social services			
Child labor			
Education			
Population size			
Transport and roads			
Traditional cultural beliefs and practices			
In migration (seasonal or permanent) (mobility)			

Out migration (seasonal or permanent)			
Electricity or energy access (e.g., fuelwood)			
Other (specify)			

16. Who will benefit from the mining operations? (**Rank the following**)

Beneficiaries	**Ranks (1, 2, 3, 4……….)**	**Comments**
Central government		
Local government		
Mining companies		
Mine (Artisanal, small-scale miners))		
Immigrants		
Middlemen/women		
Others (Specify)		

17. Who will lose out from mining operations? (**Rank the following**)

Beneficiaries	**Ranks (1, 2, 3, 4……….)**	**Comments**
Central government		
Local government		
Mining companies		
Artisanal mining companies		
Immigrants		
Middlemen/women		

Children		
Fishermen		
Farmers		
Pastoralists		
Others (Specify)		

18. Are there cities or towns that have evolved/developed due to mining influence? Please describe this change (e.g., immigration, water scarcity, or social services improved).

City/town	**Description of change**

19. Since the initiation of the mine, do you think that mining has brought changes in cultural values in the area? Yes/no.

20. If yes, what are these changes?

Group	**Cultural change**
Youth	
Elders	
Men	
Women	
Other (specify)	

21. Are there any conflicts that have arisen because of the mining activities? Yes/No

22. If yes, what are the types of conflicts and their causes (select all which apply)?

Type of conflict	Yes/no	Cause
Conflict between communities and miners		
Conflict between members of a community		
Conflict between small scale and large-scale miners		
Conflict between government and communities		
Conflict between conservation agencies and miners (e.g., TANAPA, TFS)		
Conflict between government and mining companies		
Others (specify)		

23. What are the approaches used to mitigate these conflicts when they occur?

Approach	Tick (√)	Comments
Through mediation		
Through reconciliation and reconstruction programs		
Through greater stakeholder participation during project planning, implementation, and management		
Through compensation and social support		
Through use of force e.g., Army interference		
Withdrawing		
Accommodation of the other parties’ needs		
Other (specify)		

<u>Economic impacts</u>

24. How is mining effecting other sectors? (Please indicate with comments)

Sector	**Positive effect**	**Negative effect**	**No effect**
Agriculture			
Forestry			
Wildlife			
Tourism			
Industry			
Energy			
Transport			
Education			
Health			
Informal economies			
Other sectors (specify)			

25. What are the secondary economic activities which are attracted around the mining locations? (Please rank them starting with the most important economic activities)

Economic activities	**Rank (1,2,3,4….)**

26. What are economic risks of gold mining?

Future trajectories

27. What lessons have you learnt from past gold mining activities and opportunities for future acceptance of gold mining projects in Tanzania? (Free list)

28. What will be the influence of gold mining in the future development?

Concluding questions

29. Do you have any other comments or questions about the research?

30. Would you like to receive the results of the survey and if so, how can we get in contact with you?

31. Do you have any recommendations of other relevant stakeholders to interview?

End of survey.

5.9 Supplementary materials

5.9.1 Socio-economic and demographic characteristics of respondents

The difference in socio-economic and demographic characteristics of respondents between three surveyed sites was insignificant ($p > 0.05$).

Variable	Location			Total n = 180 (%)	*p*-Value
	Songwe	**Singida**	**Geita**		
Geder					
Male	41 (68.3)	37 (61.7)	40 (66.6)	118 (61.6)	1.00
Female	19 (31.7)	23 (38.3)	20 (33.3)	62 (34.4)	
Age category					
18 - 28	0 (0)	3 (5)	1 (1.7)	4 (2.2)	0.85
29 - 39	19 (36.7)	17 (28.3)	11 (18.3)	47 (26.)	
40 - 50	21 (35)	22 (36.7)	19 (31.7)	62 (34.5)	
51 - 61	9 (15)	15 (25)	17 (28.3)	41 (22.8)	
>61	11 (18.3)	3 (5)	12 (20)	26 (14.4)	
Time lived in the area					
≤10 years	0 (0)	1 (1.7)	0 (0)	1 (0.6)	0.99
11 - 20 years	2 (3.3)	1 (1.7)	2 (3.3)	5 (2.8)	
21 - 40 years	26 (43.3)	23 (38.3)	31 (51.7)	80 (44.4)	
41 -60	27 (45)	33 (55)	20 (33.3)	80 (44.4)	
>60 years	5 (8.3)	2 (3.3)	7 (11.7)	15 (7.8)	
Occupation (Multiple responses)					
Agriculture	40 (66.7)	52 (86.7)	55 (91.7)	147 (81.2)	0.39
Livestock keeping	0 (0)	16 (26.7)	5 (8.3)	21 (11.7)	
Fishing	27 (45)	0 (0)	1 (1.7)	28 (15.6)	
Small scale mining	35 (58.3)	5 (83)	32 (53.3)	72 (40)	
Business	43 (71.7)	14 (23.3)	53 (88.3)	110 (61.1)	

CHAPTER SIX

6 Indirect impacts of commercial gold mining on adjacent ecosystems

6.1 Abstract

Mining is important for economic development in many tropical countries, but it can have serious impacts on biodiversity, both directly through operations at extraction sites, and indirectly via wider social-economic development. However, mitigation efforts by large-scale mining operators focus almost exclusively on extraction sites. We provide the first assessment in Tanzania of mining impacts on vegetation structure and biodiversity with increasing distance from three commercial gold mines of varying ages (0 years, 8 years, and 19 years since establishment).

We show that mining is associated with impacts that manifest largely outside operational lease boundaries. At the two older mine sites, aboveground carbon and tree stem density are significantly higher within lease boundaries compared to outside, while there is no such effect at the new site. Further, tree stem density, aboveground carbon, and tree and butterfly species richness all decrease with increasing distance from extraction sites, with these effects again increasing with mine age. Frugivorous bird species richness is lower outside older mines, while abundance declines in frugivorous and granivorous birds are associated with declines in tree stem density, which may have implications for forest regeneration.

These impacts result from new and expanding settlements around mining concessions between 2000-2019 and associated demand for timber and wood fuel. We recommend rigorous, integrated impact assessments and conservation planning in mining landscapes, to pre-empt the development of settlements and secondary industries around mining sites and so balance outcomes across the mining sector, natural resource-based and other livelihoods, and conservation agendas.

Key words: biodiversity, ecosystem services, indirect impacts, mining concessions, Tanzania

6.2 Introduction

Mining is an important driver of global economic development but can pose serious threats to biodiversity (Asner et al., 2013; Swenson et al., 2011). However, the mechanisms of how mining leads to beneficial or adverse biodiversity outcomes are poorly documented (Estrada et al., 2017; Hughes, 2017; Kehoe et al., 2020). In some instances, the direct impacts of mining on biodiversity are considered minimal due to the relatively small footprint of mining operations (Alvarez-Berríos and Aide, 2015). In other cases, the indirect impacts driven by population growth around mining areas can be significant, not only on biodiversity but also a range of ecosystem services, such as carbon sequestration, soil regulation, pollination, and water quality (Csillik and Asner, 2020; Roy et al., 2018; Swenson et al., 2011; Tollefson, 2019). Yet, indirect impacts are often overlooked (Mancini and Sala, 2018; Sonter et al., 2014).

Commercial mining investments can help stimulate local economies, increase income and business opportunities, and improve infrastructure and social services for adjacent communities (Raufflet et al., 2014; Sonter et al., 2017). These cumulative socio-economic incentives attract significant in-migration, resulting in local population expansion and development adjacent to the mine lease (Mancini and Sala, 2018). Such activities depend on the redistribution policies of the mining company and often are implemented under Corporate Social Responsibility programs (Rawashdeh et al., 2016). Subsequently, local demand for land, charcoal, fuelwood, and roads grows, as does the knock-on impacts on deforestation and fragmentation due to greater access to natural resources (Kitula, 2006; Weng et al., 2013). Overall, these activities drive land cover change beyond the lease boundary of mining operations (Sonter et al., 2017). However, the spatial-temporal scale of these indirect impacts has not previously been quantified, making restoration or mitigation in the tropical countries highly challenging.

In sub-Saharan Africa, a reform of mining legislation and policies has attracted many multinational mining companies (Pedersen et al., 2019), which escalated large scale mining investments in mineral rich landscapes (Hilson, 2012a, 2019). While the main aim of reformed legislation was to increase the financial benefits to African governments from the mining sector (Poncian, 2018), the reforms lack consideration of dealing with environmental impacts of mining on biodiversity and other ecosystem services. This is because most governments in Africa, are lured by the prospect of gaining, financially, through royalties and taxes (Ayanoore and Hickey, 2022), and tend to forget on the impacts of these big mining project to the environment (Kolala and Umar, 2019). Availability of mining concessions can attract further exploration activities from mining companies, putting more pressure to biodiversity (Roy et al., 2018). For example, Tanzania has over one thousand unexploited mining concessions (https://www.gmis-tanzania.com/), which are expected to attract further mining investment and hence escalate mining operations and associated biodiversity alteration (Roy et al., 2018).

