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How are large-scale extractive industries affecting progress toward the sustainable development goals in Madagascar? Perceived social-ecological impacts of mining investments

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A B S T R A C T

The rapid worldwide increase in resource extraction is evident in Madagascar—a global biodiversity hotspot. This study examines the localized effects of operational and planned large-scale extractive investments on social-ecological systems in Madagascar and links them to the Sustainable Development Goals. The focus is on sites owned or explored by foreign investors, specifically Ambatovy Moramanga, Ambatovy Tamatave, QIT Madagascar Minerals/Rio Tinto, Ranobe, and Tantalum Rare Earth Malagasy. Employing a counterfactual approach, we gathered survey responses from 459 small-scale farming, agro-pastoral, and artisanal-fisheries-based households. The survey provided information on general household characteristics, land use, land management, livelihoods, well-being, and any perceived changes to these variables, as well as any perceived mining impacts related to the changes. Overall, respondents reported predominantly negative effects on land (and sea) use, livelihoods, well-being, and security. Mining pollution, primarily from operational sites, had reduced access to water and fisheries resources, and natural forest areas had diminished. Reduced productivity due to pollution of soils, water, and air had a negative impact on various land uses and affected people's health, particularly in the surroundings of QIT Madagascar Minerals/Rio Tinto. Although some projects, such as Ambatovy, had eventually improved healthcare and infrastructure, most negative mining impacts had occurred during both the exploratory and the operational phases of the projects. Overall, this study offers a comprehensive view of how large-scale extractive investments affect land (and sea) use and human well-being. In addition, we highlight policy implications that must be considered if large-scale extractive investments are to support progress on the 2030 Agenda.

1. Introduction

Mining can play an important role in sustainable development, influencing economic, social, and environmental dimensions both positively and negatively across geographic scales (Lodhia, 2018). More specifically, mining is thought to have the potential to contribute toward achieving the Sustainable Development Goals (SDGs) related to poverty eradication (SDG 1), decent work and economic growth (SDG 8), clean water and sanitation (SDG 6), life on land (SDG 15), affordable and clean energy (SDG 7), climate action (SDG 13), industry, innovation, and infrastructure (SDG 9), and peace, justice, and strong institutions (SDG 16) (Pedro et al., 2017; UNSDSN, 2013). Mining activities can, for example, contribute to domestic economies, generate government revenues, support infrastructure development, enhance access to healthcare and education, and provide improved employment opportunities (Githiria and Onifade, 2020; Pedro et al., 2017). At the same time, mining can have serious negative impacts on the environment and people's well-being, livelihoods, and local cultures, threatening the

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industry's overall contribution to sustainable development (Matikainen, 2022). Translating natural resource wealth into long-term inclusive and sustainable development, as envisaged by the 2030 Agenda (United Nations, 2015), continues to remain a serious challenge, especially given the increasing demand for mined resources (Asr et al., 2019; Pedro et al., 2017).

Global mineral resource extraction has been growing rapidly, especially since the 1950s, and is mainly driven by increasing consumption in the Global North (Schaffartzik et al., 2016; Schandl et al., 2018). Between 1970 and 2017 it has more than tripled, and the annual average material demand grew from seven tons to over 12 tons per capita (United Nations Environment Programme, 2020). Between 2000 and 2017, the global extent of active above-ground/open pit mines covered a total area of nearly 60,000 km^2, made up of 44,929 discrete areas (Maus et al., 2020). A recent update by Tang and Werner (2023) raised these figures to 65,585 km^2 and 74,548 discrete areas. The energy transition so urgently required to meet globally agreed goals of carbon emission reduction is expected to further accelerate this trend (Vidal et al., 2013), as mined raw materials are needed to manufacture many low-carbon technologies (Alonso et al., 2012). As is the case with any intensive human land use, extraction of raw materials is mostly happening on land that was previously under less intensive land uses, such as smallholder farming, pastoralism, or nature conservation. Accordingly, any investments in new mining sites will likely lead to land-use-based sustainability trade-offs. To ensure progress toward the 2030 Agenda for Sustainable Development, decision-makers at different levels will need evidence on the various impacts of mining sites in order to balance different actors' claims on land.

Mining is considered a significant driver of deforestation and forest degradation that acts both directly (e.g., through infrastructure development and the establishment of mine sites and settlements) and indirectly (e.g., through agricultural expansion or illegal logging) (Giljum et al.Giljum et al., 2022). Additional direct negative environmental impacts include loss, fragmentation, and degradation of habitats, as well as the degradation of natural resources like water, soil, and vegetation at various scales (Byrne et al., 2012; Edwards et al., 2014; Scanes, 2018; Sonter et al., 2018). Mining impacts on biodiversity can vary across spatial scales, and little is known about the cumulative impacts of multiple mining sites (Sonter et al., 2014). Protected areas for biodiversity conservation intersect with approximately 10% of the mining area identified by Tang and Werner (2023). Such an overlap is concerning, especially because past experiences have shown that this often leads to downgrading and downsizing of the protected areas affected (Edwards et al., 2014; Symes et al., 2016). It is important to note that the direct, local environmental impacts of mining, while significant, are likely overshadowed by the much larger and more widespread environmental, social, and economic impacts associated with infrastructure, pollution, migration, and socioeconomic changes that come with mining activities (Edwards et al., 2014).

Health and social problems can also be pronounced at the local level (Signé, 2021). Mine construction often entails forced relocation and destruction of important ancestral lands, and these actions can have serious socioeconomic and cultural consequences (Chuhan-Pole et al., 2017; Seagle, 2012). Communities living close to mines have observed increased levels of crime, drug and alcohol abuse, and teenage pregnancies, along with negative impacts related to increased migration (Dikgwatlhe and Mulenga, 2023). Mining activities can also weaken poverty reduction outcomes in their surrounding areas compared to non-mining areas (Al Rawashdeh et al., 2016), and in some cases, the rate of poverty reduction in mining communities is not faster than in non-mining communities (Chuhan-Pole et al., 2017). The social-ecological transformations and burdens associated with large-scale mining activities often result in processes that reinforce inequities and injustices, which can lead to widespread conflicts (Bisht and Martinez-Alier, 2023). Given the impacts on human well-being and livelihoods, mining companies are increasingly under pressure to invest in healthcare, education, training, and sanitation (Signé, 2021). These investments can deliver positive impacts and community benefits, such as by improving access to education, healthcare services, and clean drinking water (Chuhan-Pole et al., 2017; Dikgwatlhe and Mulenga, 2023). There is evidence, however, that these benefits might not be enough to make up for the negative impacts perceived by communities or for communities to consider a mining site beneficial (Yang and Ho, 2019).

The expansion of mineral resource extraction is also being observed in Africa (Edwards et al., 2014). Africa accounts for over 40% of global reserves of cobalt, manganese, and platinum, which are critical for the production of clean energy (International Energy Agency, 2022; Signé, 2021). Only a small proportion of these mineral reserves has been exploited, and there are also large parts of Africa that have not yet been geologically explored (Edwards et al., 2014). Between 2000 and 2017, around 13% of globally mapped active above-ground mines and mining features were located in Africa (Maus et al., 2020). The share of all active mining sites—including below-ground ones—located in Africa may be even greater. Many African governments are investing in infrastructure to support the mining and natural resource sector because they see a potential for national economic development (Signé, 2021). However, given the detrimental impacts that large-scale extractive investments (LEIs) have been shown to have on local communities and their environments, their promotion also carries a significant risk.

Madagascar has one of the world's highest poverty rates (The World Bank, 2023), is a key global biodiversity hotspot (Myers et al., 2000), and is experiencing continued deforestation and forest degradation (Suzzi-Simmons, 2023; Vancutsem et al., 2021). Madagascar also plays a significant role in the global production of cobalt, ilmenite, mica, nickel, and zircon, and the contribution of this industry to GDP is growing (Yager, 2017). However, despite the growth in production, the country's mineral resources are still largely underexploited; Maus et al. (2020) mapped only nine areas adding up to 12.33 km^2 in Madagascar. However, this might be an underestimation, as the study only considered above-ground/open pit mines. The number of operational LEIs in Madagascar is estimated differently, depending on the criteria used (Extractive Industries Transparency Initiative, 2022; Yager, 2017). Currently unexploited resources can be leveraged to contribute to Madagascar's economic development, especially given that poverty reduction is a key political concern (Canavesio, 2014). However, the expansion of LEIs is already having negative impacts on people's well-being, security, and livelihoods (Bidaud et al., 2017; Kraemer, 2012; Seagle, 2012), and it is also threatening Madagascar's biodiversity-rich landscapes (Jones et al., 2019).

Several laws and policies currently regulate LEIs in Madagascar. The Malagasy Mining Code is the main legal text governing all mining-related activities in Madagascar (Crawford and Nikièma, 2015). A new version was passed in 2023, containing revised rates for mining royalties, revised periods of validity of mining permits and mining titles, strengthened requirements for environmental protection measures, as well as provisions on the establishment of a "Mining Social and Community Investment Fund" and on the involvement of decentralized local authorities (*Collectivités Territoriales Décentralisées* [CTD] in French) in monitoring mining activities and preventing the destruction or desecration of places considered "sacred" (Ministère des Mines, 2022). With specific regard to large-scale mining, the Malagasy Government issued the Large Mining Investments Law (*Loi sur les Grands Investissements Miniers* [LGIM] in French) and the Decree on the Compatibility of Investments with the Environment (*Mise en Compatibilité des Investissements avec l'Environnement* [MECIE] in French). Moreover, large-scale mining investments are subject to other laws, in particular the Water Code, the country's Finance Law, the Industrial Pollution Management and Control Policy Act, as well as international standards, conventions, and commitments ratified by the Malagasy government (Crawford and Nikièma, 2015).

