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Biodiversity conservation threatened by global mining wastes

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Mine tailings—the residue remaining after mineral processing—represent a serious risk to the natural environment, and the failure of tailing storage facilities has caused some of the most serious environmental disasters in history. However, the potential biodiversity impacts globally due to tailings are mostly unknown. Here we assess the spatial coincidence between 1,721 disclosed tailings storage facilities and currently protected areas (PAs) and other conservation priorities (Key Biodiversity Areas and remaining intact ecosystems). Nine percent of storage facilities are located within PAs, half of which were established after the PA was designated. Another 20% of storage facilities are within 5 km of a PA, indicating even larger risks posed by upstream facility failures. Despite international commitments to mitigating biodiversity loss, tailings storage facilities continue to be established within PAs, with an upward trend in the proportion established within already-existing PAs. Given our findings, it is unsurprising that biodiversity factors are rarely included when assessing and categorizing the risks posed by new and existing tailings storage facilities. Greater transparency and a holistic consequence-based approach, supported by data, monitoring and new technologies are needed to drive reform at local, national and regional levels.

Mining wastes, both in the form of waste rock (blasted rock not subjected to mineral processing) and mine tailings (the residue remaining after mineral processing), are the largest solid waste stream in the world, and the tailings storage facilities (TSFs) built to contain this waste are the world's largest engineered structures[1]. Corporate disclosures with information on 1,743 TSFs reveal that these structures already contain at least 44.5 billion m^3 of waste. But the rate of waste generation is expected to increase. Each year, an additional 10 billion m^3 (~13 billion t) of tailings will require storage by either existing or new facilities over the 2019–2023 period[2]. Managing and mitigating the impacts of this waste on surrounding communities and ecosystems, while increasing mineral production, is a key challenge for sustainable development[3–5].

Failures of TSFs are frequent, and consequences can be fatal. More than 166 major failures have occurred since 1960[6], and at least 10% of current facilities have had notable stability concerns at some point in their history[2]. The vast volume and environmentally sensitive nature of material held within TSFs mean that their failure can impact biodiversity for hundreds of kilometres downstream[3]. Two recent and highly publicized TSF failures in Brazil (the Samarco disaster in 2015[7,8] and the Brumadinho disaster in 2019[9,10]) released a combined 50 million m^3 of tailings into local waterways and caused 289 fatalities and irreversible damage to aquatic and terrestrial ecosystems and human settlements.

The catastrophic nature of these two specific events sparked a group of institutional investors to initiate the Investor Mining and Tailings Safety Initiative in 2019, which issued an information disclosure request to 726 publicly listed mining companies[2]. The initiative aimed to improve the understanding and transparency related to the financial and social risk associated with tailings facilities and to act to ensure best

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practice management of mine tailings is implemented. The information request covered 20 characteristics of TSFs, including coordinates, size, age, consequence ratings (Supplementary Information provides an overview of these ratings), construction methods, history and whether a formal analysis of the downstream impacts of potential failure on local communities, ecosystems and infrastructure had been conducted[2]. The disclosed information covers 1,743 TSFs from 107 companies, representing 36% of contemporary global commodity production[2].

The disclosed information currently available does provide some insight into the threats TSFs pose to biodiversity. For example, the questions in the disclosures highlight current design and management approaches to a TSF and whether the companies are doing their environmental due diligence in terms of risk and impact assessments. Further, each TSF is assigned a consequence category based on the potential failure modes of the facility and resulting impacts of a failure to business, the natural environment and potential loss of life. However, the current disclosures do not reveal which TSFs currently threaten biodiversity, where or how future failures may cause serious environmental impacts, specifically in terms of biodiversity loss, or whether these threats are changing over time.

Some categories of protected areas (PAs) explicitly prevent mining activities[11] and, since 2003, the International Council on Mining and Metals (ICMM)—representing one-third of the mining and metals sector—have committed member companies to respecting these legal designations[12]. ICMM addresses the importance of biodiversity conservation in its Position Statement on Protected Areas and, in 2023, reiterated its ambition to achieve no net loss (NNL) of biodiversity at new mining sites and major expansions through application of the Mitigation Hierarchy[13], meaning that impacts are first avoided where possible, then minimized, restored and, as a last resort, offset through creating equivalent biodiversity elsewhere (Supplementary Information). Whereas some evidence suggests NNL of biodiversity is possible[14], it is not the norm, due to a range of theoretical and practical challenges, particularly related to generating gains through offsets[15,16].

In comparison to PAs, biodiversity-focused conservation priorities (such as Key Biodiversity Areas, KBAs) are not legally protected[17] or captured by industry best practice guidelines to achieve NNL goals. However, rapidly growing industry commitments towards nature positive outcomes will require a better understanding of how their threats extend to other conservation priorities and what opportunities exist to manage them[18]. Approximately one-third of the Earth's land area is within 50 km of a mining property or exploration site, and 8% and 7% of this area coincide with PAs and KBAs, respectively[19]. Even remaining intact ecosystems (REs)—areas supposedly free from industrial-scale activities and human pressures—frequently contain mining activities, possibly in an attempt to keep mining infrastructure and waste away from highly populated areas[19]. Since 2000, substantial areas of intact land (1.9 million km^2) have been lost[20]. Further habitat loss by TSF failures will have notable implications for biodiversity that require intact land for their continued survival.