In response to recent global and Africa-wide expansions in mining operations (Rubbers, 2020), Tanzania, like many countries, has established environmental regulations that are observed by mining companies, e.g., the Environment Management Act no. 20 of 2004. However, government regulations more specific to mining often make no mention of biodiversity, e.g., the Mining Act no. 14 of 2010 in Tanzania. As a result, internationally operating companies tend to comply with international mining standards to maintain brand reputation. These standards address social, cultural, economic, governance, human rights, and environmental sustainability considerations (Meadows et al., 2019). Examples of environmental standards that advocate for biodiversity sustainability in mining include: The Equator Principles of the International Finance Corporation Performance Standards; International Organization for Standardisation's ISO 26000 Guidance on Social Responsibility; Good Practice Guidance for Mining and Biodiversity by International Council on Mining and Metals; and the Global Reporting Initiative (Esteves et al., 2012). However, standardised quantification of mining impacts on biodiversity by collecting quality data using consistent methods and sufficient survey effort, are still lacking (Dias et al., 2017). Without governance settings that makes decisions based on such evidence, the implementation of international standards will have limited impact. Thus, more efforts are needed to quantify impacts of mining on biodiversity and ecosystem services, and the potential benefits and trade-offs to the wellbeing of the adjacent communities.

Here, we determine the indirect impacts of gold mining on vegetation composition, biomass, structure, and biodiversity indicator taxa at three case study sites in Tanzania. To capture spatial and temporal change associated with mining operations we assess these impacts with distance from commercial gold mines of varying ages. We use the results to propose a mitigation strategy for new mines to combat the inevitable effects of adjacent urban expansion. We hope our results will help optimise synergistic outcomes between gold mining, natural resource-based livelihoods, and conservation agendas, both in Tanzania and more generally across the Global South.

6.3 Material and methods

6.3.1 Study sites

We used a chronosequence approach to assess three commercial gold mines of varying age – which we called new (0 years), intermediate (8 years) and old (19 years) mines – located in the Southern Highlands (Mbeya region), Central (Singida) and Lake zone (Geita) of Tanzania. All sites span several Key Biodiversity Areas (KBAs) and Important Bird Areas (IBAs) for Tanzania (Frost, 1996; Kitula, 2006), while Mbeya site is bordered with 23,550 ha Patamela Forest Reserve. The prevailing natural ecosystem at all three sites is miombo woodland, a globally important priority ecosystem for conservation (Mittermeier et al., 2003). The Singida site is moreover characterised by Itigi thicket, a restricted ecosystem occurring in Zambia and Tanzania (White, 1983). Both ecosystems are highly valuable in delivering provisioning ecosystem services and consist of endemic and threatened species such as *Dalbergia melanoxylon* Guill. & Perr (African Blackwood) and *Bussea massaiensis* (Taub.) Harms. However, the Itigi thicket in central Tanzania has lost 65% of its total cover since 1967 (Baena et al., 2016), while miombo woodland is also under threat (Jew et al., 2016). Additionally, ecological surveys were conducted in the same sites selected for socio-economic surveys in chapter 5.

Mining and quarrying are prominent in the Lake zone due to the presence of the nation’s largest goldfield at Lake Victoria (Henckel et al., 2016). Discovery of the nation’s second largest goldfield at Lupa in 1922 expanded the importance of mining in the Southern Highlands (Gallagher, 1939). Mining is also becoming an important economic activity in central Tanzania, especially in the Singida and Tabora regions (United Republic of Tanzania, 2014). The main economic activities surrounding the study sites include commercial and small-scale agriculture, which contributes to 26.7% of the national GDP followed by livestock (7.4%), forestry (4%), fishing (1.4% of GDP, or 35% rural employment) (Food and Agriculture Organization, 2021).

Between 2002 and 2012, the human population in Geita, Singida, and Mbeya increased from 1.3 to 1.7 million (2.5%/a growth), 1.0 to 1.4 million (2.3%/a) and 2.0 to 2.7 million (2.7%/a), respectively (United Republic of Tanzania, 2014). This growth resulted from both natural population growth and in-migration of people seeking mining and agriculture employment, business opportunities, and other income-generating activities, with corresponding impacts on land use. In the three mining regions, between 2000 and 2019, built-up areas (defined as the union of all spatial units containing buildings or part of it - Pesaresi et al., 2016) and cropland with scattered settlement, increased by 14% and 20% at the intermediate site and 39% and 56% old at the old site, respectively. Annual rate of change for built-up areas and agriculture with scattered settlement increased from 1% and 3% before mining to 7% and 11% after mining at the intermediate site while annual rate of change for the same land cover increased from 6% and 24% before mining to 13% and 43% after mining at the old site (Seki et al., in review). All of these events reflect an increase in human population adjacent to mining landscapes, as observed previously for Geita Gold Mine (Lange, 2006).

Population increased since the opening of the old mine site, from 595,475 in 2002, to 807,619 in 2012, while for the same period in intermediate site, the population rose from 205,915 to 290,478 and in the new site the population rose from 209,908 to 272,959 (The United Republic of Tanzania, 2013). By 2019, the population was projected by Tanzania National Bureau of Statistics as 996,336, 368,529 and 327,444 at the old, intermediate, and new sites respectively.

6.3.2 Sampling design

We collected data on trees, birds, and butterflies between March and July 2019. To establish the sampling regime, we first digitised the boundaries of the commercial gold extraction pits within lease boundaries using Google Earth, and then generated spatial buffer zones at 500 m increments up to 5 km from each mine. We determined sample point locations using stratified random sampling, designed to capture geographic variation across the landscape. Within each 500 m distance band and habitat type, we sampled at 4 to 7 random points, resulting in 60 to 90 sample points per mine and 211 points in total, some of which were laid outside, and some inside, the mining lease (Figure 25). Sampling points within 500 m of one another were rejected to avoid pseudo replication.

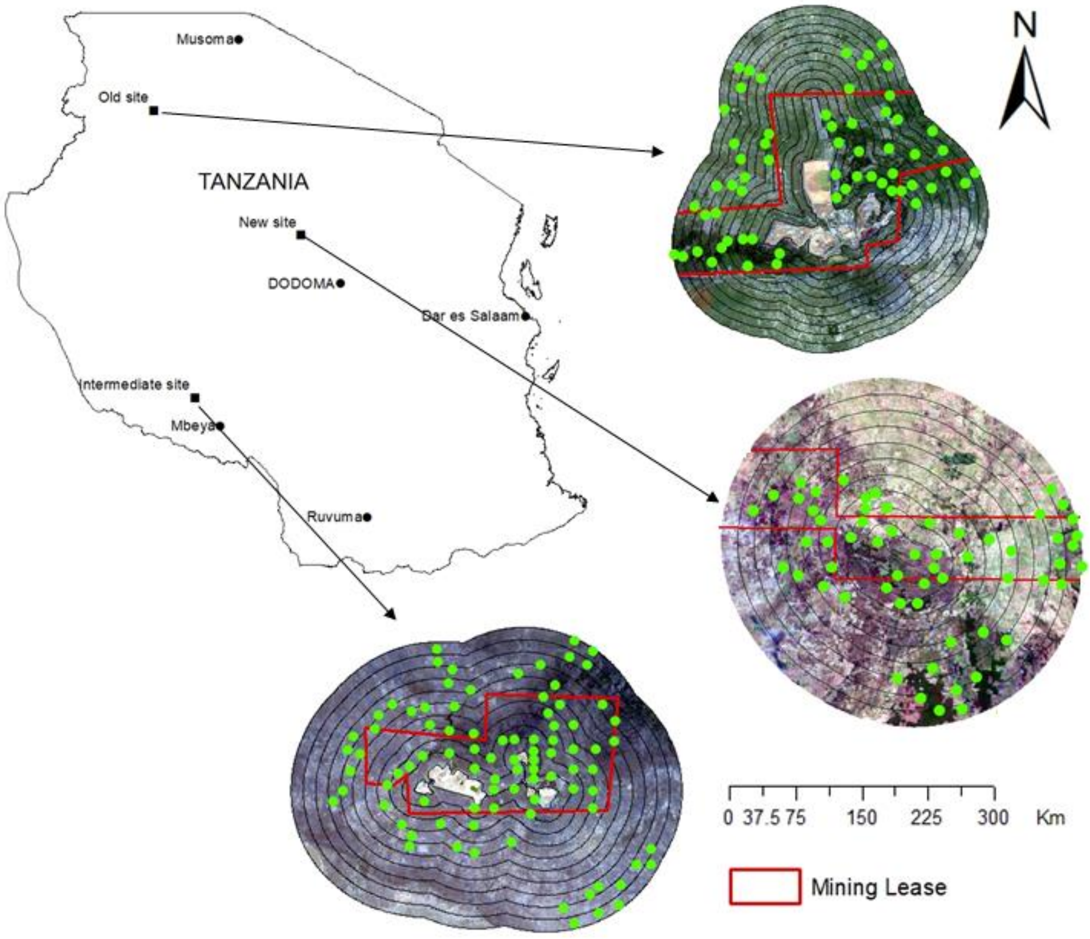

Figure 25. Location of three sites for assessing the impacts of mining in Tanzania. Green points are randomised sampling locations, stratified within concentric circles (500 m distance bands), mining lease boundaries (red lines), and habitat type around each mine site. Background images are Sentinel imagery from https://earthexplorer.usgs.gov/. Imagery taken on 15th August 2018 were selected and downloaded in March 2019 for all three sites.

6.3.3 Tree survey

Trees were surveyed to understand the main impact of gold mining on ecosystem composition, biomass, and structure. At each sample point, we surveyed plots of 20x40 m (0.08 ha) within which all trees with diameter at breast height (dbh) ≥ 5 cm were measured. For trees ≤10 m, we measured the height of all the stems in each plot using a pole of 10m. For trees ≥10 m, we measured the height using a laser range finder (following Marshall et al., 2012). We identified all the trees in the plot to a species level *in situ*, where possible. For trees that could not be identified, samples were collected by a botanist and taken to the National Herbarium of Tanzania for further identification. All tree species included in the analysis were identified to species level.