Most studies on LEIs in Madagascar focus on site-level impacts of two of the largest mining sites, the QIT Madagascar Minerals (QMM, a subsidiary of Rio Tinto)/Rio Tinto ilmenite mine and the Ambatovy lateritic nickel and cobalt mine. They shed light on the early impacts of infrastructure development and initial mining activities, often with a focus on biodiversity impacts and biodiversity offsets (e.g., Devenish et al., 2022; Dickinson and Berner, 2010; Hase et al., 2014). Social impacts have been considered, but mostly in relation to the QMM/Rio Tinto site (Evers and Seagle, 2012; Kraemer, 2012; Seagle, 2012; Smith et al., 2012). The impact of biodiversity offset projects on well-being has also been explored for the Ambatovy mine (Bidaud et al., 2017). All these studies mostly focus on biodiversity and social impacts experienced within a relatively short time after the start of mining operations, such as after construction or shortly after the initial operationalization. There is a lack of studies that holistically assess environmental, social, and economic impacts of LEIs in Madagascar, as well as studies looking at the longer-term impacts of sites that have been operational for more than a decade, such as QMM/Rio Tinto and Ambatovy. Considering the different lifecycle stages (i.e., exploration, construction, operation, closure) and the lifespan of LEI projects, it is essential that we understand their impacts over time as well as space, especially if LEIs continue to increase in Madagascar.

The main research gaps—which this study helps to fill with novel empirical insights—can be summarized as follows: (1) The only scientific studies on LEI impacts in Madagascar published to date focus on Ambatovy and QMM/Rio Tinto (the two operational LEIs) and a limited selection of impacts. No scientific studies have been conducted on the exploratory LEIs of Tantalum Rare Earth Malagasy (TREM) and Ranobe. (2) A counterfactual approach has rarely been applied anywhere in the world to evaluate a wide range of impacts of large-scale mining investments. While some studies used econometric models to establish causality, they each focused on a very limited number of impacts—for example, household income only (Aragón and Rud, 2013). In addition, we bring conceptual novelty to the debate on the environmental and social sustainability of the extractive industries in Madagascar by explicitly linking the impacts observed to the Sustainable Development Goals. To address these empirical and conceptual gaps, we investigated in a spatially explicit manner the impacts perceived by small-scale farming, agro-pastoral, and artisanal-fisheries-based households of LEIs on land use and land management, livelihoods, and human well-being. We explored perceived impacts at two operational mining sites, QMM/Rio Tinto and Ambatovy (both the extraction site and the tailings dam), and two exploratory sites, TREM and Ranobe. Taking a counterfactual sampling approach, we collected and analyzed survey data from 459 households, of which 233 lived close to the selected sites and 226 lived far from the selected sites. With these surveys, we aimed to answer the following research questions: (1) How have land use and land management, resource access, livelihoods, and human well-being changed since the establishment of the mining site or the start of exploration activities, respectively? (2) What are the overall impacts perceived by smallholders of LEIs on the environment and social-ecological systems? And (3) how do these impacts help or hinder achievement of the 2030 Agenda's Sustainable Development Goals?

2. Methods

2.1. Conceptual overview

LEIs have a range of social-ecological impacts, and these impacts vary across space and time. We took the sites of the mining activities as the starting points for investigating where the impacts manifest, and

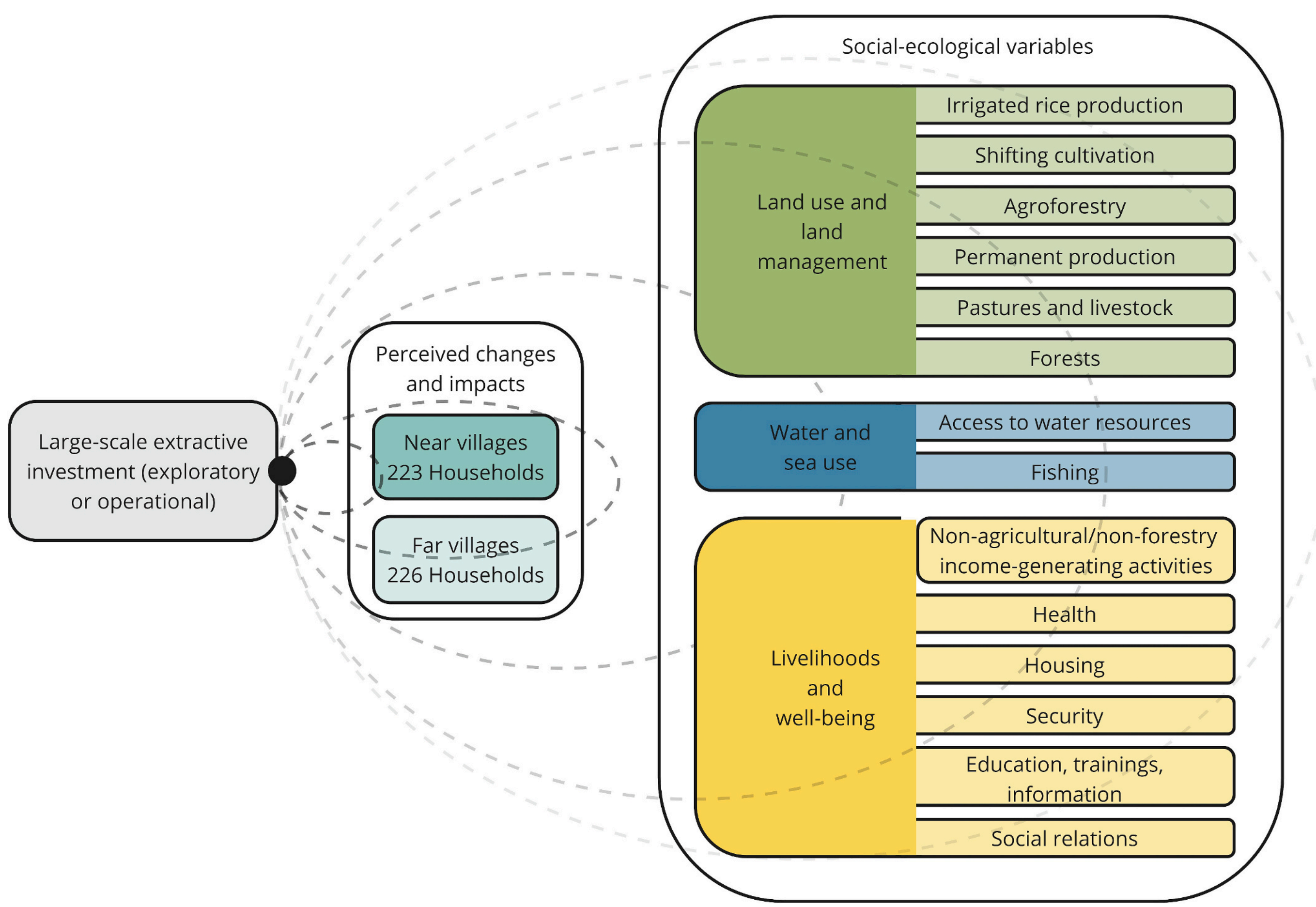

Fig. 1. Conceptual overview of our study design.

examined to what extent they were perceived by households living "near" and "far" from those sites (Fig. 1). We hypothesized that changes and impacts on land use and land management, water and sea use, and livelihoods and well-being would be felt and perceived differently by households depending on the activities they engaged in and on their location in relation to the mining site.

2.2. Case study sites

To understand the place-based impacts of operational and planned LEIs on social-ecological systems in Madagascar, we adopted an empirical approach based on case studies. Given the different available estimates regarding the number of operational LEIs in Madagascar, we first identified potential case study sites using the Environmental Justice Atlas (EJOLT, 2019), the most recent USGS Minerals Yearbook of Madagascar (Yager, 2017), and consultations with academic and non-academic research partners in Madagascar, such as WWF, Organisations de la Société Civile sur les Industries Extractives (OSCIE), and others. From the few operational LEIs in the country, we then selected the two most prominent ones, Ambatovy and QMM/Rio Tinto, as they had been the subject of several scientific studies and media reports mentioning substantial social-ecological impacts. Similarly, for the planned LEI sites, we chose those that seemed most likely to become operational in the near future, namely Ranobe and TREM. All sites are mainly surrounded by economically poor agro-pastoral communities, but three of the sites are also relatively close to major urban centers (Moramanga in the case of Ambatovy, Taolagnaro in the case of QMM/Rio Tinto, and Toliara in the case of Ranobe). In addition, these sites are all owned, operated, or being explored by foreign investors, and they are located in different parts of the country and different ecological zones (Table 1, Fig. 2). Exploratory fieldwork showed that the Ambatovy LEI was best treated as two separate but interconnected sites: the mining site (Ambatovy Moramanga) and the tailings site (Ambatovy Tamatave).