TSFs store mining waste to avoid its interaction with the environment. However, understanding the threats their failures pose to biodiversity is important and useful to guide conservation and management action. Therefore, this study aims to examine associations between TSFs and PAs and biodiversity conservation priorities. We use the global disclosure database of 1,721 tailings facilities[2] and examine their coincidence with current PAs[21] and other sites deemed important for achieving conservation goals: KBAs[17] and REs (Methods include descriptions)[22]. Focusing on PAs, as these are recognized and managed through legal means to achieve the long-term conservation of biodiversity, further explore temporal trends in facility establishment. Specifically, we: (1) compare the trends in TSFs established at different distances to PAs (that is, within PAs, <5 km from PA boundaries and >5 km from PA boundaries); (2) determine if factors, such as year of PA designation (that is, specifically whether TSFs established before or after the PA) and company membership to industry groups with position statements on reducing biodiversity impacts (that is, International Council on Mining and Metals), affect the rate of TSFs established within PAs and (3) assess whether TSFs categorized as either 'high-risk' or 'high consequence' of failure are located further away from PA boundaries.

Fig. 1 | Spatial coincidence between TSFs and PAs, KBAs or REs. a,b, Bars show the proportion of TSFs and random points found within (**a**) and in proximity (**b**) (that is, outside but within 5 km) to PAs, KBAs and REs. Blue bars show the proportion of TSFs within PAs (9%), KBAs (5%) and REs (4%). Red bars show the proportion of TSFs in proximity to the boundaries of PAs (20%), KBAs (8%) and REs (5%). We compared the proportion of TSFs within and in proximity to PAs, KBAs and REs with the proportion of randomly distributed points within and in proximity to PAs, KBAs and REs (control sample), shown with the grey bars.

Results

TSFs within and near PAs and conservation priorities

We found 9% of TSFs were located within the boundaries of PAs and a further 5% were within KBAs and 4% within REs (Fig. 1a). The proportion of TSFs located within PAs and KBAs was slightly less than what we would expect by chance alone (that is, compared to the same number TSFs randomly distributed across the study region; Methods). The proportion of TSFs located within REs was much lower than we would expect by chance but not as low as it should be (that is, zero; Fig. 1a). We also found 20% of TSFs were located outside but within 5 km of PAs, and a further 8% were within 5 km of KBAs and 5% within 5 km of REs (Fig. 1b). Across all categories, this coincidence was greater than we would expect by chance alone and for PAs was almost three times greater (Fig. 1b).

Temporal trends of TSFs within and near PAs

The number of TSFs established each decade increased on average 1.4 times between 1910 and 2020; while the number of TSFs established within and near PAs during this time increased 1.6 times each decade (Supplementary Fig. 1). As a result, the proportion of TSFs established within and near PAs each decade remained relatively stable.

We found 89 of the TSFs within PAs were established after the PA was designated, representing 5% of TSFs globally and half of the TSFs within PAs (Figs. 2 and 3). We also found the proportion of TSFs within PAs established after PA designation increased over time (Fig. 2). Additionally, we found that the proportion of TSFs within PAs that were established after PA designation increased over time in comparison to those TSFs established before PA designation (Fig. 3 and Supplementary Table 1).

Most TSFs within PAs (87%, $n = 130$) were owned by ICMM member companies. From these TSFs, 40 (31%) were established after the Position Statement on Biodiversity was released in 2003 (Supplementary Table 2).

High-risk and high-consequence TSFs within and near PAs

The proportion of TSFs categorized as having very high consequences of failure was greater for those established further than 5 km from PAs (Fig. 4a). Thirty five percent of TSFs within PAs were categorized to have high or very high consequences of failure (Fig. 4a).

Using the TSF raise structure (construction method; Supplementary Information) as an indicator of risk of failure (Methods), we found similar distributions of structures between those TSFs within, near and far from PAs. However, 32% of TSFs within PAs had the riskiest upstream raise type (Fig. 4b).

We found similar distributions of active TSFs between those within (36%), near (34%) and far (45%) from PAs (Supplementary Fig. 2). A third of TSFs within PAs ($n = 49$) did not assess downstream effects of potential failures in their consequence ratings. However, 37 out of the 49 TSFs were not active at the time of reporting. When considering TSFs near PAs, 110 (32%) did not assess downstream impacts of potential failures, 79 of which were reported as inactive. In total, 43 (18%) active TSFs within and near PAs pose environmental threats that were not determined at the time of reporting (Supplementary Table 3).

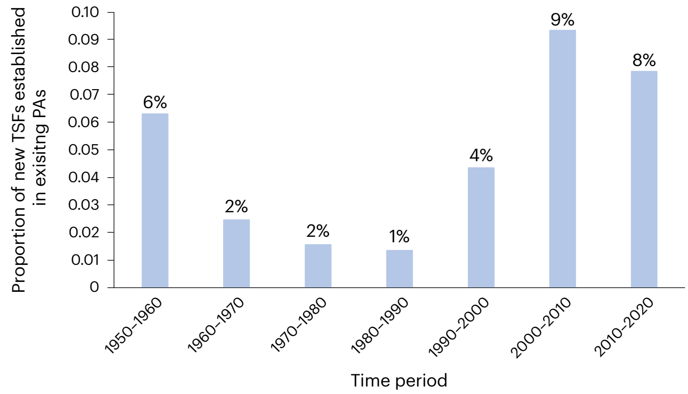

Fig. 2 | Temporal trends in TSFs established in already-existing PAs. Bars illustrate the proportion of new TSFs established every decade from 1950 to 2020 within existing Protected Areas. Note: the proportion of new TSFs established within already-existing Pas was calculated by dividing the number of new TSFs established within existing PAs by the total number of new TSFs established each decade.