6.3.4 Birds and butterflies survey

Birds and butterflies were sampled to determine the impact of gold mining on their distribution, composition, and richness. At each sample point, an ornithologist with extensive experience of birds (see Acknowledgements) in the study regions counted the number of individuals per species in a fixed station of 50 m radius (which was determined by laser range finder; Thomas et al., 2010. We adopted this point count method because birds could be counted from a fixed location due to the relatively open habitat in all sites (Sutherland, 2006). Recording lasted for 30 minutes, which is sufficient to avoid the under-estimation of rarer species (Sorace et al., 2000). Before commencing each count, we waited for five minutes to allow the bird population to come to "rest".

To survey butterflies, we used direct observation and sweep nets (Oliver and Beattie, 1996; Sutherland, 2006). This involved walking slowly within 50 m radius assessment points, counting the number of individuals per species, and capturing at least one individual of each species for identification. All individual butterflies captured were released immediately after a successful identification.

6.4 Data analysis

6.4.1 Structural data

We used aboveground carbon stock (AGC) and stem density to measure the structural intactness of the ecosystems, hence inferring the mining's impact on both biomass and potential for carbon sequestration. We estimated AGC using an allometric equation for biomass developed for tropical vegetation, multiplying by 48% (Martin et al., 2018) to convert biomass to carbon, giving the following equation (Réjou-Méchain et al., 2017):

$$AGC = (0.0673 \times (\rho \times \text{height} \times \text{dbh}^2)^{0.976}) \times 0.48$$

where

ρ = wood specific gravity (WSG [g cm^{-3}]), from the Global Wood Density Database (Zanne et al., 2009)

height = tree height (m)
dbh = diameter at breast height (cm)

WSG was obtained at species level for 42.0% of stems, and otherwise obtained at the nearest taxonomic unit (genus 50.6%, family 6.1%) or failing that, for all remaining taxa in the same plot (1.2%).

6.4.2 Species and abundance data

Species richness of each taxonomic group was estimated as total number of species in each 0.08 ha plot (for trees), or in each 50 m circle (for birds and butterflies). To account for sample size bias in species richness, rarefactions were computed for each taxonomic group (Chao et al., 2014), using EstimateS 9.1.0 (Colwell et al., 2012). For trees, we also used Species IVI, to disentangle species composition within and outside lease boundaries in each of the sites (new, intermediate, old). Species IVI is an index to assess species composition, dominance, and distribution (Kacholi, 2014; Mwakalukwa et al., 2014), and was calculated for each tree species using the following equation (Curtis and McIntosh, 1951):

$$\text{IVI} = (\text{relative frequency} + \text{relative basal area} + \text{relative density})/3$$

6.4.3 Bird foraging guilds

To investigate potentially causal links between vegetation change and impacts on birds, at each sampling point we investigated the functional diversity of foraging guilds (categorised as frugivores, granivores, omnivores, insectivores, and carnivores; Bennun et al., 1996). Functional traits summarise a species' role in an ecosystem (e.g., their foraging behaviour), and are increasingly used to prioritise conservation efforts by indicating the extent to which ecosystem stability has been gained or lost through changes in the relative abundance of species with similar traits, i.e., changes in functional redundancy (Bihn et al., 2010; Pla et al., 2012; Thorn, 2016).

6.4.4 Statistical analysis

All statistical analysis was carried out using R version 3.6.2 (R Core Team, 2019). We used generalised linear models (GLM) with a Gaussian error function to determine the influence of different variables on stem density, AGC and species richness for the three taxonomic groups (trees, birds, butterflies) separately for each site. To understand structural variation, the stem density GLM was carried out for three different stem size classes (i.e., ≥10 – 19.9 cm, ≥20 – 29.9 cm, and ≥30 cm). We used six predictor variables to represent disturbance and environmental gradients: elevation, distance from the extraction pits which we coined as distance from the mine, presence/absence of large scale mine, distance from settlements, roads, and charcoal production areas. Before running the models, predictor variables were explored for intercorrelation using Pearson correlation (r) and Variance Inflation Factors (VIF) following Marshall et al. (2012). Variation in AGC and stem density within and outside lease boundaries was also tested using a permutation test (Fraker and Peacor, 2008)

All surveyed plots were included in the analysis for each site, except for 13 plots in the intermediate site. This is because these plots were in a Government Forest Reserve and thus interpretation about disturbance from mining would have been influenced by the level of protection. We did however separately assess biodiversity and biomass within the reserve, compared to other points at the same site.

Minimum adequate GLMs was obtained by the evaluation of set of alternative different models made of exhaustive combination of predictor variables based on our knowledge on the data and research question. Each alternative full model for each site comprised a selection of non-correlated predictor variables in various combinations, plus the primary predictor variable of interest (i.e., distance from the mine, presence/absence of large scale mine). Predictor variables that had non-linear relationship with the response variable were fitted by quadratic terms. Final models were validated by observing the spread of residual patterns.

We used redundancy analysis (RDA; Legendre and Andersson, 1999) to determine the influence of variation in species composition within each mining area. For this analysis we added rarefied tree species richness and aboveground carbon as predictor variables to those used in the GLMs.

Hellinger transformation was applied to matrices of species to evade problems associated with the Euclidean distance. For the redundancy analysis, to reduce Type I error from full (global) models, forward selection was applied to retain predictor variables that explained the most variation.

We used variation partitioning to determine the percentage variation in species composition explained by each predictor variable and determined statistical significance by a Monte Carlo permutation test (n = 1000).

6.5 Results and discussion

6.5.1 Stem density and Above Ground Carbon

GLMs revealed negative, linear relationships with the distance from the mine for stem density in all dbh classes at the intermediate site and non-linear relationships for dbh ≥ 20 – 29.9 cm and dbh ≥30 cm at old site (Figure 26a-c). For AGC, GLMs revealed a negative, non-linear relationship with distance from the mine for AGC in the old site (Percentage deviance explained, %*D* = 59, AIC = 620.59, *t* = 7.201, *p* = 0.001) and negative, linear relationships in the intermediate site (%*D* = 25, AIC = 960.24, *t* = 12.423, *p* = 0.001) (Figure 26d). Stem density was significantly higher within lease boundaries at the old (*F* = 6.3, *p* = 0.001) and intermediate (*F* = 5.2, *p* = 0.001) sites. AGC was also significantly higher within compared to outside lease boundaries at the old (*F* = 6.1, *p* = 0.001) and intermediate (*F* = 5.8, *p* = 0.001) sites. The differences for stem density and AGC inside versus outside the lease boundaries were not significant at the new site. Summaries of the model results are shown in Appendix 2.

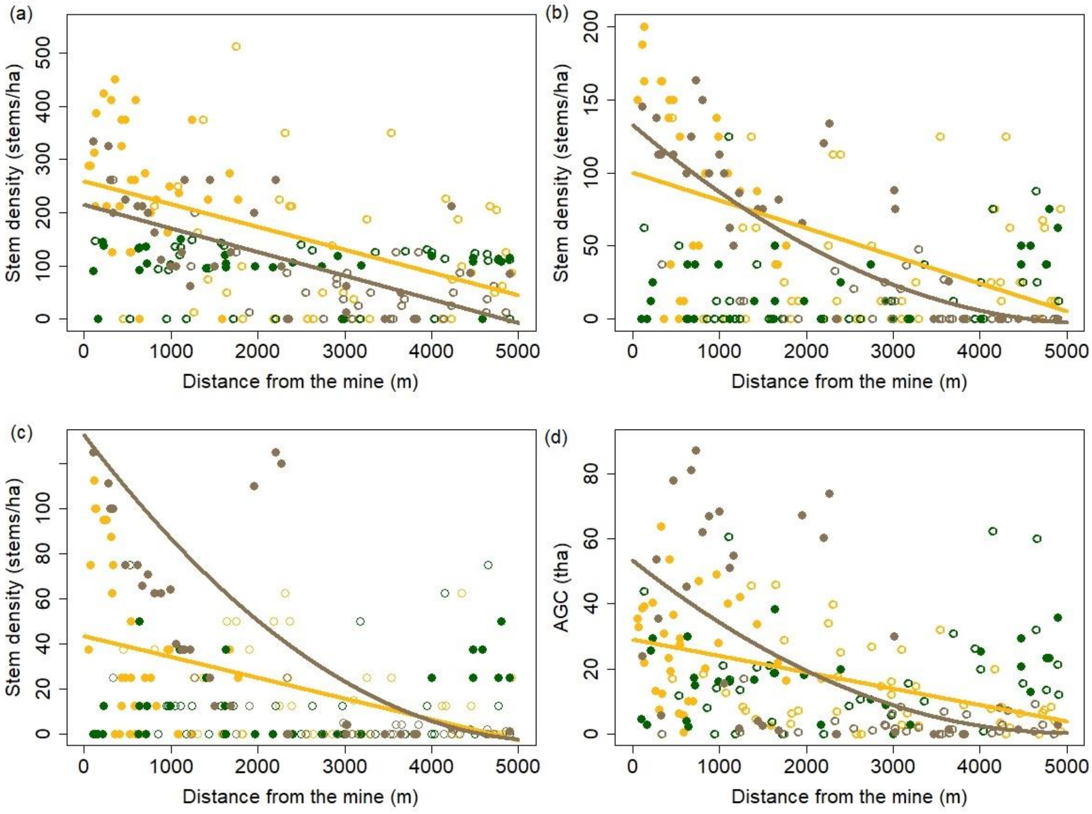

Figure 26. Relationships between AGC and stem density versus distance from the mine, showing GLM trendlines.