2.3. Sampling approach and design

We took a counterfactual approach to enable the causal attribution of perceived changes in land use and land management, resource access, livelihoods, and well-being to LEIs. "Case" and "control" villages around each LEI site were selected independently using spatially explicit propensity score matching (Rosenbaum and Rubin, 1983). This was based on three variables: (1) accessibility, (2) population density, and (3) land cover and land use composition within the villages. We considered all villages within a 50 km buffer area around the five LEI sites, requiring "case" villages to be "near" the sites, namely within a 5 km buffer area around the sites, and "control" villages to be "far" from the sites, namely either at a distance of 5–10 km or, if there were no such villages, at a distance of 10–20 km from the LEI sites. We developed logistic regression models and estimated propensity scores based on these two groups of "near" and "far" villages and the calculated variable averages for all villages. The scores represent the probability of villages being affected by the mining activities. Based on the calculated averages and scores, we identified similar (i.e., matching) pairs of villages across the two groups. Before starting the household survey in the field, we made exploratory field visits to the selected villages and confirmed or adjusted the selection, for example, if there was evidence that a selected "control" village was strongly affected by the mining activities. Matching was done using the Matchit package (Ho et al., 2011) in the R software (R Core Team, 2022).

2.4. Household survey data collection

Household surveys were conducted across the five case study sites between August 2021 and January 2022. A total of 459 households responded to the survey across the five sites, 233 in "near" villages and 226 in "far" villages (Table 2). The surveys were carried out by Malagasy research assistants who had been trained by Malagasy and Swiss senior researchers during the Covid-19 pandemic. The original household survey was conceptualized in French and then translated to Malagasy. Initially, paper survey forms were used to collect responses. This was the case in the villages around Ambatovy Moramanga, Ambatovy Tamatave, and TREM. In the villages around QMM and Ranobe, responses were then collected using the KoboToolbox software (KoboToolbox, 2021) on smartphones.

The survey questionnaire included closed and open questions to obtain information on general household characteristics, land use, land management, livelihoods, well-being, and any perceived changes to these variables, as well as any perceived mining impacts related to these changes (Appendix 1). Specifically, the household survey covered: access to water, access to fisheries resources, irrigated rice, shifting cultivation, agroforestry, permanent crops, pastures and livestock, forests, non-agricultural and non-forestry income-generating activities, health, housing, security, education, and social relations. Response options were informed by the Malagasy researchers, the first author's long-term field research experience in different regions of Madagascar, and the existing literature on mining impacts in the country.

2.5. Data analysis

Household survey responses were translated from Malagasy into French and transferred into Microsoft Excel; qualitative responses were coded deductively using a codebook with predetermined codes (Zaehringer et al., 2024). Additional qualitative responses that were not included in the original codebook were coded retrospectively. Data cleaning and additional coding of qualitative information was carried out in R before calculating response frequencies (R Core Team, 2022). Frequencies are reported as percentages, where n is the total number of responses to a given question per site. Due to small sample sizes, Fisher's Exact Tests were used to test for a significant association between perceived LEI impacts in "near" and "far" villages. Two-proportion z-tests were used to test whether the proportions of "near" and "far" responses for all other variables differed significantly from each other (only when there were at least 10 responses per village type ["near" and "far"] per site).

3. Results

3.1. Overview of respondents

The average age of the respondents was 44 years (± 14 years standard deviation) and about half of the respondents were female (Appendix 2; Table A1). The majority of respondents were parents, whereas only 2% were village elders. More than two-thirds of respondents were born in the village they lived in. Villages around the TREM and Ambatovy Tamatave LEI sites had the highest share of respondents who were not born in the village. Half of the respondents who had moved near TREM had done so for work and one-third for marriage. Among the respondents who had moved near Ambatovy Tamatave, 50% had moved for marriage and 38% for work.

3.2. Access to water resources, perceived changes, and LEI impacts

The main sources of water for households were rivers and groundwater, and access to water was reduced for 67% of respondents (n = 458) (Appendix 2; Table A2). The main reasons for reduced access were pollution and reduced water availability. However, water availability had improved for many households in Manafiafy, the village near the QMM Ste. Luce site, mainly due to increased availability of drinking water and wells. About one-third of households across all sites (n = 384) perceived an LEI impact on their access to water, but it was felt most strongly around the QMM and Ambatovy Tamatave and Moramanga sites, and less strongly around Ranobe and TREM (Fig. 3). For Ambatovy

Table 1
Overview of case study sites, mining operations, and ecological context.

Site name	Operations	Minerals	Current status	Ownership	Ecological and social context
Ambatovy Moramanga	Extraction and operational since 2012	Nickel, cobalt	Still operational. Suspended operations between March 2020 and March 2021 due to Covid-19 restrictions (Reuters, 2021).	Japanese (Sumitomo Corporation) and South Korean (KOMIR)	Mid-elevation forests, ecotone between eastern rainforest and montane Central Highland forests, at least 1367 plant species and 214 vertebrate species, including 13 lemurs (Dickinson and Berner, 2010). Development of the mine site involved occupying agricultural land, resettling households living within the future mine footprint and barring access to culturally significant sites (Dynatec Corporation of Canada, 2006). Some households experienced better health outcomes due, for example, to improved access to health care thanks to Ambatovy, and Ambatovy's biodiversity offsets were thought to have a potential positive impact on health due to perceived improvements in air quality (Bidaud et al., 2017). Ambatovy has invested in biodiversity offsets to mitigate biodiversity loss and compensate forest clearance associated with their mining activities (Devenish et al., 2022).
Ambatovy Tamatave		Tailings dam site (processing plant)			Slurry pipeline, buried and passes through 2 km of relatively intact forest, crosses Ramsar site. The processing plant is located in coastal shrubland/ grassland (Dynatec Corporation of Canada, 2006). Industrial complex located in a suburban setting (Dickinson and Berner, 2010). Villages near the tailings management facility and plant site were resettled between December 2007 and February 2008 and cultural sites were also relocated (Dynatec Corporation of Canada, 2006).
QMM/Rio Tinto (Fort Dauphin and Sainte Luce)	Extraction since 2009 at the Fort Dauphin site; three sites to be mined sequentially (Fort Dauphin, Ste. Luce, and Petriky)	Ilmenite, zirsill, monazite	Negotiations ongoing regarding the terms of a new convention between Madagascar and QMM, which had been due to expire on 18 February. Current convention extended to May 2023 to allow more time for negotiations. Ceased production in December 2022 due to local protests against alleged pollution (Africa Intelligence, 2023).	British-Australian (Rio Tinto) and 20% owned by Malagasy government	Deposits were located under some of the last remnant coastal forests in south-eastern Madagascar (Huff, 2016). People were relocated during construction of the mine site (Smith et al., 2012). Ancestral land was taken away from the people of Ravitany, an estimate of up to 500 people were displaced from their homes, and hundreds more lost access to land used for cultivation (Seagle, 2012). QMM created an ecological research center and established a conservation zone in the largest remaining primary coastal rainforest. The company also supported various local economic opportunities, for example with a microfinance program, a honey-producing initiative, and a reforestation program to provide wood for everyday needs. Literacy programs were set up, community health services were improved, and the establishment of education institutions was supported (Olegario et al., 2012).
Ranobe	Exploration since 2013	Ilmenite, zircon, rutile	Activities have been suspended since November 2019 due to local resistance and insufficient tax revenues (Vyawahare, 2019).	Australian (Base Resources)	Dry, sub-arid ecological transition zone between dry deciduous forest and spiny thickets. Surrounded by protected areas (Huff, 2016). Serious friction between the project management and local communities which peaked in April 2019, when forty people allegedly vandalized the mine's exploration campsite (Vyawahare, 2019). The mining company is cognizant of the disruptive impacts its mining activities will have on people's livelihoods and well-being. Base Resources therefore

(continued on next page)

Table 1 (*continued*)

Site name	Operations	Minerals	Current status	Ownership	Ecological and social context
					carried out social outreach activities, such as restoring wells and installing foot pumps in three villages, paying for four Australian doctors to visit Toliara, donating furniture to local schools, and improving sports facilities (Huff, 2016).
TREM	Exploration since 2011	Rare earth metals	Submitted an application for a full mining license on 18 September 2020 (Reenova Investment Holding Limited, 2021).	Singaporean (Reenova Investment Holding Limited) and German	Northwest Madagascar, Ampasindava peninsula, a highly biodiverse region. Close to a protected area that is home to endangered lemurs. The company has already helped build schools, bridges, and a church, and employs local men. Women perceive the company to discriminate against them. Communities are frustrated by the thousands of deep exploratory pits TREM has dug, especially as they have not been properly refilled and can injure highly prized zebu cattle (Carver, 2017).

Tamatave, Ranobe, and TREM, this was significantly more often the case in “near” villages than in “far” villages (Appendix 2; Table A3). Of those who reported an LEI impact, 52% ($n = 130$) observed reduced access due to pollution from the LEI site and 43% perceived a decrease in water availability due to the LEI site (Table A2).

About one-third of households (n = 458) had access to the sea or a river for fishing, but access to the sea or river had diminished for all responding households ($n = 29$) (Table A2). These households were located around Ranobe and Ambatovy Moramanga. The availability of fisheries resources, such as lobsters, had also deteriorated for almost all respondents, significantly more so in “far” villages across all sites, and especially around QMM. This was mainly perceived to result from climate change, overfishing, pollution, and a weir that QMM had built close to the “near” village of Hovatraha. Among the responding households, 15% ($n = 154$) did not know why the availability of fisheries resources had deteriorated. Nearly one-third of households ($n = 153$) thought that the establishment of an LEI site had played a role in these changes, mainly around QMM and significantly more often in “near” villages (Fig. 3). The main reasons given were water pollution and infrastructure construction (Table A2).