Discussion

Recent high-profile TSF failures caught the attention of investors, who called for public disclosure of current practice. These disclosures made an enormous contribution towards enhancing transparency within the industry but tended to focus on TSF design and management, rather than the environmental risks associated with failures. Here we provide insights into these factors by analysing the spatial and temporal associations between TSFs and PAs and other conservation priorities. Our results suggest that the proportion of TSFs occurring within PAs is on the rise, despite industry commitments to mitigating biodiversity impacts of mining activities. We also find that some of the riskiest TSF raise types occur within PAs where failures would undoubtedly impact biodiversity but, because the methods used to classify the consequences of failure do not systematically consider environmental issues, these facilities were considered 'low consequence'. Here we explain the new data and risk methods needed to further enhance industry transparency and improve environmental outcomes of mining and storage of waste.

Threats of TSF failures to biodiversity

Over the past 30 years, the number of TSFs built worldwide has increased substantially, with an upward trend in the proportion established within already-existing PAs. The first TSF to be established within a PA was built in the 1950s, which coincides with the designation of the first protected areas. The proportion of TSFs established within PAs decreased between 1970 and 1990 as the first national parks (category II) that strictly ban extraction activities started to be established. The proportion of TSFs within already-existing PAs then started to increase after the 1990s as the number of less strict PAs (categories V–VI) increased (Supplementary Table 1). Most TSFs (45%) within PAs were established in less strict IUCN (International Union for Conservation of Nature) management categories (Supplementary Table 4). Despite their unique capacity to support economic growth, IUCN VI management areas contribute significantly to protecting biodiversity as they are among the largest PAs on average, with most of the area in their natural condition[23]. At the local level, minimizing these threats will require information on the distribution of TSFs, site-specific data and well-established methods and metrics to address the magnitude of potential TSF failures.

Most TSFs within PAs continue to use upstream raise structures, which are considered the least safe of all conventional raise structures, as they report the most failure incidents[24,25] and stability concerns[2]. It could therefore be expected that these raise structures would be avoided in locations where the environmental consequences of failure are high. However, our data do not reveal a trend away from situating high-risk facilities within and near PAs. Alternative methods of tailings management are available (for example, dry stacking of dewatered tailings and in-pit disposal) that report less stability concerns[2] and present lower environmental risk[4,26]. Dry-stack facilities are typically associated with higher operating costs and lower production capacity, though they have the potential to reduce long-term tailings management and environmental costs. The uptake of dewatered tailings by the industry has been low[2], indicating that the economic and policy incentives, at least in the short term, have been insufficient. New recycling technologies could also provide opportunities to reduce the amount of waste generated (for example, the production of ore-sand by-products for the construction industry to reduce tailings)[27,28].

We would expect the majority of TSFs within PAs to be classified as high or very high consequence due to the threats they pose to biodiversity. Yet, only 29% and 6% of TSFs within PAs were classified as high and very high consequence, respectively, which is derived from the metrics (population at risk) that most classification schemes use to assign the consequence of failure categories and the low human population densities inside PAs[29,30]. The global dataset of TSFs reports on 62 different consequence classification systems that use different metrics to estimate the risk potential of a TSF failure, and a considerable number of classifications do not include environmental factors[2]. Therefore, classification guidelines that use only population at risk as a metric of consequence of failure fail to provide clear and consistent definitions of potential habitat and wildlife loss that can be used for qualitative and quantitative assessment of environmental consequences. We recommend that TSFs located within and near PAs be re-classified to higher consequence categories to be more consistent with the actual risks they pose to biodiversity.

More than half of TSFs within and near PAs were inactive. While the majority of TSF failures reported occurred in active facilities, inactive facilities remain of concern as these facilities are often abandoned. Hence, continued monitoring of these TSFs is important to prevent future failures. Also, our results suggest that most TSFs with high consequences of failure occur in developing countries with high corruption perceptions indexes and were, in most cases, owned by global mining companies (Supplementary Table 5). Given the trajectory of TSF