(a) dbh ≥10 – 19.9 cm, (b) dbh ≥ 20 – 29.9 cm (c) dbh ≥30 cm and (d) AGC. Age of mine sites: green = new; yellow = intermediate; brown = old. Symbols: filled circles = within lease boundaries, open circles = outside lease boundaries. Mine site with no lines showed no significant trends. *%D* for the intermediate site (dbh ≥10 – 19.9 cm = 22, dbh ≥ 20 – 29.9 cm = 19, dbh ≥30 cm = 32), *%D* for the old site (dbh ≥10 – 19.9 cm = 47, dbh ≥ 20 – 29.9 cm = 61, dbh ≥30 cm = 65).

We attribute these results to increased anthropogenic pressure beyond lease boundaries as mines age. While the establishment of large-scale mines can help to protect local biodiversity (i.e., within the lease area, notwithstanding the direct impacts of active mining operations), mines typically do not protect biodiversity adjacent to the mine lease due to indirect impacts. This provides empirical support for previous research that assessed deforestation rates using satellite imagery in the Brazilian Amazon (Sonter et al., 2017), which found that deforestation was far greater outside lease. Similarly, in our study while we attribute the high stem density and AGC within the lease boundary of operation to environmental compliance by mining companies in Tanzania (as indicated in the Environmental Management Act no. 20 of 2004), we find evidence for increased utilisation of natural resources beyond lease boundaries. However, this was not the case at the new site, where there has been very limited time for in-migration and thus lesser impact on adjacent ecosystems compared to the more established sites. The increasing non-linearity of stem density decline with stem size further shows that large trees were the most affected at the older mines. Abundant medium to large trees species in the genera *Brachystegia* and *Julbernadia* tends to be targeted for charcoal and firewood (because they give good embers, hot fire, burn easily for a long time (Chomba, 2018)), while small to medium trees of various species are targeted for timber and poles for building construction. Large stems of less abundant species such as *Pterocarpus angolensis* DC, *Pterocarpus tinctorius* Welw, *Afzelia quanzensis* Welw and *Pericopsis angolensis* (Baker) Harms are also utilised for timber. The high demand of these tree species for charcoal, firewood and timber has also been reported in other parts of Tanzania (Jew et al., 2016; Manyanda et al., 2020).

The continuous utilisation of trees will have resulted in considerable CO_2 release to the atmosphere (Csillik and Asner, 2020). Our observed progression from linear to non-linear negative trends with mine age indicate increasingly degraded ecosystems and AGC near to ageing mines, due to excessive selective removal of large stems. AGC emission from gold mining has also been reported in the Peruvian Amazon (Csillik and Asner, 2020), Guyana (Brown et al., 2020) and Australia (Mudd, 2007). Similarly, decrease in AGC from legally managed to unmanaged landscapes has also been reported in Zambia (Kutsch et al., 2011).

In the intermediate site, stem density was significantly higher in the Government Forest Reserve (F = 4.9, p= 0.001) than in other plots of similar distance bands.

The mean AGC was also higher in the forest reserve (45 t/ha) than in than other plots (22 t/ha). This emphasizes that the impact of mining has the potential to be mitigated by establishing protected areas within mining catchments. However, one potential risk is leakage or spillover to adjacent areas, whereby protected areas displace land use activities that are harmful to conservation, such as mining or illegal logging (Fuller et al., 2019)

6.5.2 Species richness and functional diversity

GLMs revealed negative, linear relationships with distance from the old mine, for tree species richness (%D = 57, AIC = 570.31, t = 6.725, p = 0.001) and butterfly species richness (%D = 7.3, AIC = 925.142, t = 11.252, p = 0.1), and a positive, linear relationship for bird species richness (%D = 7.3, 824.253, t = 13.651, p = 0.1) (Fig. 27). The positive distance trend for bird species richness was reversed for frugivorous birds, showing a progressively stronger negative relationship with mine's age. At the intermediate site, the relationship was negative for tree species richness (%D = 40, AIC = 610.81, t = 8.262, p = 0.001) and not significant for butterflies and birds. We found no significant relationships with increasing distance from the new site. Similarly, while the new and intermediate sites showed non-significant differences in species richness inside versus outside the lease boundaries, tree species richness was significantly higher within the lease boundary at the old site compared with outside (F = 5.6, p = 0.001).

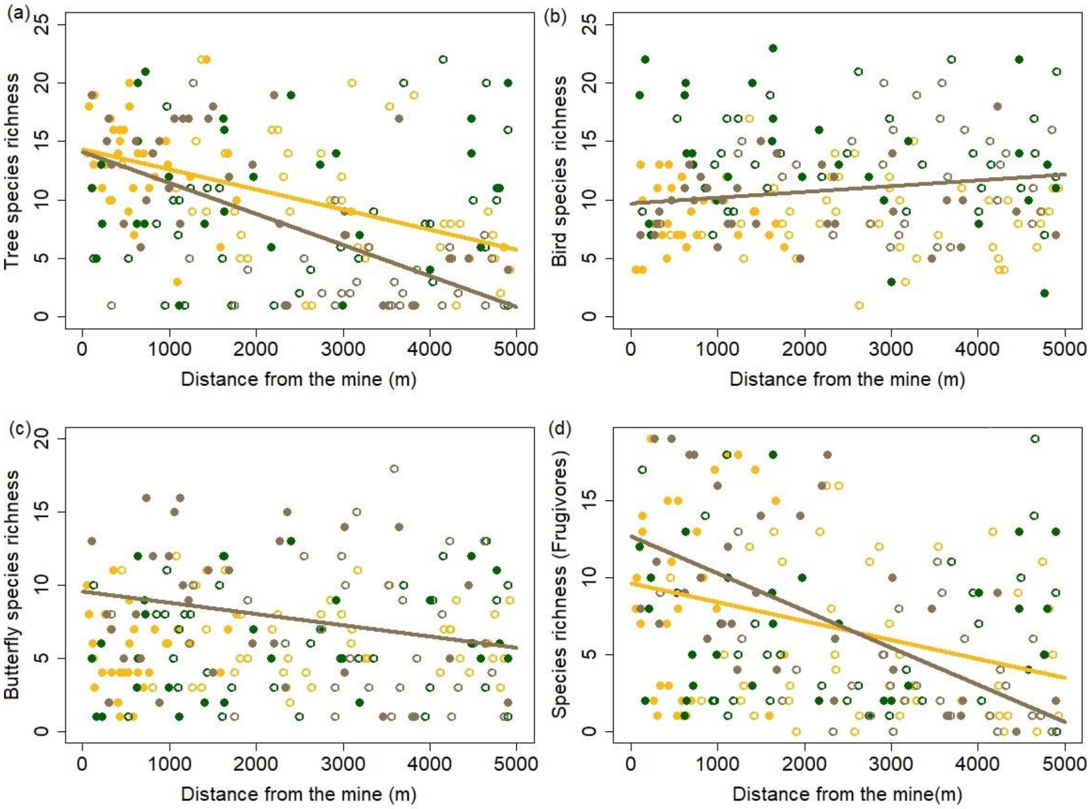

Figure 27. Relationships between biological ecosystem attributes and distance from the mine, showing GLM trendlines.

(a) tree species richness, (b) bird species richness, (c) butterfly species richness, (d) frugivores species richness. Age of mine sites: green = new; yellow = intermediate; brown = old. Symbols: filled circles = within lease boundaries, open circles = outside lease boundaries. Mine sites with no lines showed no significant trends.

The tree, butterfly and frugivorous bird species richness data somewhat mirror the stem biomass/density data, i.e., negative effects increasing with the mine’s age. Negative effects in this case are the decline of biodiversity components with increasing age of the mine. Changes in species richness could be explained by the increased conversion of natural vegetation to other land uses and a growing demand for specific tree species. This has resulted in the disruption of the vegetation structure and reduced number of species beyond lease boundaries. This information adds to what has been reported in the southern highland (Jew et al., 2016), Malawi (Yamashina et al., 2021) and other parts of the East Africa (Jimu et al., 2017), where they found that the loss of species was associated with other factors including high charcoal production, timber, tobacco curing and building poles – although authors did not study mining activities.

We also found a significant increase in the richness of granivores and frugivores in high carbon areas (i.e., those areas with the highest density of large trees), which may be due to the availability of food (Figure 28). Relationships were weaker for granivores, only showing a significant relationship for the old mine site. While the positive relationship observed for overall bird richness versus mine distance appears to contradict the general trend, this resulted from the lack of relationships observed for non-frugivorous and granivorous birds.

Thus, we infer that the indirect impacts of mining have led to decreasing habitat suitability for (particularly frugivorous) birds, and hence greater dependence on the few remaining trees at older mine sites. The greater dependence of frugivores on tree biomass across the mine sites is likely due to their greater dependence on large trees with fleshy fruits (Deikumah et al., 2014). Since frugivores play a vital role in seed dispersal, the indirect impacts of mining on frugivore populations could hinder forest regeneration (Farwig et al., 2017; Jordano et al., 2011).