3.3. Small-scale farmers' land use and land management, perceived changes, and LEI impacts

In terms of land use, 61% of households ($n = 332$) engaged in irrigated rice production, most of them living around QMM, Ambatovy Moramanga, and Ambatovy Tamatave (Appendix 2; Table A4). None of the respondents around Ranobe engaged in irrigated rice production, and very few around TREM. Most of the rice grown under irrigation is used for subsistence consumption. The majority of households use between 0.1 and 2 ha of land for irrigated rice production, and the area of land under irrigated rice production changed for only 11% of households ($n = 201$); of these, 57% perceived a decrease and 43% an increase ($n = 21$). More importantly, 95% of respondents (n = 201) reported a change in irrigated rice productivity or plot management. Households around Ambatovy Moramanga experienced changes in the management of their plots due to the introduction of plowing or mechanization and external inputs. As many as 81% of households ($n = 190$) perceived a decrease in productivity, especially those living around QMM, Ambatovy Tamatave, and Ambatovy Moramanga, in both “near” and “far” villages. A decrease in productivity was perceived significantly more often in villages “near” Ambatovy Tamatave than in “far” villages (Appendix 2; Table A5). Almost all of the households attributed the decrease in productivity to changes in environmental conditions and soil fertility (Table A4). About one third of households ($n = 199$) perceived an impact of the LEI on the productivity of their irrigated rice fields, especially around QMM, with significantly more respondents in the “near” villages, and to a lesser extent around Ambatovy Tamatave, in both “near” and “far” villages (Fig. 3). Of those who perceived an impact, 79% perceived the impact to be related to soil, water, and air pollution (Table A4). Soil pollution associated with QMM was observed significantly more often in “near” villages (Table A5).

One-third of households ($n = 330$) practiced shifting cultivation, mainly around TREM, Ambatovy Tamatave, and Ambatovy Moramanga (Table A4). Of these households, most had already been practicing shifting cultivation 20 years ago. The majority of households used the rice only for subsistence. Regarding changes, 16% of households ($n = 83$) believed that the land available for shifting cultivation had changed over the past 20 years; they mainly reported a decrease in land size due to changes in soil fertility and in environmental conditions such as precipitation and temperature. Half of these households lived around TREM, mostly “near” the site. Over the past 20 years, most households also perceived a decrease in productivity. Commonly cited reasons were changes in environmental conditions around Ambatovy Moramanga and TREM, and changes in soil fertility around Ambatovy Moramanga, Ambatovy Tamatave, and TREM. Only 14% of households ($n = 57$) perceived an LEI impact on their shifting cultivation, and these were distributed across all sites except QMM (Fig. 3). Very few households provided a reason for this perceived impact. Those who did mentioned, for example, reduced water availability and restricted access to land due to the Ambatovy mine and the Torotorofotsy protected area, which is managed by a Malagasy NGO (Asity Madagascar) that receives funding from the mining company.

Almost one-fifth of households ($n = 329$) grew crops in an agroforestry system, mostly around TREM and QMM (Table A4). The percentage of households that were involved in agroforestry had increased over the past 20 years. Households used their crops mainly for subsistence consumption and less for sale. Households mainly used between 0.1 and 1 ha of land and did not perceive any change in land size over the past 20 years. However, 64% of households ($n = 50$) observed a decrease in productivity, mostly in the “near” villages around QMM and TREM and in the “far” villages around Ambatovy Tamatave. Considering all sites, a change in management was perceived significantly more often in “near” villages than in “far” villages (Table A5). Changes in environmental conditions and soil fertility were frequently cited as reasons for the decrease in productivity (Table A4). Almost one-third of households ($n = 59$) perceived an LEI impact on their agroforestry systems, mostly those in villages “near” QMM and “far” from Ambatovy Tamatave (Fig. 3). However, none of these perceptions differed significantly between “near” and “far” villages (Table A5). Of the households who perceived an impact, 65% ($n = 17$) had experienced a decrease in productivity due to soil, water, and air pollution (Table A4).

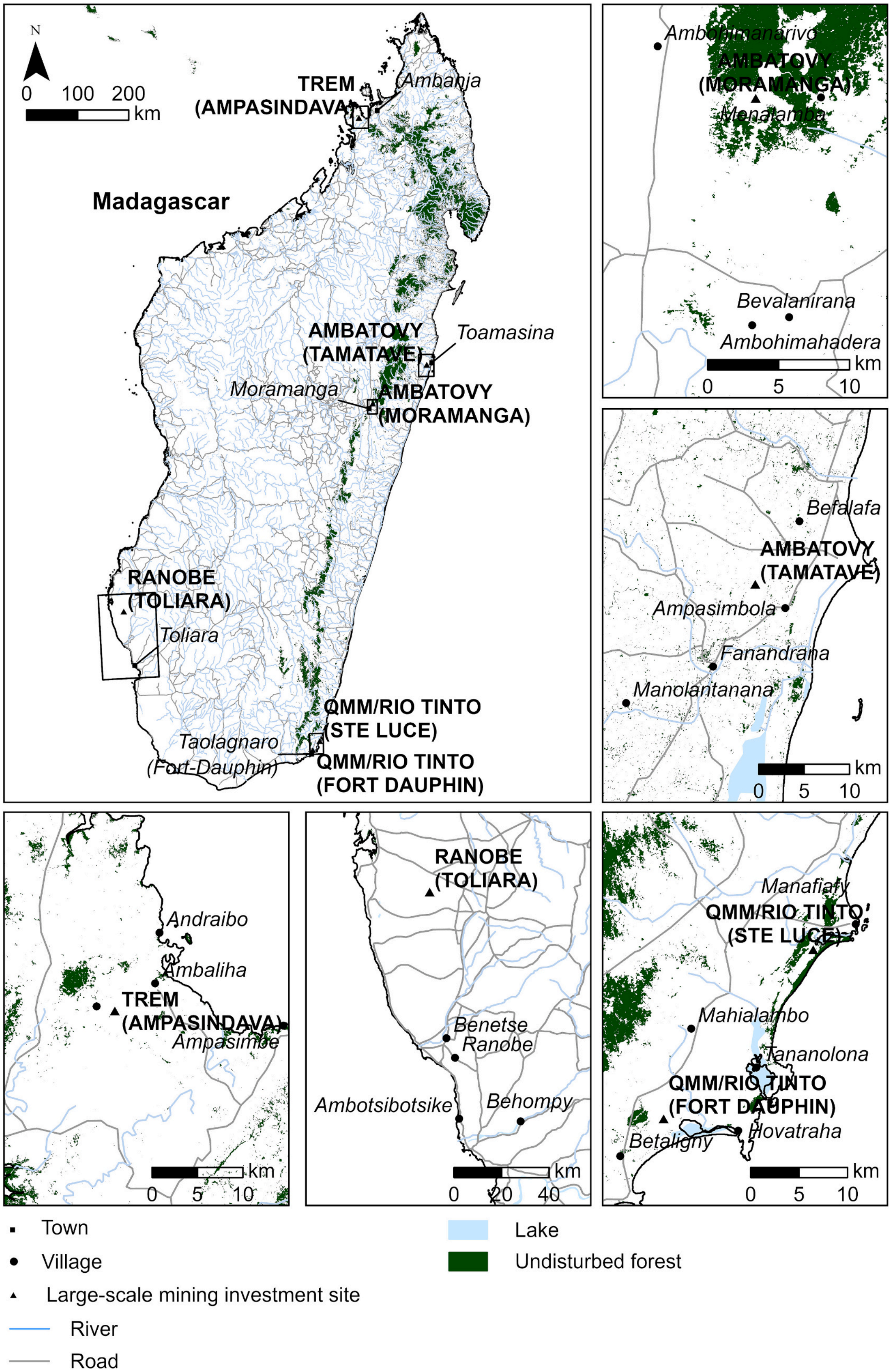

Fig. 2. Map of the large-scale extractive investment case study sites in Madagascar. Sources: Undisturbed forest (Vancutsem et al., 2021).

Table 2
Number of villages sampled and total household survey responses per site.

Site name	No. of villages	No. of responses		
		Near	Far	Total
Ambatovy Moramanga	4	40	40	80
Ambatovy Tamatave	4	40	40	80
QMM/Rio Tinto, including Ste. Luce	6	65	60	125
Ranobe	4	48	46	94
TREM	4	40	40	80
Total	**22**	**233**	**226**	**459**

Most households (n = 332) were engaged in permanent crop production at the time of the survey, and this share had increased only slightly over the past 20 years (Table A4). Households grew a range of crops, the most common being cassava. About one-third of households (n = 294) used their crops only for subsistence consumption, and slightly fewer used their crops mainly for sale. In terms of land size, 79% of households (n = 283) used between 0.1 and 2 ha for permanent crop production, and only 8% of households (n = 295) perceived a change in land size over the past 20 years, with slightly more perceiving a decrease than an increase across all sites. In addition, households across all case study sites observed a decrease in crop productivity. In Ambatovy Tamatave, significantly more respondents in "near" than in "far" villages perceived a decrease in crop productivity (Table A5). Overall, almost one-third of respondents (n = 293) perceived that the establishment of the LEI site had influenced these observed changes (Fig. 3). Impacts were mostly perceived around QMM, Ambatovy Tamatave (in both village types, but mostly in "near" villages) and Ranobe (significantly more often in "near" villages). Around QMM, impacts were perceived to be due to soil, water, and air pollution, whereas households around Ranobe mostly attributed the impacts to a decrease in water availability (Table A4).