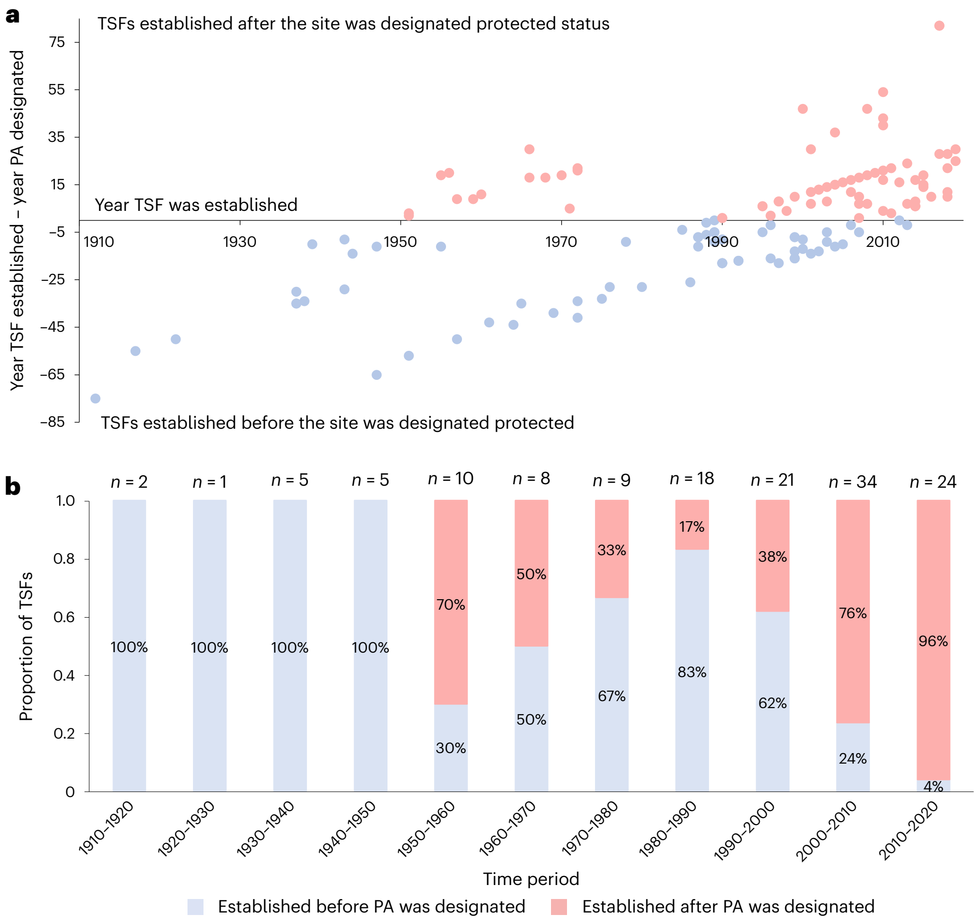

Fig. 3 | Temporal distribution of TSFs within PAs relative to the year the corresponding PA was designated. a, Graph showing the TSFs established before/after the corresponding PAs were designated. Each dot represents a tailings facility from the dataset found within the boundaries of PAs. The *x* axis shows the year the TSF was established. The *y* axis shows the difference between the year the TSF was established and the year the corresponding PA was designated. Positive values show tailings facilities established after the protected area was designated. Negative values show tailings facilities established before the protected area was designated. **b**, The proportion of TSFs established before (in blue) and after (in red) the corresponding PAs were designated were assessed for every decade from 1910 to 2020.

failures has shifted from developed to developing countries[31], addressing the consequences associated with failures may represent serious challenges in resource governance for these nations[32–34]. Opportunity exists for these governments to understand the costs associated with TSF failures post mine closure. Increasing bonds to better capture the consequences of failures could be one way to prevent TSFs being established in high-risk areas and ensure that recovery action is financially feasible.

Impacts of TSF failures within PAs on biodiversity

We found many TSFs were located within or near PAs and other conservation priorities. Failures of these TSFs will cause harm to biodiversity either when the TSF is located within PA boundaries (infrastructure causes habitat loss and any failure will cause direct harm to its waterways) or when a nearby TSF is located upstream of a PA. While TSF failures release large volumes of potentially hazardous material that can quickly travel hundreds of kilometres from the source, using proximity as a measure of consequence of failure needs to be applied with caution; many factors will affect the ultimate outcomes (for example, topography, tailings water content and flow rate, size and volume, method of storage). Other complex factors, such as climate change, can also complicate the risks of TSF failures. Climate change will both increase the likelihood of failures in the future[24], and any failure that occurs will probably affect facets of biodiversity that are under pressure from climate change. Whereas it is highly unlikely that all TSFs within and nearby will fail, it is important to understand the distribution of risks and overcome the current lack of knowledge on site-specific impacts of TSF failures on biodiversity features and ecological conditions, including contamination of aquatic ecosystems at varying distances from the sites. Independent biodiversity impact assessment of potential TSF failures throughout the facilities' life cycle should be included in the environmental impact assessment to categorize the potential risks and consequences of failures within and near conservation priorities.

Modelling the downstream impacts of TSF failures requires information that is often not readily available, such as tailings properties and terrain characteristics. Efforts have been made to examine the local risks of TSFs to environmental and social variables on a global scale and to develop simple[35] and high-level tools[36–38] that could be useful to transform the information in the disclosures into results that model the run-out distance and inundation zones in cases of potential failures. These models could be implemented as part of the biodiversity impact assessment of TSF failures to identify areas where consequences of failure are higher. Thus, triggering stricter management standards and guiding policy development and implementation.

The increasing global demand for energy transition metals, declining ore grades and associated increases in mine waste mean that high-risk TSFs will continue to be built in the future[39,40]. Total tailings production is predicted to reach 300 Gt over 2020–2050,

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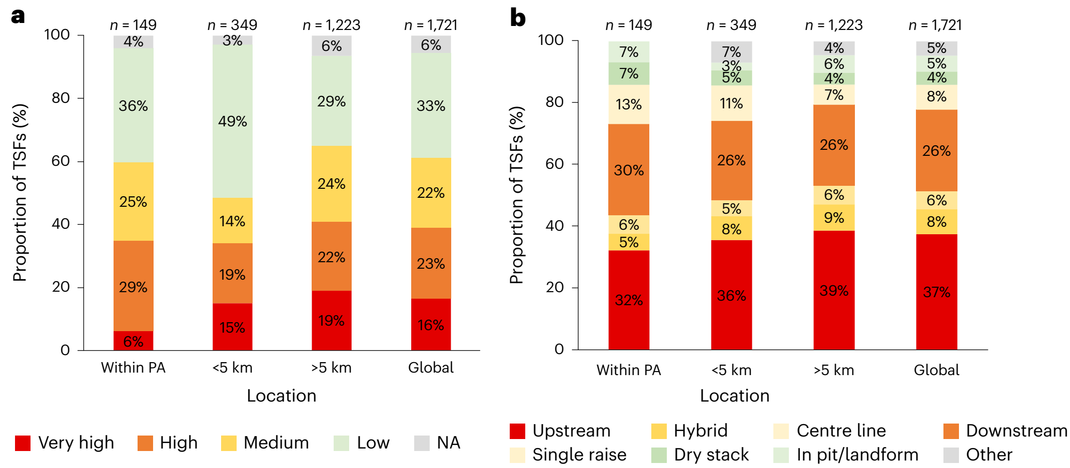