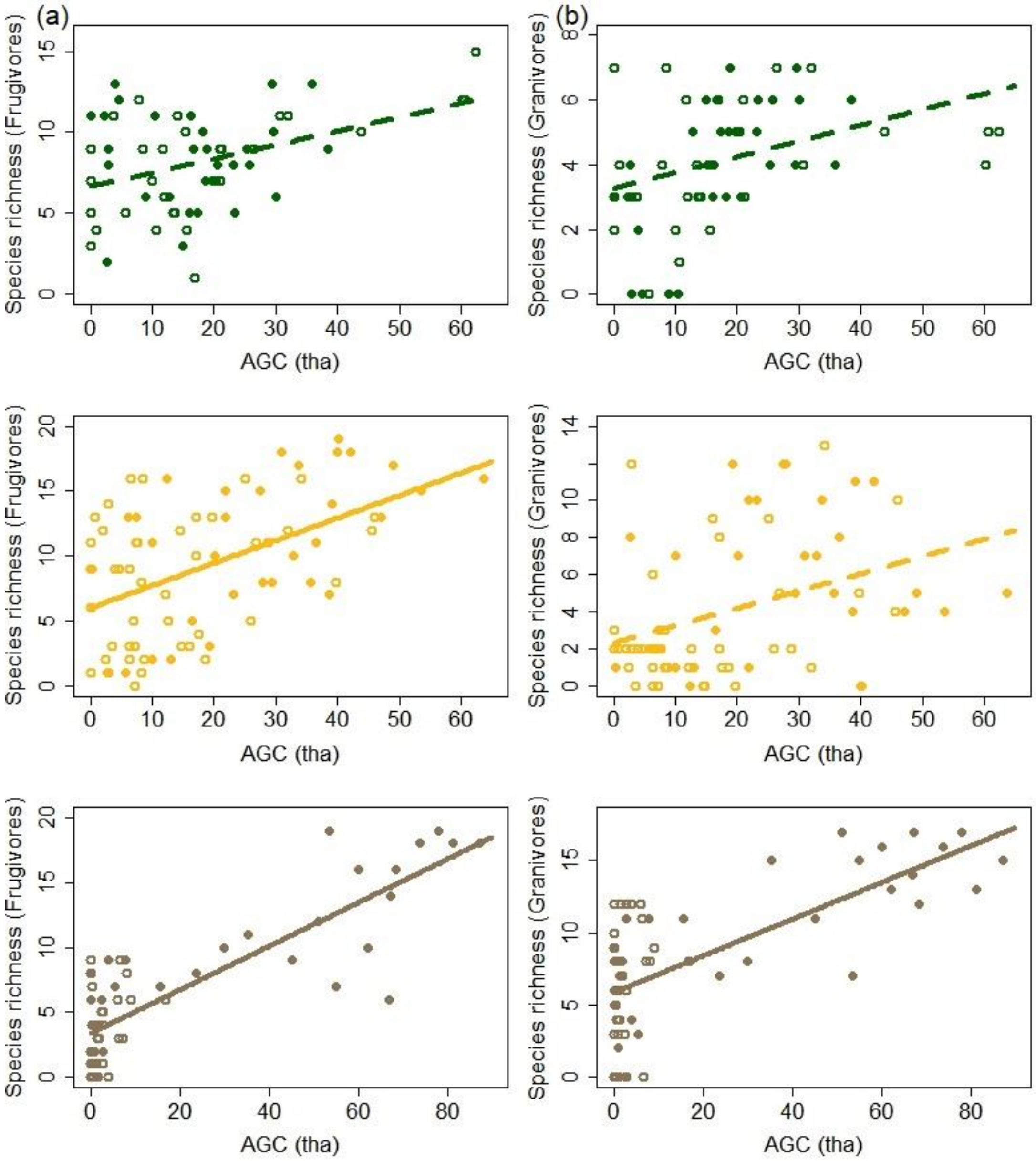

Figure 28. Relationships between bird foraging guilds (frugivores and granivores) versus AGC, showing GLM trendlines.

(a) column = frugivores. (b) column = granivores. Age of mine sites: green = new; yellow = intermediate; brown = old. Symbols: filled circles = within lease boundaries, open circles = outside lease boundaries. Dashed lines indicate non-significant relationships. *%D* for frugivores (intermediate site = 70, old site = 82). *%D* for granivores = (intermediate site = 23, old site=80).

6.5.3 Species composition

The redundancy analysis revealed that species composition varied significantly within versus outside mine leases (trees), with distance from settlements (trees, birds), with distance from the mine (birds), with tree species richness (birds, butterflies), and with elevation (butterflies) (Figure 29). Tree species richness and elevation had positive effect on birds and butterfly species composition at the old site. While the presence of the lease boundary affected tree species composition at the intermediate site, there was no indication of the anthropogenic drivers to influence species composition at the new site. Thus, these findings largely mirror the previous data, showing altered ecosystem properties because of increasing indirect effects with increasing age of the mines.

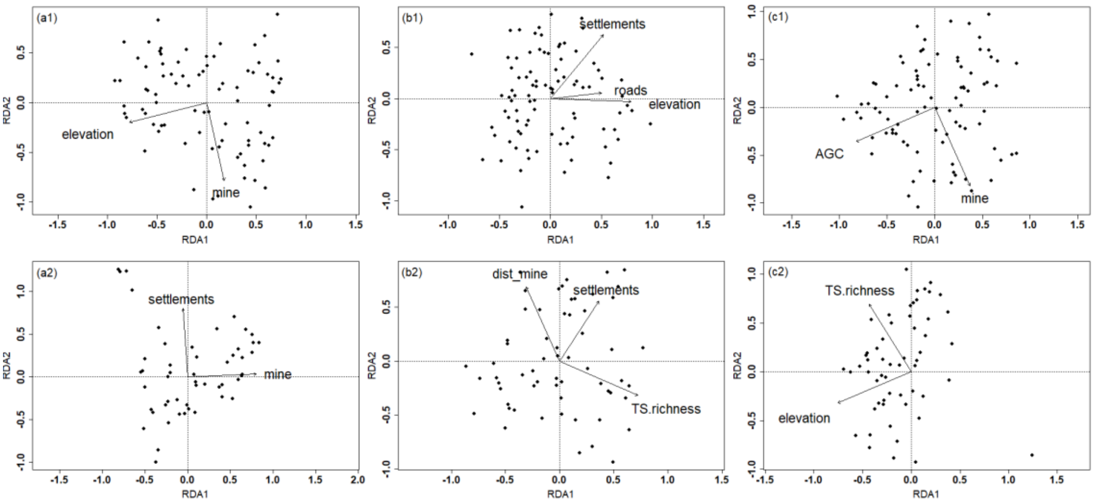

Figure 29**.** Redundancy analysis (RDA) attribute plot for different taxonomic indicator taxa. Plots shown are for sites with significant relationships.

(a) = tree species, (b) = bird species and (c) = butterfly species. Numbers: 1 = intermediate site, 2 = old site. Variables which had a significant association with species composition are represented by arrows: elevation = height above sea level (m), mine = within or outside mine lease, settlements = distance from settlements, roads = distance from the roads, AGC = above ground carbon, dist_mine = distance from the mine and TS.richness = tree species richness. Mine site that has not shown in the graph showed no significant trends. Statistical summaries for these relationships are given in Appendix 3.

The observed trends within compared to outside of the mining leases were largely driven by keystone miombo species from the genera *Brachystegia* and *Julbernadia* and timber species such as *Pterocarpus angolensis* DC, *Pterocarpus tinctorius* Welw, *Afzelia quanzensis* Welw and *Pericopsis angolensis* (Baker) Harms. These species were abundant in the leased areas at both the intermediate and old sites (Appendix 4) but outside of the leases, were replaced by other species at the old site and were less dominant at the intermediate site. There was little difference in dominance of these keystone species within versus outside the new mine site. Alteration of key miombo species composition in the genus

Brachystegia and *Julbernadia* and key timber species such as *Pterocarpus angolensis* in areas of high human utilization has also been reported in Zambia (Chidumayo, 2019; Kutsch et al., 2011). There was high dominance of trees in the genera *Combretum* and *Diplorhynchus* outside lease areas in intermediate and old mine sites as keystone miombo species are replaced with faster-growing, early succession species (Backéus et al., 2006).

We found fewer frugivorous birds (Fig. 27d) outside the leased areas, relative to within the leased areas. Specifically, frugivores such as the African green pigeon (*Treron calvus*) and spot-flanked barbet (*Tricholaema lacrymosa*) were less abundant, while the abundance of omnivorous birds, such as violet-backed starling (*Cinnyricinclus leucogaster*), crowned hornbill (*Lophoceros alboterminatus*) and helmeted guineafowl (*Numida meleagris*) was similar across lease boundaries. Our results indicate that this could be caused by the higher abundance of large, fruited trees inside leased areas. However, we did not have baseline or time series data to capture seasonality, which limits the strength of our conclusions regarding the influence of the gold mines on bird species (Howard et al., 2014; Katuwal et al., 2016).

We also found fewer butterfly species outside lease area at the old site (Figure 27c). Species such as African migrant butterfly (*Catopsilia florella*) and African leaf butterfly (*Precis tugela*) occurring in leased areas were more driven to specific resource requirements that suit their needs (Kirika et al., 2008; Larsen, 2008). However, the few butterfly species that were found outside the leased area are species which are tolerant to disturbance (e.g, monarch, *Danaus plexippus*, and painted lady, *Vanessa cardui* (Davros et al., 2006)).