Almost half of the households (n = 332) had access to pastures, and 16% (n = 136) thought that the size of their pastures had changed over the past 20 years (Table A4). Of these, 95% (n = 22) perceived a decrease. A decrease was mainly perceived by households living around Ambatovy Moramanga and QMM. Around QMM, the decrease was mainly attributed to smaller livestock numbers, population growth, and conversion to agricultural land. Across all sites, the majority of households had their own animals, but almost half (n = 260) were less involved in breeding than 20 years ago. This was mainly due to livestock diseases, reduced fodder availability, livestock theft, and a reduction in pasture size. Around QMM, this was significantly more common in villages "far" from the mine (Table A5). A decline in livestock productivity over the past 20 years was observed by 64% of households (n = 221) and was attributed mainly to a decrease in available land, extreme weather events, changes in environmental conditions, and, to a lesser extent, changes in soil fertility (Table A4). Around QMM, this was significantly more common in villages "far" from the mine (Table A5). Only 9% of households (n = 269) thought the establishment of LEI sites had played a role in these changes, mainly in villages "near" QMM, Ranobe, and Ambatovy Tamatave (Fig. 3). The main reasons given for this perceived impact were polluted water or land, mostly near to the QMM site; in-migration of resettled people "near" Tamatave; and a perceived lack of water in villages "near" Ranobe (Table A4).

From 2001 to 2021, the level of access to natural forests was maintained by 53% of households (n = 455) (Table A4). By contrast, 28% of households had lost access to natural forests; most of these were located around Ambatovy Moramanga, Ranobe, and Ambatovy Tamatave, and, in the case of Ambatovy Moramanga, significantly more were located in "far" villages than in "near" villages (Table A5). Households who had experienced a loss of access attributed this to the establishment of a protected area, the fact that the forest was now owned by a private company, the fact that there was no forest left in the area, or a lack of time to go to the forest (Table A4). In the case of QMM, reduced access for reasons other than a change in forest size was perceived significantly more often in "far" villages than in "near" villages Table A5). Impacts of protected areas had mostly been experienced by households around QMM, Ambatovy Moramanga, and Ranobe (Table A4). The greatest reduction in forest access had occurred around QMM, because the mining company converted the forest into an extraction site, thus blocking access to the previously accessible natural forest. Improved access to natural forests was experienced only by households around TREM, QMM, and Ranobe; in the case of TREM, this was reported significantly more often in "near" villages (Tables A4 and A5). Across all sites, 13% of households had never had access to natural forests (Table A4). The majority of households (n = 328) perceived a change in the size of the natural forest, and of these, 80% (n = 262) perceived a decrease in forest size. A decrease in forest size was perceived significantly more often in villages "far" from Ambatovy Moramanga than in villages "near" this site, and in villages "near" to TREM than in villages "far" from it. Only 6% of households (n = 209) perceived that forest had been lost at the expense of large-scale mining, and 85% of these were in Betaligny, the village closest to the QMM site (Table A4). According to 26% of households (n = 342), the establishment of the LEI site in their area had played a role in either a change in access to forests or a change in the size of forests (Fig. 3). QMM and Ambatovy Moramanga had the highest number of households who perceived an impact; these were located entirely or mostly in "near" villages. The main reasons given were closure of forest access, forest degradation, and forest clearance (Table A4). These perceptions are supported by a detailed spatiotemporal analysis of deforestation and forest degradation patterns in the vicinity of the Ambatovy Moramanga site. It showed that the mine and its direct and indirect effects have increased pressure on land and forest resources in the surroundings of the mining lease area and the company's main biodiversity offset area (Eckert et al., 2024).

3.4. Small-scale farmers' livelihoods and well-being, perceived changes, and LEI impacts

Non-agricultural and non-forestry income-generating activities were carried out by 44% of households (n = 459) (Appendix 2; Table A6). The most common type of activity around Ambatovy Moramanga was creative and crafts activities, whereas around QMM and TREM, the most common income-generating activity was running a private business, including stores. Many of these private enterprises, especially around QMM, are service providers (e.g., maintenance and food catering) for the mining company. These income-generating opportunities attract people from other regions to the area. Very few households had members who were permanently or temporarily employed by a company, including the mine. Only 15% of households (n = 155) perceived the LEI to have had an impact on changes in their level of involvement in non-agricultural and non-forestry income-generating activities; most of these were located in the villages of Betaligny and Hovatraha "near" QMM (Fig. 3). The main reason for this perceived impact was a reduction in available raw materials that could be used for handicrafts (Table A6).

About half of the households found it difficult to maintain good health at the time of the survey, and 35% found it easy (n = 459) (Table A6). Over the past 20 years, being healthy had become more difficult for 53% of households (n = 458), and this was significantly more common in villages "near" QMM and Ranobe than in villages "far" from these sites (Appendix 2; Tables A6 and A7). Conversely, being healthy had become easier for 27% of households, and this was significantly more common in "far" villages across all case study sites. The majority of positive health changes were reported around Ambatovy Moramanga and TREM, and the main reasons given for the improvements were changes in health infrastructure around Ambatovy Moramanga, Ambatovy Tamatave, TREM, and QMM (Table A6). However, changes in health infrastructure had a negative impact on some households, especially around TREM. Proximity to a health center and changes in health infrastructure improved household health mainly

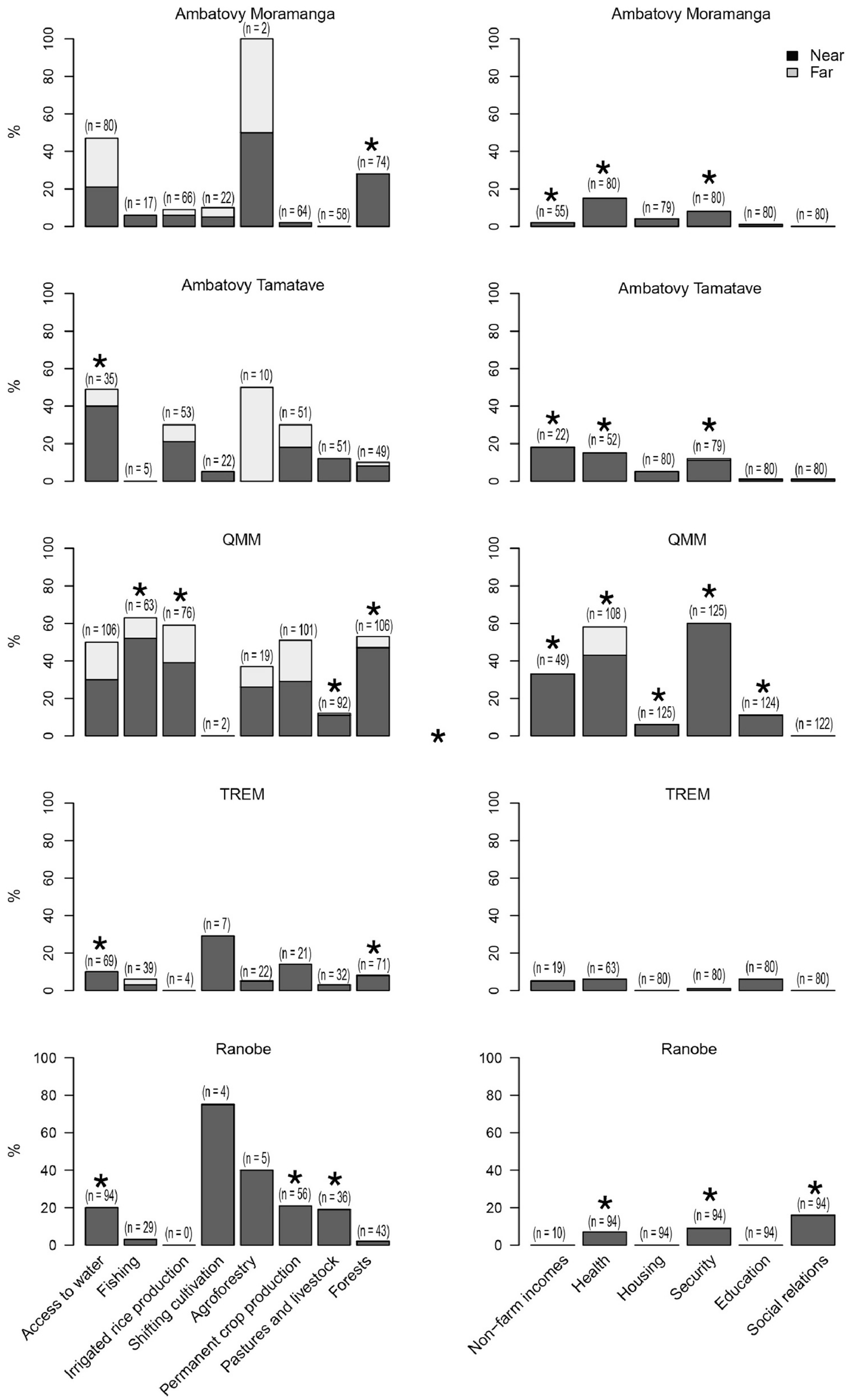

Fig. 3. Perceived mining impacts (x-axis, %) on land use, livelihoods, and human well-being (y-axis). The percentage refers to the number of respondents who reported a perceived LEI impact. N refers to the total number of households who responded to the question. An asterisk (*) represents a statistically significant association between village type ("near" and "far") and perceived LEI impact.

around Ambatovy Moramanga and, to a lesser extent, around Ambatovy Tamatave. Around TREM, improvements were mainly due to a change in health personnel and improvements in hygiene and sanitation infrastructure and general health infrastructure. Insufficient financial resources had a negative impact on household health mainly around Ranobe, but also around the two Ambatovy sites. Increased pollution was cited as a reason for a negative health change by 45% of respondents reporting a deterioration in health around QMM—significantly more often so in "near" villages—and by 21% in villages "near" Ambatovy Moramanga (Tables A6 and A7). Households in villages "near" TREM experienced negative health changes due to financial problems significantly more often than those in "far" villages (Table A7). Around QMM, personal reasons and changes in food availability also had a negative effect on household health (Table A6). Some households around Ranobe and Ambatovy Tamatave were located far from a health center, which made it harder for them to be healthy. When asked directly, almost one-quarter of households perceived LEI impacts on their health, and these impacts were mainly negative (Fig. 3). This was significantly more common in villages "near" all sites except TREM, and especially around QMM (Table A7). For 95% of these households ($n = 62$) around QMM, the most frequently given reason for negative health impacts was increased pollution of air, water, and soil, and this was significantly more often the case in "near" villages than in "far" villages (Tables A6 and A7). Around Ranobe, all seven respondents who perceived a negative health impact from the LEI related it to droughts (Table A6). Positive health impacts due to LEIs were mostly perceived around Ambatovy Moramanga, due to changes in health infrastructure, contributions to healthcare, and changes in hygiene and sanitation infrastructure, all reported in "near" villages only. In Ambatovy Tamatave, some households also reported positive impacts due to changes in health infrastructure.