Fig. 4 | Distribution of TSF categories across three distance parameters. **a**, The proportion of consequences of failure categories found within PAs, <5 km from PAs and >5 km from PAs. Colour shading (red to light green) illustrates the different consequence of failure categories starting with 'very high' consequence of failure in red to 'low' consequence of failure in green. Unclassified TSFs were designated as NA (Not Applicable). **b**, The proportion of different raise structure categories found within PAs, <5 km from PAs and >5 km from PAs. Colour shading (red to light green) illustrates different tailings raise structures, arranged by their propensity to report a stability issue, with upstream tailings facilities in red to dry-stack and in-pit/landform facilities in light green.

which is more than 2.4 times that produced since 1900[28]. For copper, which makes up 46% of the global tailings volume, the total amount of tailings and waste rock predicted over 2020–2050 is 858 Gt (ref.37). Further, due to the decrease in lithium grade, a great increase in production will be required to meet future demands for clean energy transition. Current estimates suggest that tailings production is projected to increase to 2Gt per year by 2050[28] and production of lithium-ion batteries could require 80 new TSFs, equivalent in size to the Brumadinho TSF in Brazil[41]. Considering the spatial distribution of TSFs over coming decades and their failure rate (3.45 failures per year)[31], consequences of facility failures on biodiversity could be devastating. Future establishment of TSFs must be guided by biodiversity risk assessments.

Outlook on the future of TSF management

Our results suggest TSFs continue to threaten biodiversity within and near PAs. The dataset analysed herein constitutes only 36% of global mineral commodity production;[2] thus, our findings, while illustrative of the threats, represent only a fraction of the absolute number of TSFs that threaten PAs. In the future, greater transparency by state-owned and privately owned companies that are under-reported in the TSF disclosures is necessary to improve understanding. The level of global spatial coincidence between TSFs and conservation areas and the high impact of TSF failures highlights the need for urgent action.

Clearly, there is a need for a more holistic approach to disaster risk disclosures that reinforce the importance of biodiversity threats. In August 2020, the Principles for Responsible Investment, the ICMM and the United Nations Environment Programme released the Global Industry Standard on Tailings Management (the 'GTR Standard' or the 'Standard')[42]. The GTR Standard aims to achieve zero harm to people and the environment. Necessary strategies brought by the new standard include a holistic environmental impact assessment of TSFs, potential failures throughout its life cycle and a robust classification scheme that considers the consequences of failures on the natural environment. It is hoped that when the standard is implemented, all existing TSFs will review their failure classification to meet the new criteria, ideally including biodiversity considerations to be more consistent with the actual risks posed, which would trigger higher management standards. We would also expect any new TSFs classified as high/very high/extreme consequence of failure to be sited in locations where threats to biodiversity can be minimized, as required by the principles of the mitigation hierarchy[14]. The improved disclosure requirements brought by the standard will provide more insight into the threats that TSFs pose for investors but also allow national and regional governments, especially in developing countries, to make informed decisions between development opportunities and conservation objectives.

The mining industry's tailings management performance has been a serious issue for decades and the pace of reform has been slow[43]. The recent adoption of the GTR Standard by members of the ICMM will raise the bar for disclosure[44]. Focus must be on establishing a holistic approach that includes both human and environmental impacts of TSF failures. Future biodiversity assessments of TSFs must be comprehensive conducted and incorporated into these risks and disclosures to fully understand the scale of the challenge.

Methods

Mapping TSFs

The database includes 1,743 TSFs predominantly owned by publicly listed companies[2] (Supplementary Data 1). Abandoned facilities, state-owned entities and privately owned companies, including many mid-sized and junior companies are not strongly represented. This contributes to an under-representation of facilities in countries where the number of state-owned and privately owned mining operations is important (for example, China, India and Chile) and potentially an over-representation of larger facilities. Consequently, the dataset comprises only 36% of the contemporary global commodity production[2].

Franks et al. proportionally extrapolated the data from the disclosures to account for lobal mineral commodity production, estimating that the total number of active TSFs worldwide is around 3,400, and a lower bound for the total number of facilities active, inactive and closed facilities is around 8,100[2]. Previous authors have cited global estimates of 3,500 tailings facilities[45] worldwide and 12,000 facilities (just in China)[46]. The methods for determining the aforementioned estimates, however, are not stated, and it is not clear whether they refer to active, inactive, closed or abandoned facilities.

However, the relatively high sample rate provides confidence in the representativeness of the dataset for publicly owned active TSFs. We obtained point locations for 1,721 of the reported TSFs and used the WGS (World Geodetic System) 1984 World Mercator projected coordinate system to analyse the data in ArcGIS Pro 3.0.2.