Our chronosequence approach to sampling enabled us to infer the impacts of mining without embarking on a long-term study. Although the method makes crucial assumptions regarding site comparability, that can lead to erroneous conclusions when not met (Csecserits et al., 2007), it can be used to draw realistic conclusions when sites of varying age follow the same trajectory (Walker et al., 2010). In our case, mining regions are known for rapid environmental alterations due to increasing human population (Sánchez-Cuervo et al., 2020), and across the globe they follow the same trajectory as a given mine ages, it creates more indirect impacts on biodiversity (Sonter et al., 2017). Our findings are therefore intuitive and therefore appear to validate our chosen approach. However, in-depth spatial and temporal research would further help to better understand local landscape dynamics and their implications for biodiversity alteration (Deng et al., 2020).

6.6 Implications for integrated mine landscape management

Our results illustrate that commercial gold mines can have considerable indirect impacts on ecosystems beyond their lease boundaries. Since mineral deposits are increasingly located in areas of high biological diversity (Murguía et al., 2016), the potential adverse impacts on biodiversity and ecosystem services (e.g., carbon sequestration, soil quality, water, air, and supply of edible plants) are supposed to be considered by relevant authorities (e.g., national government authorities) when granting mining concessions for future mineral extraction (Sonter et al., 2020). However, authorities often promote environmental degradation by placing almost all administrative effort towards revenue collection (e.g., taxes on income, profits, and capital gains in Tanzania) (Poncian, 2018), with limited enforcement of regulations for environmental impact mitigation (Choi and Baek, 2020). Conversion of natural ecosystems to other land uses can result in loss of species, changes in ecosystem composition, fragmentation of wildlife habitats and increased carbon emissions (Csillik and Asner, 2020; Jew et al., 2016). Hence, sustainable development in these landscapes requires integrated land use planning (Kodir et al., 2017), to better support mining investments and ensure continued local well-being and community livelihoods (Selmier and Newenham-Kahindi, 2021), and ecosystem functioning after the mining activity ceases.

Our study highlights that implementation of established international mining standards is still poor in Tanzania, as for many countries. Such standards include for instance the Code of Practices which advocates for comprehensive baseline studies at the initial stage of establishing a mine (Responsible Jewellery Council, 2019). Other standards include the Global Reporting Initiative Sector Standards 304 that increase organisations' transparency and accountability around impacts derived from exploration and extraction of minerals (https://www.globalreporting.org/) (GRI Sector Standards, 2018) and the International Finance Corporation performance standards (https://www.ifc.org/) (Esteves et al., 2012). However, in our study areas, baseline assessments conducted by mining companies were below standard, lacking uniformity and consistency as suggested by Dias et al., (2017); and sufficient information to assess ecosystem structure, carbon stocks and biodiversity within and beyond the mine leases. Therefore, we recommend that prior to approvals, all exploration and mining activities undergo detailed impact assessments and develop comprehensive monitoring plans, to include consideration of carbon, biodiversity, ecosystem services and social impacts by establishing current estimates and forecasting their future change. The carbon and biodiversity impact assessment could include baseline survey of the species composition, woody vegetation structure, and ecosystem service variation across the project area (Dias et al., 2017). Together, the impact assessments could also identify all areas of potential influence from the proposed mine site (e.g., key biodiversity areas, critical habitats, protected areas, community development) (Wu et al., 2019), the transport corridors required to haul the ore to the processing facilities and point of sale (Juffe-Bignoli et al., 2021), and confirm any cumulative impacts (e.g. associated commercial and artisanal mining developments in the region (Franks et al., 2010) and mitigation measures (Juffe-Bignoli, et al., 2021).

Ultimately, there is an urgent need for companies, civil society, governments, investment institutions, labour organisation and other entities to improve the mitigation of mining impacts beyond extraction sites and to develop broader management plans at landscape level (Sonter et al., 2018). Companies have a responsibility to mitigate all impacts at approval stages of development, for all phases of operation – from prospecting, exploration, construction, operations, transportation, shipping, ecosystem rehabilitation, closure, and subsequent repurposing (Agboola et al., 2020; Jain et al., 2015). Mining companies can also learn from each other (e.g., Skorpion

Zinc Mine in Namibia, Gregory Crinum Coal Mine and Placer Exploration Limited in Australia) to involve stakeholders (especially from the adjacent communities) in making key decisions on long-term land use issues for the entire lifespan of the mine (International Council on Mining and Metals, 2006). This is an important element in the planning and decision-making processes of the mining industry as it paves the way for a mining company to achieve and maintain its social licence to operate (Moffat et al., 2016).

6.7 Conclusions

Our results show that biodiversity, ecosystem composition, bird foraging guilds and carbon stocks in landscapes surrounding commercial gold mines are impacted by accompanying socio-economic development. Impacts at our sites are greatest outside of the mine lease boundary and their magnitude increased with mine age. Thus, the temporal, landscape impacts should be considered by mining companies, both before and during mining operation. To ensure wider sustainable development, mining operatives should plan to reduce and mitigate off-site impacts before they stimulate significant unplanned development (Thatte et al., 2018), especially working with local people (Komnitsas, 2020), who may rely on ecosystem services for their livelihoods and well-being and yet may lack decision-making power or formal land rights (Selmier and Newenham-Kahindi, 2021). Independent biodiversity and socio-economic experts can help to enhance the effectiveness of safeguarding mechanisms such as community consultation, sustainable economic development, environmental impact assessments, protected areas and socio-ecological monitoring. There furthermore a need for governments, and the mining industry, to strengthen the corporate social responsibility (Hilson et al., 2019; Hilson, 2012b) and accountability of companies within the post-2020 global biodiversity framework of the Convention of Biological Diversity (Campbell, 2012; Koh et al., 2022). Doing so could enhance mining operatives' role as responsible ambassadors for sustainable economic development under the UN Sustainable Development Goals (Yakovleva et al., 2017). Such a proactive approach would benefit multiple threatened ecosystems and millions of people living in mining regions, both during and long after mining operation.

6.8 References

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6.9 Appendices B

Appendix 2:Generalised linear models of biological response variables versus mining and environmental predictor variables. Minimum adequate models were obtained by the evaluation of sets of alternative different models made of exhaustive combinations of predictor variables based on our knowledge of the data and research question. The direction and strength of each of the most important univariate relationships is presented in the results section.

Site	Response variable	Minimum adequate model	Model results
Intermediate	Stem density (dbh ≥10 – 19.9 cm)	dist_mine + elevation	AIC = 951.16, %D = 42, t = 11.136, p = 0.001
	Stem density (dbh ≥ 20 – 29.9 cm)	dist_mine + elevation	AIC = 841.56, %D = 37, t = 8.852, p = 0.001
	Stem density (dbh ≥30 cm)	dist_mine + elevation	AIC = 645.31, %D = 54, t = 8.703, p = 0.001
	AGC	dist_mine + elevation	AIC = 614.82, %D = 41, t = 11.387, p = 0.001
	tree.rich	dist_mine + elevation + dist_set	AIC = 720.28, %D = 61, t = 13.132, p = 0.001
	Frugivores	dist_mine + mine	AIC = 324.65, %D = 83, t =7.891, p = 0.001
	Granivores	dist_mine + mine	AIC = 924.56, %D = 25, t = 16.212, p = 0.92
Old	Stem density (dbh ≥10 – 19.9 cm)	dist_mine + mine + dist_set	AIC = 421.25, %D = 71, t = 8.601, p = 0.001
	Stem density (dbh ≥ 20 – 29.9 cm)	dist_mine + mine + dist_set	AIC = 326.17, %D = 88, t = 9.710, p = 0.001
	Stem density (dbh ≥30 cm)	dist_mine + mine + dist_set	AIC = 430.76, %D = 92, t = 7.615, p = 0.001
	AGC	dist_mine + mine + dist_set	AIC = 554.17, %D = 81, t = 6.089, p = 0.001
	tree.rich	dist_mine + mine	AIC = 516.72, %D = 90, t = 9.521, p = 0.001
	Frugivores	dist_mine + mine	AIC = 256.21, %D = 95, t = 9.321, p = 0.001
	Granivores	dist_mine + mine	AIC = 237.35, %D = 91, t = 6.551, p = 0.001

dist_mine = distance from the mine, dist_set = distance from settlements, mine = presence/absence of mine lease, tree.rich = tree species richness, AGC = above ground carbon

Appendix 3. Variation partitioning to determine the percentage variation explained by each predictor on species composition of two mining sites that showed significant trends in Tanzania.

Site	Predictor	Taxonomic groups								
		Trees			Birds			Butterfly		
		Variation explained (%)	*F* ratio	*P* value	Variation explained (%)	*F* ratio	*P* value	Variation explained (%)	*F* ratio	*P* value
Intermediate	Elevation	30	5.1	0.005**	39	3.6	0.005**	-	-	-
	Mine	58	2.5	0.005**	-	-	-	27	2.4	0.005**
	Settlements	-	-	-	29	2.6	0.005**	-	-	-
	Roads	-	-	-	24	2.1	0.005**	-	-	-
	AGC	-	-	-	-	-	-	36	3.1	0.005**
Old	Mine	61	3.8	0.005**	-	-	-	-	-	-
	Settlements	28	1.7	0.025*	28	1.7	0.010**	-	-	-
	TS.richness	-	-	-	46	2.9	0.005**	30	1.8	0.020*
	Dist_mine	-	-	-	28	1.6	0.005**	-	-	-
	Elevation	-	-	-	-	-	-	52	3.2	0.005**

Key: elevation = height above sea level (m), mine = within or outside mine lease, settlements = distance from settlements, roads = distance from the roads, AGC = above ground carbon, dist_mine = distance from the mine and TS.richness = tree species richness. Mine site that has not shown in the graph showed no significant trends

Appendix 4. Important Values Index (IVI) for tree species within lease and outside lease areas at three mining sites in Tanzania.