The majority of households felt bad about their current housing situation ($n = 459$), and of these, 34% thought their housing situation had deteriorated over the past 20 years, significantly more often so in villages "far" from QMM than "near" it (Tables A6 and A7). Another 47% said their housing situation had not changed, and 19% thought it had improved (Table A6). Those who reported an improvement explained that they had previously lived in houses built entirely of wood and plant materials, whereas their new homes were made of cement, with corrugated iron sheets for roofs. Housing was perceived to have deteriorated significantly more often in villages "far" from QMM than "near" it, and the deterioration was attributed mainly to a change in income opportunities (Tables A6 and A7). Personal reasons, changes in available materials, and changes in income opportunities were more frequently associated with improved housing (Table A6). Only few households ($n = 458$) thought that the LEI site had affected their housing situation; most of these perceived their housing situation to have worsened (Fig. 3). These households were all located in villages "near" QMM, Ambatovy Tamatave, and Ambatovy Moramanga. The most frequently mentioned reason for a perceived negative impact was a change in income opportunities (Table A6).

Most households felt good about the current security and road safety situation ($n = 459$) (Table A6). Most of the respondents who felt bad about security and road safety lived around Ranobe. Households around Ranobe also reported that the security situation had worsened over the past 20 years due to an increase in theft and/or burglary. For 21% of households ($n = 157$), mostly those living around QMM and TREM, new security actors and agents were perceived as having a positive influence on security. Only 7% of households (n = 458) thought that the creation of the LEI site had played a role in these changes (Fig. 3), and 85% of these ($n = 34$) felt that the security situation had worsened. The main reasons for perceived negative impacts were an increase in theft around Ranobe, Ambatovy Tamatave, and Ambatovy Moramanga, and population growth and immigration around Ambatovy Tamatave and Ambatovy Moramanga (Table A6). All of these developments were reported almost exclusively in "near" villages. In villages close to Ranobe, perceived impacts were related to droughts.

More than two-thirds of households ($n = 457$) perceived current opportunities for schooling education, training, and information as poor (Table A6). For 57% of households (n = 457), opportunities had worsened over the past 20 years, significantly more so in villages "near" Ambatovy Moramanga than "far" from it (Tables A6 and A7). Improved opportunities for schooling, training, and information were perceived by 18% of households (n = 457), most of whom lived in the villages "far" from Ambatovy Moramanga and TREM (Table A6). The main reason for this improvement was a change in school infrastructure. Reduced opportunities were perceived by 57% of households (n = 457), mainly due to a change in tuition fees or their ability to pay (significantly more often so in villages "near" Ambatovy Tamatave than "far" from it), or a change in their means of obtaining information and in school staff (Tables A6 and A7). Only 5% of households (n = 458) thought the LEI sites had played a role in these changes, mainly those "near" QMM and TREM (Fig. 3). The main reasons given for these perceived impacts were the abandonment of programs that had introduced new agricultural techniques and knowledge around QMM, and changes in school staff that provided both poorer and better educational possibilities around TREM (Table A6).

The majority of households (n = 459) felt good about their social relations and their opportunities to participate in social activities (Table A6). For most households, social relations and activities had either remained the same or improved over the past 20 years. Improvements were mainly attributed to greater unity and people helping and respecting each other more. Greater unity was perceived significantly more often in villages "near" QMM than in villages "far" from it (Table A7). For 16% of households (n = 459), social relations and opportunities to participate in social activities had deteriorated, mainly due to less unity and to people helping and respecting each other less (Table A6). Most households in Benetse, the village closest to the Ranobe site, thought that the LEI site played a role in these changes (Fig. 3), mainly because there was less unity in the village, people respected each other less, and there was a drought (Table A6).

4. Discussion

4.1. Perceived impacts of the LEIs on the use and management of land (and the sea)

In this section, we discuss how LEIs in Madagascar are perceived to affect land use and land management activities as well as fisheries as a sea use activity, and how the perceived impacts might influence the achievement of several SDGs. In all case study sites, households perceived impacts of the mines on all land (and sea) use activities present, albeit to varying degrees. With regard to land use, LEI impacts were most widely perceived in relation to irrigated rice production, agroforestry, and permanent crop cultivation (e.g., cassava). While the LEIs did not affect the size of land users' irrigated rice fields, agroforestry systems, and plots for permanent crop cultivation, they did affect the management of these plots. In fact, almost all respondents reported a decrease in soil productivity in irrigated rice fields. They did so in both "near" and "far" villages, thus not indicating any influence of the mines. But around the QMM and Ambatovy Tamatave mines, which have been in operation since 2005 and 2012, respectively, about one-third of respondents in both "near" and "far" villages perceived that the mines had affected the productivity of irrigated rice. Damage to rice fields due to erosion had been reported previously by communities living near the mine (Soustras, 2017). The results regarding crop productivity in agroforestry systems and permanent crop cultivation were very similar and occurred in the same case study sites.

In all cases, the main mechanisms cited for the perceived impact of the mines on land use were soil, water, and air pollution. This indicates an adverse effect of some of the LEIs on SDG 12 (responsible consumption and production) and more specifically target 12.4 (environmentally sound management of chemicals and wastes). Water pollution from the LEIs affects SDG 6 (clean water and sanitation) and more specifically target 6.3 (improved water quality, wastewater treatment, and safe reuse) as well as SDG 14 (life below water). Acidic, sulfur-laden wastewater is known to be a common by-product of industrial mining operations (Johnson and Hallberg, 2005). Benidire et al. (2021), in their review focusing on abandoned mines in Morocco, found that tailings with a high acid-generating potential had led to a significant decrease in pH levels and severe metal contamination in soils. In addition, mining can affect soils over large areas, for example by harming soil structure, damaging soil microbial communities, and disrupting nutrient cycles. In the case of QMM, preliminary investigations showed that radioactive uranium and thorium were present in several upstream and downstream surface waters at concentrations well above the WHO limits for safe drinking water (Emerman, 2019; Swanson, 2019). The mine's tailings dam failed four times in recent years—twice in 2022 and twice in 2019 (Swanson Environmental Strategies, 2022). Dust contaminated with long-lived radionuclides is transported by wind, as was confirmed by collecting air monitoring data (Swanson, 2019). However, in the case of QMM, there are no quantitative data on radioactive soil contamination, so its impact on agricultural productivity remains hypothetical. Another potential reason for the decline in productivity cited by respondents around Ambatovy Tamatave is the use of insecticides. Communities living within a 30 km range of the mine noticed a decrease in bees and loss of crops after the LEI company had sprayed insecticides to protect construction workers from malaria (Soustras, 2017), which might also explain the decline in crop productivity. As the majority of respondents in our study villages produced irrigated rice, permanent crops, and agroforestry crops for subsistence, the perceived decrease in soil and crop productivity might negatively affect their food security in the longer term, thereby impeding the achievement of SDG 2 (zero hunger). Nonetheless, changes in soil fertility in irrigated rice and agroforestry plots were also an issue for land users around other LEI sites or in villages farther away from the mines, and they did not associate this with pollution from the LEIs. Based on the available scientific literature (e.g. Benidire et al., 2021; Bisht and Martinez-Alier, 2023; Humsa and Srivastava, 2015; Pourret et al., 2016), this indicates that while there seems to be an overall trend of decreasing soil productivity in all case study sites, the currently operational LEIs may be further exacerbating and accelerating this trend.