Mapping PAs and conservation priorities

We obtained spatial data on three types of conservation area across terrestrial systems, including protected areas (PAs), Key Biodiversity Areas (KBAs) and remaining intact ecosystems (REs). We included 28,409 PAs (23.38 million km^2) that are formally designed to conserve biodiversity and ecosystem services[21]. We included 13,320 KBAs (13.87 million km^2) that constitute sites that contribute significantly to global biodiversity persistence[17]. We also examined REs, which are areas free from industrial-scale activities and human pressures[22]. To do this, we used the 2009 Last of the Wild indicator that includes the top 10% of intact habitats for each of Earth's 60 biogeographic realms (12.12 million km^2)[22]. These areas are not formally considered in global conservation policies but are attracting attention as proactive means to protect biodiversity[47].

Standardizing the consequence of failure categories

Each company reported on the consequence of TSF failures. These facilities were classified against 62 different classification schemes that use different metrics of consequence[2]. The most common schemes are the Canadian Dam Association, Australian National Committee on Large Dams, South African National Standards, Brazilian Ordinance 70.389/17 and Anglo-American Technical Standard, which cover 68% of all TSFs and 71% of those within PAs. To calculate the proportion of TSFs that fall within each consequence category across three distance parameters (within PA, <5 km from PA, >5 km from PA), we standardized the consequence ratings to fit in four consequence of failure categories including very high, high, medium and low (Supplementary Data 1 and 2). For example, tailings facilities that reported their classification as very high to extreme consequence (that is, extreme, major, very high, categories A, B and so on) were assigned to the very high-consequence category. Tailings facilities that reported their consequence categories as high (that is, high, category C and so on) were assigned to the high-consequence category. Moreover, tailings facilities reported as medium consequence of failure (that is, medium, moderate, significant, categories 2, 3 and so on) were assigned to the medium consequence category. Lastly, the tailings facilities with the lowest consequence ratings (that is, very low, low, insignificant, minor, stable, category 1 and so on) were assigned to the low consequence category. We included 1,721 tailings facilities, and 95 that lacked the relevant information were assigned to the NA (Not Applicable) category.

Data analysis

To assess the spatial coincidence between TSFs and PAs, KBAs and REs, we conducted a two-step analysis: (1) near-distance analysis between the point locations of the TSFs and each of the biodiversity conservation areas to determine biodiversity threats of a potential facility failure; (2) spatial join analysis to append the construction year of TSFs within PAs to the corresponding PA designation year and determine whether construction of TSFs is becoming more or less influenced by area status.

We determined the distance between TSFs and PAs and other conservation priorities (Supplementary Data 1). We estimated the number of facilities located within and in proximity (<5 km) to the boundaries of PAs, KBAs and REs. The spatial coincidence between TSFs (n 365 = 1,721) and conservation areas was compared with a control sample of point locations (n = 1,721) distributed randomly across terrestrial systems (excluding Antarctica; Supplementary Data 3). To confirm the possibility of bias in the distribution of TSFs in relation to biodiversity areas, we compared the proportion of TSFs that fall within and in proximity to PAs, KBAs and REs to the proportion of random point locations that fall within and in proximity to PAs, KBAs and REs (random distribution).

We sampled TSFs located within PAs (n = 149), in proximity (<5 km) to PAs (n = 349) and within distances of more than 5 km from the boundaries of PAs (n = 1,223). We assessed the total number and proportion of new TSFs being built every decade from 1910 to 2020 across three distance parameters. We then compared the trends in the number and proportions of TSFs established over time across these distance parameters (Supplementary Fig. 1).

We used the results obtained from the spatial join to sample the TSFs that occur within PAs and determine the relationship between the year the TSFs were established with the year its PA was designated (Supplementary Data 4). First, we sampled TSFs within PAs (n = 149; 11 TSFs with missing information were excluded). We divided the number of new TSFs built within already-established PAs between each decade from 1910 to 2020 by the total number of new TSFs built worldwide within the same period to determine whether construction is influenced by area status (Fig. 2). Then, we calculated the difference between the year the TSFs were established and the year the PAs were designated (Fig. 3a). Positive values ($y > 0$) indicate that the facilities were established after the PA was designated, and negative values ($y < 0$) indicate that the facilities were established before the PA was designated (Fig. 3a). We compared the proportion of TSFs established after the PAs were designated with the proportion of TSFs established before the PAs were designated for each decade from 1910 to 2020 (Fig. 3b). We also calculated the percentage of companies owned by ICMM members (information available in Supplementary Data 1).

Finally, we investigated the associations between high-risk factors (that is, construction method/raise type, activity status and consequence categories) and three distance parameters (within PAs, <5 km from PAs, >5 km from PAs). Upstream construction, followed by downstream construction, is the most common raise type. Centre-line, hybrid and single-raise construction methods are the next most common raise types. In pit/natural landform and dry stacked are the least common facility types. Upstream raise type facilities have long been known to pose the greatest stability risks[2,24]. However, these raise types continue to be widely used by the industry. Hence, we compared the proportion of TSFs associated with high-risk factors across all three distance parameters to determine whether the protection of conservation areas is effective at keeping these facilities away from their boundaries. We also assessed the proportion of TSFs that fall within each consequence of failure category for the same distance parameters. The results were used to establish whether TSFs characterized by high consequences of failure are also associated with sites with the most threats to biodiversity.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Spatial data and the information disclosed from the extraction companies on TSFs are available from ref. 2. Spatial data on Protected Areas and Conservation Priorities are available from refs. 17,21,22.