Site	Within lease		Outside lease	
	Species name	IVI	Species name	IVI
New site	*Brachystegia spiciformis*	9.4	*Craibia brevicaudata*	9.1
	Julbernardia globiflora	7.8	*Brachystegia spiciformis*	8.6
	Bussea massaiensis	7.3	*Albizia petersiana*	7
	Craibia brevicaudata	6.9	*Brachystegia boehmii*	6.5
	Vachellia tortilis	6.8	*Combretum collinum*	6.1
	Brachystegia boehmii	6	*Julbernardia globiflora*	5.9
	Commiphora mossambicensis	5.3	*Brachystegia microphylla*	5.2
	Commiphora africana	3.9	*Haplocoelum foliolosum*	4.5
	Dichrostachys cinerea	3.6	*Bussea massaiensis*	3.1
	Brachystegia microphylla	3.5	*Commiphora mossambicensis*	2.8
Intermideate site	*Brachystegia boehmii*	11.9	*Combretum zeyheri*	8.2
	Brachystegia spiciformis	10.3	*Diplorhynchus condylocarpon*	6.6
	Pterocarpus tinctorius	7.5	*Julbernardia globiflora*	3.8
	Brachystegia manga	5.9	*Bauhinia petersiana*	3.4
	Pterocarpus angolensis	5.8	*Combretum molle*	3.3
	Pseudolachnostylis maprouneifolia	5	*Brachystegia boehmii*	2.5
	Julbernardia globiflora	4.3	*Brachystegia spiciformis*	1.8
	Brachystegia bussei	2.9	*Lannea schimperi*	1.2
	Pericopsis angolensis	2.6	*Lannea humilis*	0.9

Site	Within lease		Outside lease	
	Species name	IVI	Species name	IVI
	Terminalia mollis	2.5	*Combretum adenogonium*	0.8
Old site	*Brachystegia spiciformis*	10.5	*Combretum molle*	4.1
	Brachystegia longifolia	8.9	*Combretum zeyheri*	3.3
	Julbernardia globiflora	6.1	*Anisophyllea boehmii*	2.6
	Brachystegia boehmii	4.5	*Annona senegalensis*	2.1
	Pterocarpus angolensis	4.4	*Sterculia africana*	1.8
	Pseudolachnostylis maprouneifolia	3.6	*Brachystegia spiciformis*	1.7
	Parinari curatellifolia	2.9	*Vachellia hockii*	0.9
	Pericopsis angolensis	1.5	*Searsia pyroides*	0.8
	Afzelia quanzensis	1.2	*Ficus sur*	0.8
	Brachystegia utilis	1.1	*Lannea schimperi*	0.8

CHAPTER SEVEN

7 Discussion and conclusion

7.1 Introduction

The aim of this thesis was to critically explore the impacts of mining on biodiversity and ecosystem services, and the potential for landscape restoration in mining impacted areas. To this end, we used a global systematic review to identify and map the distribution of the common mined commodities, their underlying impacts on diverse ecosystems and existing restoration efforts and through field work in Tanzania to evaluate the indirect impacts of mining brought by historical development adjacent to mining areas.

This chapter summarizes the thesis chapters and shows how the individual sections contribute to the general aim and individual research questions. Broader contributions of this thesis, limitations of this research and recommendations are discussed.

7.2 Chapter summaries

In chapter one, the research gap is identified. Although mining is not considered as top drivers of environmental destruction due to small areas coverage (Murguía et al., 2016), it can cause significant environmental damage and pressure on biodiversity. Mining activities have direct and indirect impacts on habitats at temporal and spatial scale (Sonter et al., 2018). It is also shown in chapter one that most research on mining is more focused on evaluating sink impacts compared to source impacts of mining (Franks et al., 2010).

In chapter one gold mining in Tanzania was the emphasis, looking at the impacts of gold mining on biodiversity. Results revealed that, the impacts of mining activities on ecosystems biodiversity can vary with mined commodities (Boldy et al., 2021). Gold mining has increased exponentially due to increase in its price (Asner et al., 2013) and being considered as safe way to protect economy during pandemic (Akhtaruzzaman et al., 2021). Thus, there is a likelihood for gold mining to increasingly impacts natural ecosystems in the future, necessitating the needs to look for a balance between gold mining for stable economy and conservation agendas (Agboola et al., 2020). Chapter one thus provides the knowledge gap and the case study from which this thesis is built. Chapter one is also linked to chapter two where general review of mining concepts, stages of mining and socio-economic impacts of mining are introduced. Chapter two also described the context of mining in Tanzania and at a global scale.

Chapter three focuses on global systematic review on the impacts of subterranean mining on biodiversity and ecosystem services. Although mining minerals and metals is vital to the improvement of national and regional economies for production of daily goods and services (Agboola et al., 2020), results revealed that, mining produces enormous impacts on biodiversity and ecosystem services (Sonter et al., 2017) during the abstraction and processing of minerals (Porgo and Gokyay, 2017), yet global efforts on evaluating ecological impacts of mining are still limited. In this chapter, 2093 academic literature examining mining impacts to on biodiversity and ecosystems services were reviewed.

Out of the 2093 studies that reported on mining impacts on biodiversity, it was found that, 95%, n = 1986 reported on the direct impacts, while only 5%, n = 107 reported on the indirect impacts and majority (87%, n = 1816) reported on sink impacts, while only 13%, n = 276 studies reported on source impacts. However, majority of the reported sink impacts were surface water contamination (51.0%, n = 1068), soil contamination (48.1%, n = 1007) and bioaccumulation (35.0%, n = 731), while vegetation cover (12.1%, n = 253) was the most reported source impact. This shows that, sink impacts of mining are much researched than source impacts.

While majority of the studies reported on negative impacts of mining on high biodiversity and conservation areas, vegetation cover, land use change, wildlife habitats, threatened and endemic species, coral reefs, forest carbon and at least 15 biodiversity hotspots, positive impacts were associated with deliberate establishment of water ponds for mining purposes and ponds caused by subsidence which attracted freshwater biodiversity.

In chapter four, a global systematic review on the restoration outcomes in mining landscapes was conducted. This chapter is linked with chapter three. While chapter three looked on the impacts of mining on biodiversity and associated ecosystem services, chapter four looked at the effectiveness of restoration efforts in mining landscapes.

Restoration of degraded mining landscapes has been a top priority in recent research agenda (Festin et al., 2019). This chapter systematically reviewed the findings of 830 publications studying restoration of the mining landscapes. Results revealed slower pace of research in restoration studies as compared to that of studying mining impacts with few average numbers of papers published per annum before and after 2000. There was a gap of at least six decades between studies on the mining impacts and restoration studies, leaving important biodiversity areas with mining legacy without scientific intervention on their recovery potential.

A total of 38 commodities were reported, with coal mining (23.5%, n = 195), being the most targeted commodity in restoration studies. Results also revealed that, most studies focused on remediation experiments (43.9%, n = 364) to (i) identify species suitable for phytoremediation (43.7%, n = 159), (ii) evaluating biological components suitable for bioremediation (11.2%, n = 41), and other organic amendments applicable for remediation (45,1%, n = 164), while 26.3%, n = 216 focused on reclamation, 14.9%, n = 124 focused on rehabilitation and 14.9%, n = 124 focused on restoration, with most experiments (62.4%, n = 479) being conducted in the greenhouse/laboratory (ex-situ), while only 37.6%, n = 289 reported on studies from field observation (in-situ). It was also found that, the success of restoration in mining landscapes were mostly evaluated using structural diversity indicators (41.6%, n = 585), followed by species composition (17.1%, n = 195), while ecosystem functions indicators were the least studied (9.4%, n = 107).

To achieve effective restoration projects in mining landscapes, it is vital to develop common indicators which considers heterogeneity in geological substrates, ecosystems, and climatic conditions of the mining landscapes, to provide consistent evaluation of the effectiveness of restoration project across the globe (Cadier et al., 2020). In addition, standard policies should be developed and enforced to guide restoration in mining landscapes to effectively achieve the restoration targets (Bradley, 2020; Zedler et al., 2012).

Chapter five evaluated the environmental impacts of commercial gold mining between 1990 and 2019 for six districts in Tanzania. Although, mining is important for economic development (Azubuike et al., 2022it was found that mining can cause significant impacts on land use (Basommi et al., 2016). Quantifying land use change dynamics in mining landscapes is critical in documenting and tackling aspects such as biodiversity loss and impact on ecosystem service delivery (Espejo et al., 2018), particularly in areas undergoing rapid land use change due to gold mining (Azubuike et al., 2022; Molinario et al., 2020). This chapter used a mixed method approach to analyse the dynamics of land use change in six districts with commercial gold mines and six districts without commercial gold mines across Tanzania using Landsat images from 1990 to 2019. In addition, changes in ecosystem service provisioning and availability, and possible future impacts of these changes were evaluated.

Results revealed how commercial gold mines have escalated the rate of forest loss, impacted aquatic ecosystems, and increased cropland and settlements and artisanal and small-scale mining. The highest rate of land use change was recorded between 2000 and 2010 in the districts with commercial gold mines and varied significantly before and after opening of commercial gold mines. Perspectives from communities adjacent to commercial gold mines also reported on the decline of important wildlife and plant species following increased degradation.. Local communities also reported that high wildlife populations are often found in mining leases to avoid being hunted outside mining leases indicating that, leases for commercial mines can be a save heaven for wildlife and other biodiversity components.