Another perceived LEI impact on land use management in the case of permanent crops was reported around Ranobe, where land users perceived the mining exploration to reduce water availability for irrigation. This again points to an obstacle for SDG 6 (clean water and sanitation) and more specifically target 6.4 (increased water use efficiency). For Ranobe, this was only the case in “near” villages. As regards shifting cultivation, few households across all mining sites (except QMM) perceived an LEI impact on this land use. Those who did mainly mentioned reduced access to land they needed to keep up the rotational character of this land system and thus soil fertility. While half of the respondents were less involved in cattle breeding than 20 years ago, this did not seem to be linked to the LEIs. Also, while almost all of the respondents herding cattle stated that the size of their pastures had decreased over the past 20 years, this was more often the case in villages located farther away from the mines. Indeed, less than 10% of the respondents mentioned a link between LEI operations and reduced pasture size and quality. Those who did so mostly lived in villages “near” Ranobe, Ambatovy Tamatave, and QMM. The ways in which the LEIs were perceived to affect pasture size and quality differed between sites: While the main problem reported in Ranobe was a decrease in water availability, in Ambatovy Tamatave it was people displaced by the mine, and around QMM it was contaminated drinking water for cattle. Villages “near” Tamatave experienced an increase in inhabitants because several communities had to relocate due to the construction of a large tailings dam by Ambatovy in 2012. This increase in residents in the villages “near” Tamatave has increased competition between farmers and reduced the availability of land for farming. To our knowledge, no study published to date has shown a relation between LEIs and pasture size and quality. However, this would be relevant, as a substantial number of the world's large-scale land investments are located in areas likely used by pastoralists (Messerli et al., 2014), which are often considered “idle” land by governments (Cotula et al., 2009). By causing declines in cattle breeding and pasture size and quality as well as reducing the availability of land for farming, LEIs might, in the long run, have an indirect negative effect on SDG 1 (no poverty) and SDG 2 (zero hunger).

The majority of respondents perceived a decrease in forests in the recent past. Only in one case did respondents blame the LEI for deforestation, pointing to a negative effect on SDG 15 (life on land) and SDG 13 (climate action). This was in the villages of Betaligny and Hovatraha, those closest to the QMM mine, where forest was reportedly cleared during the construction of the mine to make way for its extraction zone. Respondents in these two villages also perceived the most forest degradation. However, many more respondents perceived that the LEI had restricted or reduced their access to remaining forests. This was almost exclusively the case in villages around the operational mines of Ambatovy Moramanga and QMM, where the respective mining companies deny and restrict locals' access to the forest by posting signs and hiring guards. Households around QMM, Ambatovy Moramanga, and Ranobe have lost access to forests due to protected areas. There is a new protected area called Mandena next to QMM that is officially recognized by the state and managed by QMM, a protected area near Ambatovy Moramanga that is managed by the NGO Asity Madagascar, and one near Ranobe that is managed by the Ministry of Environment. Loss of access to forests can further exacerbate food insecurity related to reduced agricultural productivity by preventing access to natural resources and primary sources of income. This again points to negative effects on the achievement of SDG 1 (no poverty) and SDG 2 (zero hunger). The concern was already noted by communities in a social impact assessment for the QMM Fort Dauphin site (Kraemer, 2012). Large-scale mining has been observed to act as a driver of deforestation beyond the boundaries of operational mining leases across 18 pantropical countries (Giljum et al., 2022). For example, in the Brazilian Amazon, mining-related forest loss increased significantly up to 70 km beyond mining lease boundaries, resulting in 11,670 km^2 of deforestation between 2005 and 2015 (Sonter et al., 2017).

In villages around QMM, for those households who engaged in marine or riverine fishing activities, the LEI had degraded the availability of fisheries resources due to pollution and infrastructure construction. Recent tailings dam failures have invariably coincided with fish deaths downstream, most probably due to a combination of acidic water and elevated aluminum concentrations (Orengo, 2022a). There have been several leaks at Ambatovy Tamatave, both from the tailings dam and from the transport pipelines, and the main settlement pond is at risk of flooding under extreme weather (Soustras, 2017). No English-language published study has yet described the impacts of LEIs on artisanal fisheries in Madagascar, but mining impacts on fisheries have been observed elsewhere. For example, Malone et al. (2021) described perceived negative effects on the availability of river shrimps in the context of artisanal and small-scale mining in Peru. In Brazil, fishers perceived that the entire coastal ecosystem was affected after mining waste was released in the Doce River basin (Oliveira et al., 2020), and in Suriname and Indonesia, increased mercury present in fish due to artisanal and small-scale gold mining operations was found to have a potential impact on local fisheries (Lewis et al., 2020; Reichelt-Brushett et al., 2017). A literature search in Spanish and Portuguese yielded a study of mining impacts on fisheries in Madre de Dios, Peru (Tello, 2002) and an additional study on the impacts of the tailings dam rupture in the Doce River (Ribeiro et al., 2023). Our findings show that SDG 14 (life below water) should be given more attention in sustainability assessments of the extractive industries, as LEIs might impede its achievement depending on the geographical context and location of the mining activities. So far, this has not been made explicit in the published scientific literature; for example, SDG 14 is absent from the list and assessment published by Pedro et al. (2017).

Pollution was also one of the main reasons for changes in access to water, along with a decrease in water availability. The main source of water for the 15,000 people living near the QMM mine site is surface water, and many surface water sites around the QMM mine were found to exceed the limits specified in WHO drinking water guidelines for uranium and lead (Emerman, 2019). Tailings dam spills and leaks at

QMM and Ambatovy Tamatave have also significantly increased pollution in surrounding waters (Orengo, 2022b; Soustras, 2017; Swanson Environmental Strategies, 2022). As part of our wider project, we also took 10 water and sediment samples downstream from the Ambatovy Tamatave site (Appendix 3). Aquatic sediment samples taken around Befalafa and Ampasimbola ("near" villages) showed high levels of nickel, cadmium, and zinc. These findings support the perceptions of the 13 households who perceived a negative LEI impact on their access to water due to pollution from Ambatovy Tamatave. Accumulation of heavy metals in river sediments exposed to mining is a common phenomenon, as the river sediments become sinks for the heavy metals that flow downstream (e.g. Duncan et al., 2018). The water samples taken did not show elevated levels of any heavy metals at that point in time; however, it is important to note that water samples only capture data specific to the time they are taken. Samples were not taken upstream, so we could not compare up- and downstream sample sites (Emerman, 2019). Instead of pollution, perceived decreases in water availability around Ambatovy Moramanga and QMM may be related to the water-intensive nature of mining heavy mineral sands (Perks et al., 2022) and nickel (Elshkaki et al., 2017). By contrast, around Ranobe, this perception is likely related to information campaigns conducted by a national NGO working with a local association. Their campaigns raised people's awareness of the fact that the planned sediment extraction and treatment processes will use a lot of water. In a naturally semi-arid region, this could lower the groundwater table. In addition, it was estimated that several hectares of forest would have to be cleared to enable mining, and reduced forest cover could lead to less rainfall in the region. These varied negative impacts on water quality and availability are all detrimental to SDG 6 (clean water and sanitation).

4.2. Perceived impacts of LEIs on people's well-being

Only few respondents reported a perceived impact of the LEI on their involvement in non-agricultural income-generating activities. However, in two villages around QMM, a decrease in raw materials used for handicrafts was an issue. About one-quarter of respondents in various sites perceived a positive change in health infrastructure, albeit in both "near" and "far" villages. When asked directly about any perceived link between the mine and their health, the vast majority of those who answered cited negative impacts, especially around QMM, where most said that pollution of water, air, and soils made them sick. There have been reports of health impacts and concerns associated with sulfur-dioxide leaks from malfunctioning valves, the ammonia pipeline that cuts through residential areas, waste being dumped into the sea, tailings dam failures, pipeline leakages, and insecticide use (Orengo, 2022b; Soustras, 2017). The degradation of water quality is a significant change that villagers reported since the QMM mine started operating, and some of the health impacts villagers attribute to the mining activities include respiratory conditions, stomach aches, skin problems, diarrhea, coughs, and birth issues (Publish What You Pay Madagascar, 2022). In that study, households living near the QMM site reported lower fertility rates in men, more pregnancies that do not reach term, and more birth deformities. During more recent fieldwork, similar observations were noted among households living near Ambatovy Tamatave. Adverse pregnancy outcomes and negative impacts on reproductive health in communities exposed to mining pollutants have been observed globally (Dutta et al., 2022; i.e. Nyanza et al., 2020; Van Brusselen et al., 2020). Worryingly, QMM has now acknowledged that there is no in-country capacity to manage the waste residue at the mining site, and the company is also withholding reports on water quality (Publish What You Pay Madagascar and Andrew Lees Trust, 2024). By contrast, in Ranobe, all those who perceived negative impacts of the mining operation on their health said it was due to reduced water availability. The few positive impacts of LEIs on people's health were reported around the two Ambatovy sites and were related to health and sanitation infrastructure. This shows that while LEIs' contributions to SDG 3 (good health and well-being) might in principle be mixed, the impacts lean more toward the negative side in the context of Madagascar. Housing was barely affected by the LEIs, except for a few respondents around QMM and the two Ambatovy sites, who reported mainly negative impacts.

The majority of households felt safe, including on roads. Most of those who did not feel safe were located around the Ranobe site. A small share of respondents around the two Ambatovy sites, QMM, and Ranobe perceived a negative impact of the LEIs on security. While in the villages "near" Ranobe they linked this impact to drought, in the other sites it was perceived to be due to increased levels of theft, and in Ambatovy, specifically, due to an increase in population. With regard to opportunities for obtaining an education, again, it was only a small proportion of respondents who perceived any impact from the LEIs, and only in the cases of QMM and TREM. In the case of QMM, there was some disappointment about agricultural extension activities that the mine had started and later abandoned, and only in the case of TREM did a few respondents report improved opportunities for education thanks to investments made by the company during exploration. This suggests that LEIs' corporate social responsibility programs could do better in terms of improving access to education and supporting progress toward SDG 4 (quality education). Finally, most respondents were satisfied with their social relations and either perceived no change over the past 20 years or even reported an improvement. This is contrary to common assumptions that social cohesion (*Fihavanana* in Malagasy) is decreasing as traditional societal structures based on reciprocal exchange are gradually being replaced with market economy mechanisms (Wallner, 2016). Almost exclusively in Benetse, the study village closest to the Ranobe site, respondents perceived that the LEI's exploration activities had caused a decrease in unity and mutual respect in the village. Community protests in Benetse against the proposed mining activities increased over the years, especially when it appeared that the mining company was ready to start operations (Andriamanantenasoa and Mapondera, 2021; Carver, 2020; Carver, 2019). In 2019, the protests culminated in the arrest of nine community members, who were accused of participating in vandalizing the LEI company's exploration camp. Opinions about the arrival of "Base Tuléar" have been very divided in Benetse. Some households believe that the mining company will bring development and new employment opportunities, especially for their children, while others oppose the mining company because of the negative impacts they have already experienced. This divergence of opinion has reduced cohesion among residents. These findings from the Ranobe case in Madagascar are consistent with global observations of increasing social resistance to sand mining projects due to their known ecologically destructive nature (Bisht and Martinez-Alier, 2023). These tensions around processes related to planning and implementing LEIs in Madagascar point to deficiencies in the achievement of SDG 16 (peace, justice, and strong institutions) and specifically target 16.7 (responsive, inclusive, participatory, and representative decision-making).