References

1. Lottermoser, B. *Mine Wastes Characterization, Treatment and Environmental Impacts* 3rd edn (Springer, 2010).
2. Franks, D. M. et al. Tailings facility disclosures reveal stability risks. *Sci. Rep.* **11**, 5353 (2021).
3. Kossoff, D. et al. Mine tailings dams: characteristics, failure, environmental impacts, and remediation. *Appl. Geochem.* **51**, 229–245 (2014).
4. Edraki, M. et al. Designing mine tailings for better environmental, social and economic outcomes: a review of alternative approaches. *J. Clean. Prod.* **84**, 411–420 (2014).
5. Schoenberger, E. Environmentally sustainable mining: the case of tailings storage facilities. *Resour. Policy* **49**, 119–128 (2016).
6. WISE Uranium Project *Chronology of Major Tailings Dam Failures* (WISE International, 2022).

7. do Carmo, F. F. et al. Fundão tailings dam failures: the environment tragedy of the largest technological disaster of Brazilian mining in global context. *Perspect. Ecol. Conserv.* **15**, 145–151 (2017).
8. Hatje, V. et al. The environmental impacts of one of the largest tailing dam failures worldwide. *Sci. Rep.* **7**, 10706 (2017).
9. Silva Rotta, L. H. et al. The 2019 Brumadinho tailings dam collapse: possible cause and impacts of the worst human and environmental disaster in Brazil. *Int. J. Appl. Earth Obs. Geoinf.* **90**, 102119 (2020).
10. Cionek, V. M., Alves, G. H. Z., Tófoli, R. M., Rodrigues-Filho, J. L. & Dias, R. M. Brazil in the mud again: lessons not learned from Mariana dam collapse. *Biodivers. Conserv.* **28**, 1935–1938 (2019).
11. Durán, A. P., Rauch, J. & Gaston, K. J. Global spatial coincidence between protected areas and metal mining activities. *Biol. Conserv.* **160**, 272–278 (2013).
12. ICMM *Mining and Protected Areas Position Statements* (ICMM, 2003).
13. Cross Sector Biodiversity Initiative *A Cross-sector Guide for Implementing the Mitigation Hierarchy* (Biodiversity Consultancy, 2015).
14. Devenish, K., Desbureaux, S., Willcock, S. & Jones, J. P. G. On track to achieve no net loss of forest at Madagascar's biggest mine. *Nat. Sustain.* **5**, 498–508 (2022).
15. zu Ermgassen, S. O. S. E. et al. Evaluating the impact of biodiversity offsetting on native vegetation. *Glob. Change Biol.* **29**, 4397–4411 (2023).
16. Maron, M. et al. The many meanings of no net loss in environmental policy. *Nat. Sustain.* **1**, 19–27 (2018).
17. IUCN *A Global Standard for the Identification of Key Biodiversity Areas* Version 1.0 (IUCN, 2016).
18. zu Ermgassen, S. O. S. E. et al. Are corporate biodiversity commitments consistent with delivering 'nature-positive' outcomes? A review of 'nature-positive' definitions, company progress and challenges. *J. Clean. Prod.* **379**, 134798 (2022).
19. Sonter, L. J., Dade, M. C., Watson, J. E. M. & Valenta, R. K. Renewable energy production will exacerbate mining threats to biodiversity. *Nat. Commun.* **11**, 4174 https://doi.org/10.1038/s41467-020-17928-5 (2020).
20. Williams, B. A. *Assessing the State and Planning for the Conservation of Intact Ecosystems*. PhD thesis (Univ. of Queensland, 2022).
21. UNEP–WCMC *World Database on Protected Areas User Manual 1.4* (UNEP–WCMC, 2016).
22. Allan, J., Venter, O. & Watson, J. Temporally inter-comparable maps of terrestrial wilderness and the Last of the Wild. *Sci Data* **4**, 170187 https://doi.org/10.1038/sdata.2017.187 (2017).
23. Leroux, S. J. et al. Global protected areas and IUCN designations: do the categories match the conditions? *Biol. Conserv.* **143**, 609–616 (2010).
24. Rico, M., Benito, G., Salgueiro, A. R., Díez-Herrero, A. & Pereira, H. G. Reported tailings dam failures: a review of the European incidents in the worldwide context. *J. Hazard. Mater.* **152**, 846–852 (2008).
25. ICOLD *Tailings Dams: Risk of Dangerous Occurrences: Lessons Learnt From Practical Experiences* (ICOLD, 2001).
26. Furnell, E. et al. Dewatered and stacked mine tailings: a review. *ACS ES&T Eng.* **2**, 728–745 (2022).
27. Golev, A. et al. *Ore-sand: A Potential New Solution to the Mine Tailings and Global Sand Sustainability Crises* (Univ. of Queensland, 2022).
28. Valenta, R. K. et al. Decarbonisation to drive dramatic increase in mining waste—options for reduction. *Resour. Conserv. Recycl.* **190**, 106859 (2023).
29. *Canadian Dam Association (CDA) Consequence Classification Ratings for Dams* (Canadian Dam Association, 2016).
30. *Guidelines on the Consequence Categories for Dams* (The Australian National Committee on Large Dams, 2012).
31. Islam, K. & Murakami, S. Global-scale impact analysis of mine tailings dam failures: 1915–2020. *Glob. Environ. Change* **70**, 102361 (2021).
32. Hopkins, A. & Kemp, D. *Credibility Crisis: Brumadinho and the Politics of Mining Industry Reform* 1st edn (CCH Australia, 2021).
33. El Bizri, H. R., Macedo, J. C. B., Paglia, A. P. & Morcatty, T. Q. Mining undermining Brazil's environment. *Science* **353**, 228–228 (2016).
34. Azevedo-Ramos, C., do Amaral, B. D., Nepstad, D. C., Filho, B. S. & Nasi, R. Integrating ecosystem management, protected areas, and mammal conservation in the Brazilian Amazon. *Ecol. Soc.* **11**, 17 (2006).
35. Owen, J. R., Kemp, D., Lèbre, É., Svobodova, K. & Pérez Murillo, G. Catastrophic tailings dam failures and disaster risk disclosure. *Int. J. Disaster Risk Reduct.* **42**, 101361 (2020).
36. Ghahramani, N. et al. Tailings-flow runout analysis: examining the applicability of a semi-physical area–volume relationship using a novel database. *Nat. Hazards Earth Syst. Sci.* **20**, 3425–3438 (2020).
37. Rana, N. M. et al. Catastrophic mass flows resulting from tailings impoundment failures. *Eng. Geol.* **292**, 106262 (2021).
38. Innis, S. et al. The development and demonstration of a semi-automated regional hazard mapping tool for tailings storage facility failures. *Resources* **11**, 82 https://doi.org/10.3390/resources11100082 (2022).
39. Prior, T., Giurco, D., Mudd, G., Mason, L. & Behrisch, J. Resource depletion, peak minerals and the implications for sustainable resource management. *Glob. Environ. Change* **22**, 577–587 (2012).
40. Bowker, L. N. & Chambers, D. M. In the dark shadow of the supercycle tailings failure risk and public liability reach all time highs. *Environments* **4**, 75 https://doi.org/10.3390/environments4040075 (2017).
41. Kosai, S., Takata, U. & Yamasue, E. Natural resource use of a traction lithium-ion battery production based on land disturbances through mining activities. *J. Clean. Prod.* **280**, 124871 (2021).
42. Global Tailings Review *Global Industry Standard on Tailings Management* (ICMM, 2020).
43. Franks, D. M. & Vanclay, F. Social impact management plans: innovation in corporate and public policy. *Environ. Impact Assess. Rev.* **43**, 40–48 (2013).
44. Kemp, D., Owen, J. R. & Lèbre, É. Tailings facility failures in the global mining industry: will a 'transparency turn' drive change? *Bus. Strategy Environ.* **30**, 122–134 (2021).
45. Davies, M. & Martin, T. Upstream constructed tailings dams—a review of the basics. In *Tailings and Mine Waste 2000* 1st edn, (CRC Press, 2000).
46. Yin, G. et al. Stability analysis of a copper tailings dam via laboratory model tests: a Chinese case study. *Miner. Eng.* **24**, 122–130 (2011).
47. Watson, J. E. M. et al. Catastrophic declines in wilderness areas undermine global environment targets. *Curr. Biol.* **26**, 2929–2934 (2016).