Results will support a range of stakeholders, such as government officials, conservation NGOs and mining companies, to manage the mining landscapes by tackling the issues of deforestation, biodiversity loss and growth of urban centresadjacent mining sites. Results can further support more comprehensive and participatory land use planning, adaptive co-management, and designing effective approaches to limit environmental degradation in Tanzania and other landscapes of sub-Saharan Africa.

Chapter six explored the indirect impacts of commercial gold mining on adjacent ecosystems. Mining is important for economic development in many tropical countries (Ofosu et al., 2020), but mining can have serious impacts on biodiversity (Sonter et al., 2018), both directly through operations at extraction sites (Haddaway et al., 2019), and indirectly via wider social-economic development (Jackson, 2018). However, mitigation efforts by large-scale mining operators focus almost exclusively on extraction sites. This was a rare assessment of mining impacts on vegetation structure and biodiversity with increasing distance from three commercial gold mines of varying ages in Tanzania (0 years, 8 years, and 19 years since establishment).

This chapter show that mining is associated with impacts that manifest largely outside operational lease boundaries. At the two older mine sites, aboveground carbon and tree stem density are significantly higher within lease boundaries compared to outside, while there is no such effect at the new site. Further, tree stem density, aboveground carbon, and tree and butterfly species richness all decrease with increasing distance from extraction sites, with these effects again increasing with mine age. Frugivorous bird species richness is lower outside older mines, while abundance declines in frugivorous and granivorous birds are associated with declines in tree stem density, which may have implications for forest regeneration. These impacts result from new and expanding settlements around mining concessions between 2000-2019 (Chapter 5) and associated demand for timber and fuelwood.

7.3 Thesis contribution

This thesis contributes to science knowledge through critical review of literature and case studies addressing the underlying impacts of mining on biodiversity and ecosystem services which has been reported in form of chapters three, four, five and six.

Chapter three revealed an increasing trend of research efforts evaluating mining impacts on biodiversity and ecosystems services, with more focus on sink and direct impacts than source and indirect mining impacts. Most of the reviewed studies reported on negative impacts, while positive impacts were associated with artificial establishment of water dams and subsidence areas filled with water. In addition, it was revealed that majority of existing literature focused on how sink impacts affect different components of terrestrial and aquatic ecosystems, but very little is known on how sink affects birds, reptiles, and large fauna especially wild mammals. This provides an opportunity to establish scientific research to fill this identified gape.

The knowledge generated in chapter three will be of interest to international conservation, mining companies and development professionals such that, by understanding mining impacts on specific indicators of biological components in mining, research will enhance global efforts to manage threats and be able to achieve a no net loss of biodiversity (Sonter et al., 2018). This will also contribute to sustainable mining that sustain natural ecosystems and ensures the continuous flow of ecosystem services.

Chapter four provided information of the existing efforts on restoring degraded mining landscapes. This chapter revealed that, there is a limited attention to restoration of degraded mining landscapes, whereby most of the reviewed studies were looking on the ways to restore, rehabilitate, remediate, or conduct reclamation altered mining landscapes through conducting ex-situ experiments, leaving the actual degraded mining landscape unattended. In addition, there are number of studies using geographic maps to express current and future mining threats on various ecosystems (Durán et al., 2013; Sonter et al., 2020; Wanghe et al., 2020), but very few similar studies exist for prioritizing restoration in mining landscapes. Mapping of priority areas degraded by mining for restoration is highly needed to halt degraded landscapes (Festin et al., 2019b).

The knowledge from chapter four will be of interest to ecologist, international conservation agencies, mining companies, governments and non-government organizations and global restoration initiatives. There is a need for future restoration studies to focus on *insitu* experiments on degraded landscapes for which it can define trajectories of restoration targets (Wolff et al., 2019). This can be achieved by adhering to principles of ecosystem restoration when planning for restoration projects (FAO et al., 2021), which are largely ignored. These principles for ecosystem reforestation are comprehensive guidelines on integrating carbon stocking, biodiversity conservation, human well-being (Brancalion and Chazdon, 2017). Global initiatives on restoration of degraded mining landscapes should also prioritize degraded mining landscapes as vital ecosystems to be restored by identifying areas biodiversity hotspots.

In addition, ecosystem restoration requires long term monitoring of the selected indictors to predict the time required for degraded ecosystem to be restored (Leps et al., 2016). Ecosystem function indicators must be one among the key selected indicators on evaluating restoration success (Cadier et al., 2020; Wolff et al., 2019), especially when when selecting indicators to assess restoration effectiveness. In addition, there is a need to develop common indicators which considers heterogeneity in geological substrates, ecosystems, and climatic conditions of the mining landscapes (Gwenzi, 2021), that are guided by restoration policies and regulations (Zedler et al., 2012), particularly in developing countries (Bradley, 2020).

Chapter five demonstrate the use of integrated community and remote sensing data to evaluate the impact of commercial gold mining on land use change. Findings demonstrated extensive land use change in district with commercial gold mines associated with population “pull” due to increased infrastructure and economic development (Mwitwa et al., 2012). Significant impacts were recorded on the loss of forest cover and aquatic ecosystems with increased cropland and scattered settlement, built up areas and artisanal and small-scale mining. There are also evidences of ecosystem biodiversity losses which denies adjacent communities with important ecosystem services such as reduced clean water for drinking, edible wild fruits, and valuable timber species.

The knowledge generated in chapter five is of relevance to government officials, conservation NGOs and mining companies for managing the mining landscapes by tackling the issues of land degradation and forest deforestation, ecosystem biodiversity loss and emerging new towns adjacent mining sites. A comprehensive land use planning and designing effective approaches for corporate social responsibility to limit environmental degradation in Tanzania mining landscapes is key in addressing the land degradation, forest deforestation, and ecosystem biodiversity loss.

Chapter six showed that surrounding commercial gold mines has impact on biodiversity, ecosystem composition, bird foraging guilds and carbon stocks in landscapes which is accelerated by socio-economic transformation. Impacts are high outside the mine lease boundary and their magnitude increase with mine age. Thus, the temporal, landscape impacts should be considered by mining companies, both before and during mining operation. To ensure wider sustainable development, mining operatives should plan to reduce and mitigate off-site impacts before they stimulate significant unplanned development (Thatte et al., 2018), especially working with local people (Komnitsas, 2020), who may rely on ecosystem services for their livelihoods and well-being and yet may lack decision-making power or formal land rights (Selmier and Newenham-kahindi, 2021).

This knowledge is of interest to international conservation agencies, government and non-government organizations, mining companies and global sustainable initiatives to help to enhance the effectiveness of safeguarding mechanisms such as community consultation, environmental impact assessments, protected areas and socio-ecological monitoring.

7.4 Limitations

There were two main limitations during this study (i) lack of baselines in biodiversity studies in mining landscapes, (ii) The complexity of the systematic review and time bound limitations.

Baselines studies before the actual mining starts are critical for which changes in biodiversity when mining operation starts can be measured over time (Dias et al., 2017). This is when the targets for biodiversity conservation in mining landscapes are defined and re-evaluated through monitoring programmes. Lack of baseline biodiversity information before the actual mining operations is a setback for identifying temporal changes in biodiversity that can be associated with mining operations (Mihoub et al., 2017).

Chapter six was based on field collected data, collected using a comprehensive assessment but can only be used to explain status and no baseline to compare. On that note, future mining projects should consider establishing baselines studies through an appropriate sampling design that can consistently be monitored to generate reliable data for which mining impacts can be evaluated.

Systematic review involved reviewing 23,663 documents which consumed much of my PhD allocated time, as did the training of the five reviewers and the screening for the inclusion criteria. In addition, as the requirement of the systematic review methodology, about five reviewers were involved in the systematic review. Some of them required training which also consumed time.

Lack of common understanding on the studies that passed the inclusion criteria could also cause some relevant studies to be missed out in the analysis. In addition, not all relevant studies that were published, thus there is a big chance that some of the existing research on mining impacts and potential for restoration in mining landscapes were not retrieved.

7.5 Conclusion

Overall, as presented in each chapter of the thesis, biodiversity and ecosystem services are impacted across the globe. A local scale impacts of mining activities such as gold mining on species composition and carbon stocks in landscapes and their surroundings due to increased socio-economic development, which intensifies as the mine is aging.

While mining impacts are distributed across the globe, there is limited attention given to degraded mining landscapes. Most of the studies in the literature were looking on the ways to restore, rehabilitate, remediate or reclamate mining landscapes through conducting ex-situ experiments, leaving the actual degraded mining landscape unattended.

Insights from this thesis feed into recommendation on rigorous, integrated impact assessments and conservation planning in mining landscapes. Such planning could mitigate the wider social and environmental impacts and balance outcomes across the mining sector to support livelihoods, development, and conservation agendas.

I recommend rigorous, integrated impact assessments and conservation planning in mining landscapes, to pre-empt the development of settlements and secondary industries around mining sites and so balance outcomes across the mining sector, natural resource-based and other livelihoods, and conservation agendas. This should be applied to all mining landscapes at a global and spefically to Tanzania where there is lack of these types of research and where environmental management is inadequate.

There is also a need to strengthen the accountability of companies within the post-2020 global biodiversity framework of the Convention of Biological Diversity (Koh et al., 2022). Doing so could enhance mining operatives' role as responsible ambassadors for sustainable economic development under the UN Sustainable Development Goals (Yakovleva et al., 2017). Such a proactive approach would benefit multiple threatened ecosystems and millions of people living in mining regions, both during and long after mining operation.

7.6 References

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