4.3. LEI impacts occur before extraction and can reach far

Through our study, we have gained a holistic picture of the perceived impacts of two operational LEIs and two in their exploration phase. For the first operational LEI, QMM, a substantial share of respondents reported impacts on land use and land management related to irrigated rice fields, agroforestry, and permanent crops. In addition, they perceived that the LEI had negatively affected pasture size and quality and fisheries, and that it had caused deforestation of the biodiversity-rich coastal forests. Using satellite data (Sentinel-2 A, 10 m resolution), we were able to confirm the deforestation perceived by the households. Specifically, we observed deforestation between November 2017 and November 2021, and a recent satellite image from 2023 shows that mining activities have expanded inland and along the eastern edge of some of the remaining Mandena coastal forest (Eckert et al., 2023). In terms of human well-being, respondents around QMM also mentioned negative health impacts from pollution, as well as reduced non-agricultural income-generating activities due to more limited availability of natural materials for handicrafts. Finally, to a lesser extent, QMM also had a negative impact on security and on educational opportunities. The other operational LEI, Ambatovy—or, more specifically, the Ambatovy Tamatave site—showed a very similar picture in terms of reported impacts on land use and land management for irrigated rice fields, agroforestry, and permanent crops, as well as on pasture size and quality. Around the Ambatovy Moramanga site, the only substantial perceived impacts were reduced access to forests and a decrease in forest size, both significantly more often reported in "far" villages. However, impacts were also perceived in villages "near" the mine site—for example, in Menalamba, where three-quarters of the households we surveyed had lost access to natural forests over the past 20 years. Menalamba is located in the Torotorofotsy wetland, one of Ambatovy's biodiversity offset sites (Ambatovy, 2022; Devenish et al., 2022). The wetland was classified as a Ramsar site in 2006 and consists of wetlands, forests, and other important habitats (Ramsar Sites Information Service, 2016).

For the Ranobe LEI, which was in the exploration phase, the main impact that some respondents ascribed to the mining explorations was reduced groundwater availability. They believed that this had a negative impact on the irrigation of permanent crops, on cattle rearing (due to decreased drinking water availability), and on people's health. However, the reason for the observed decline in groundwater availability is highly contested among different stakeholders, as a lack of groundwater could be a justification for the mining company to abandon its extraction plans. In addition, respondents around Ranobe reported negative security impacts, again linked to the issue of water availability and resulting social conflicts. Around TREM, very few households perceived LEI impacts. Some households perceived reduced access to water due to pollution, reduced access to forests due to the closure of forest access, and one respondent mentioned holes dug by the company that caused damage to their livestock. Our results show that while impacts of LEIs mostly occur once the mine has become operational and resource extraction has started, people living around these sites perceive negative impacts already during the exploration phase of planned investments. This is important, because mining companies are currently required to conduct an environmental and social impact assessment (ESIA) only for the operational phase. During the exploration phase, semi-detailed ESIAs are only required for activities with high or exceptional risks (Nikièma et al., 2023). This is a major shortcoming in the overall regulatory oversight by governments, such as the Government of Madagascar, to prevent damage to the natural environment and the lives of local people (Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development, 2020).

Despite the seemingly adequate regulation of Madagascar's mining sector, the majority of respondents exhibited predominantly negative perceptions with regard to impacts of both operational and exploratory LEIs. This might be explained by the limited participation of local populations in developing and shaping these regulations, associated with issues of enforcement and compliance. Okyere et al. (2021) show how the lack of participation of the local population in large-scale mining regulation in Ghana resulted in loss of livelihoods and income for host communities and it affected households' already reduced ability to meet basic needs such as food and school fees for children. In addition, enforcement is an essential element in the implementation of regulations. According to Marimuthu et al. (2021), developing countries such as India face difficulties enforcing adherence of the mining industries to policies on environmental sustainability, labor and management relations, and fair wages, which is also likely to cause negative impacts of mining activities on local populations.

4.4. Study limitations

In terms of limitations, our study highlights a methodological challenge with rigorous impact evaluations using counterfactuals for interventions that affect several sustainability dimensions. While our aim was to conduct an impact assessment of LEIs using a counterfactual approach, for which we selected two groups of villages (those affected and those not affected by the LEIs), we also included a direct question about the perceived impact of the mine for each aspect. The results showed that in some cases there was no statistical difference in perceptions between respondents from villages closer to the mine (which we had assumed were affected) and those farther away (which we had assumed were not affected). As explained above, the reason for this was that even respondents in villages farther away from the mines perceived many impacts, which became evident in their responses to the direct question. However, based on propensity score matching, the villages we selected as the counterfactual were the only ones that were somewhat similar to those we hypothesized to be affected. Villages located even farther away from the mines than the ones we selected were already too different from those affected to be comparable, for example regarding land use or spatial accessibility. This means that, in the context of these mines, there simply is no counterfactual. This is a challenge that should be considered in future impact evaluations using a counterfactual study design. At the same time, use of counterfactual approaches for impact evaluations of land use interventions (e.g. protected areas) is important for generating robust evidence on the causality of a given intervention and its impacts (Ferraro, 2009; Schleicher et al., 2020). When evaluating multifaceted impacts of land use interventions on multiple environmental and social variables, it might be advisable to combine a quantitative, statistically robust assessment with qualitative information obtained through open questions in the same survey. In our case, this allowed us to shed light on impacts in "near" and "far" villages that would have been masked had we relied only on closed questions and the interpretation of statistically significant differences.

Furthermore, our study is fully based on respondents' perceptions of impacts. It would have been ideal to complement these with quantitative assessments of some of the impacts, for example pollution and health. However, this was clearly beyond the scope of our own project's resources, and to date only few studies offer empirical quantitative data in the context of the mines we examined. The only ones relate to QMM and focus on water quality (Emerman, 2019) and the release of radioactive material (Swanson, 2019). In addition, it is important to consider that households living in villages farther away from the mining sites may be less likely to attribute perceived changes to mining activities because they are farther away from the activities and associated controversies. Perception bias may also arise from households' emotional memories associated with extreme experiences (e.g., a tailings dam failure), as emotions can influence our perception of environmental issues (Yang et al., 2018).

5. Conclusion

Our results provide a holistic overview of how two operational and two planned LEIs in Madagascar affect land (and sea) use and human well-being from the perspective of people living in their vicinity. We focused on the most important land (and sea) use activities in our case study sites. Regarding sea use, the main livelihood activity is fishing, so we focused only on this one use, whereas a whole range of land uses support the livelihoods of people in the area and were therefore examined. Perceived impacts on land mainly affected the land uses of irrigated rice, agroforestry, and permanent crops, whereas shifting cultivation was less affected. Reports revolved predominantly around LEIs negatively affecting soil and crop production, due to perceived soil, water, and air pollution. While a substantial number of respondents considered the LEIs to be responsible for deforestation or for changes in their access to forests, decreases in livestock productivity were rarely associated with the LEIs. In terms of human well-being, positive impacts are limited to few perceived benefits from investments in health and sanitation infrastructure made by the two operational LEIs. Negative impacts on well-being are mainly related to people's health and security problems, which are perceived to be linked to the activities of the two operational LEIs. In addition, one of the exploratory LEIs led to social conflicts due to a perceived decrease in water resources. Overall, perceived impacts occur not only in villages "near" (i.e., within 5 km of) the mines, but also in villages farther (up to 20 km) away. Furthermore, we show that not only the operational LEIs were perceived as having negative impacts on the environment and human well-being, but also those in their exploratory and planning phases. This evidence could help to improve procedural and content-related aspects of current environmental and social impact assessments (ESIAs) in Madagascar.

Finally, our empirical insights into the diverse and wide-ranging impacts of operational and planned LEIs in Madagascar highlight broader issues regarding the contribution of LEIs to sustainable development. Currently, the studied LEIs directly impede the achievement of SDG 6 (clean water and sanitation), SDG 12 (responsible consumption and production), SDG 13 (climate action), SDG 14 (life below water), SDG 15 (life on land), and SDG 16 (peace, justice, and strong institutions); indirectly, they also hinder progress toward SDG 1 (no poverty) and SDG 2 (zero hunger). While LEIs might contribute to SDG 8 (decent work and economic growth) via tax contributions to national budgets, such growth cannot be considered "sustainable" under the present circumstances. Our findings clearly indicate for which aspects of their explorations and operations LEIs must take action in order to turn the tide and start supporting rather than hindering the urgently needed transformation of the mining sector in Madagascar.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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