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Author contributions

B.A., L.J.S., D.M.F. and M.S. designed the study and conceptualized the paper; B.A. and L.J.S. performed the analysis; B.A., M.S, D.M.F. and L.J.S. interpreted the data; B.A., L.J.S. and D.M.F. wrote and edited the paper.

Competing interests

The authors declare no competing interests.

Additional information

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used in the collection of data.
Data analysis	We used the WGS 1984 World Mercator projected coordinate system to analyse the data in ArcGIS Pro 3.0.2.

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Spatial data and the information disclosed from the extraction companies on TSFs are available from reference 2 in the manuscript. Spatial data on Protected Areas and Conservation Priorities are available from references 12,21 and 22.

Human research participants

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Reporting on sex and gender	Not applicable.
Population characteristics	Not applicable.
Recruitment	Not applicable.
Ethics oversight	Not applicable.

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Study description	To assess the spatial coincidence between TSFs and biodiversity areas, we conducted a two-step analysis: 1) Near distance analysis between the point locations of the TSFs and each of the biodiversity conservation areas – Key Biodiversity Areas (KBAs), Protected Areas (PAs)and Remaining Intact Ecosystems (REs) – to determine biodiversity threats of facility failures. Then,). To confirm the possibility of bias in the distribution of TSFs in relation to biodiversity areas, we compared the proportion of TSFs that fall within and in proximity to PAs, KBAs and RWs to the proportion of random point locations that fall within and in proximity to PAs, KBAs and REs (random distribution). 2) Spatial join analysis to append the construction year of TSFs within PAs to the corresponding Protected Area status year and determine whether construction of TSFs is becoming more or less influenced by area status.
Research sample	The TSFs database includes 1743 tailings facilities predominantly owned by publicly listed companies, comprising only 36% of the contemporary global commodity production.
Sampling strategy	The TSFs database was obtained from ref 2, where the information on TSFs was extracted from the disclosures on the mining companies' websites. The information enhanced with information regarding seismicity, commodity production, wind speed, and precipitation and then complied and in a global dataset of TSFs.
Data collection	Spatial data and the information disclosed from the extraction companies on Tailings Storage Facilities (TSFs) are available from ref 2. Spatial data on Protected Areas and Conservation Priorities are available from refs 12,17 and 18.
Timing and spatial scale	Data was analyzed at the global scale.
Data exclusions	From the 1743 tailings facilities in the global TSFs database, 22 TSFs were excluded as there were no information on its location coordinates.
Reproducibility	NA
Randomization	A control sample of 1721 point locations was generated in ArcGIS Pro across terrestrial systems (excluding Antarctica).
Blinding	NA

Did the study involve field work? ☐ Yes ☒ No

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☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging