Evidence of the impacts of metal mining and the effectiveness of mining mitigation measures on social–ecological systems in Arctic and boreal regions: a systematic map

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Abstract

Background: Mining can directly and indirectly affect social and environmental systems in a range of positive and negative ways, and may result in societal benefits, but may also cause conflicts, not least in relation to land use. Mining always affects the environment, whilst remediation and mitigation efforts may effectively ameliorate some negative environmental impacts. Social and environmental systems in Arctic and boreal regions are particularly sensitive to impacts from development for numerous reasons, not least of which are the reliance of Indigenous peoples on subsistence livelihoods and long recovery times of fragile ecosystems. With growing metal demand, mining in the Arctic is expected to increase, demanding a better understanding of its social and environmental impacts. We report here the results of a systematic mapping of research evidence of the impacts of metal mining in Arctic and boreal regions.

Methods: We searched multiple bibliographic databases and organisational websites for relevant research using tested search strategies. We also collected evidence from stakeholders and rightsholders identified in the wider 3MK project (Mapping the impacts of Mining using Multiple Knowledges, https://osf.io/cvh3u). We screened articles at three stages (title, abstract, and full text) according to a predetermined set of inclusion criteria, with consistency checks between reviewers at each level. We extracted data relating to causal linkages between actions or impacts and measured outcomes, along with descriptive information about the articles and studies. We have produced an interactive database along with interactive visualisations, and identify knowledge gaps and clusters using heat maps.

Review findings: Searches identified over 32,000 potentially relevant records, which resulted in a total of 585 articles being retained in the systematic map. This corresponded to 902 lines of data on impact or mitigation pathways. The evidence was relatively evenly spread across topics, but there was a bias towards research in Canada (35% of the evidence base). Research was focused on copper (23%), gold (18%), and zinc (16%) extraction as the top three minerals, and open pit mines were most commonly studied (33%). Research most commonly focused on operation stages, followed by abandonment and post-closure, with little evidence on early stages (prospecting, exploration, construction; 2%), expansion (0.2%), or decommissioning/closure (0.3%). Mitigation measures were not frequently studied (18% of articles), with groundwater mitigation most frequently investigated (54% of mitigations), followed by soil quality (12%) and flora species groups (10%). Control-impact study designs were most common (68%) with reference sites as the...
most frequently used comparator (43%). Only 7 articles investigated social and environmental outcomes together. The most commonly reported system was biodiversity (39%), followed by water (34%), societies (20%), and soil/geology (6%), with air the least common (1%).

**Conclusions:** The evidence found highlights a suite of potential knowledge gaps, namely: on early stages prior to operation; effectiveness of mitigation measures; stronger causal inference study designs; migration and demography; cumulative impacts; and impacts on local and Indigenous communities. We also tentatively suggest subtopics where the number of studies could allow systematic reviews: operation, post-closure, and abandonment stages; individual faunal species, surface water quality, water sediment quality; and, groundwater mitigation measure effectiveness.

**Keywords:** Resource extraction, Extractive industries, Base metal mining, Mitigation effectiveness, Environmental impact, Social impact, Arctic biome

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**Background**

**On the impacts of mining**

Mining activities, including prospecting, exploration, construction, operation, maintenance, expansion, abandonment, decommissioning and repurposing may affect social and environmental systems in a range of direct and indirect, positive and negative ways. Exploration, construction, operation, and maintenance of mines can change land-use substantially, and may negatively affect environments, for example through deforestation, erosion, contamination and alteration of soil profiles, contamination of local streams and wetlands, and an increase in noise level, dust and emissions [1–5]. Abandonment, decommissioning and repurposing of mines can also cause significant environmental impacts, for example soil and water contamination [e.g. 6–8]. Additionally, infrastructure put in place to support mining activities (i.e. roads, ports, railway tracks, power lines) may affect migratory routes of animals and worsen habitat fragmentation [9, 10]. Such infrastructure, together with accompanying institutions, can indeed create new social-technological mega-systems [11–13].

Mining also affects people and societies. Negative effects include impacts on human health [e.g. 14 and living standards [15]. Mining is known to affect traditional practices of Indigenous peoples [16], and land-use conflicts are also often present, as are other societal impacts including those related to public health and human wellbeing [e.g. 17, 18–20]. In terms of positive impacts, mining is typically a source of local employment and may contribute to economies locally and regionally [e.g. 21, 22]. Remediation of the potential environmental impacts (e.g. water treatment and ecological restoration) can have positive net effects on the environment [23]. Mine abandonment, decommissioning and repurposing may positively and negatively affect social impacts. Examples of negative impacts include loss of jobs and local identities [24], while positive impacts may include opportunities for new economic activities [25], for example through repurposing of mines into tourist attractions.

**Mitigation measures**

‘Mitigation measures’ (as they are commonly described in the impact assessment literature) are implemented to avoid, eliminate, reduce, control or compensate for the negative effects of an intervention and ameliorate the local impacts [23]. Typically, these measures should be considered and described in environmental and social impact assessments (EIAs and SIAs) conducted before major activities, such as resource extraction, begin [26–28]. If there will be a significant impact, mitigation measures are required by law in most countries to be implemented and monitored. Mitigation of negative environmental effects in one system (e.g. water or soil) can influence other systems in a positive or negative manner, such as the wellbeing of local communities [23]. A wide range of technologies have been implemented in the treatment of contaminated waters (e.g. constructed wetlands [29], reactive barriers treating groundwater [30], conventional wastewater treatment plants). Phytoremediation of contaminated land is also an active research area [31].

Mitigation measures designed for the alleviation of negative impacts of mining on social and environmental systems may not always be effective and may have undesired and unintended consequences, particularly in the long-term and across diverse systems (e.g. the intersection between environmental and social): for example, a mitigation measure designed to effect an environmental change may have unintended knock-on social impacts.

To date, there appears to be little research on the effectiveness of mitigation measures applied to mining projects to achieve the desired mitigation outcome, and we are not aware of any synthesis of the effectiveness of metal mining oriented mitigation measures that considers impacts on both society and the environment.

**Mining in the Arctic and boreal regions**

The Arctic and boreal regions are particularly sensitive to the effects of mining and mining-related activities [32, 33], both on social and environmental systems.
However, the Arctic is home to substantial mineral resources [34, 35] and has been the focus of interest and resource extraction for centuries. These activities significantly increased during the early 20th Century and there has been an intensification of interest in exploration and exploitation in recent years to meet a growing global metal demand. Given the region’s geological features and expectations of growing global demand for metals, resource extraction already dominates discourse on development here and is likely to continue to do so for the near future. As of 2015, there were some 373 mineral mines across Alaska, Canada, Greenland, Iceland, The Faroes, Norway (including Svalbard), Sweden, Finland and Russia (see Table 1), with the top five minerals being gold, iron, copper, nickel and zinc [36]. Mining in the Arctic has generally intensified: for example, whilst the number of mines in Sweden has decreased substantially over the last 100 years, from a peak of > 260 in 1917 to just 12 in 2019, the volume of production has conversely increased from < 5 m tonnes to 86.5 m tonnes over the same period [37].

There is little empirical research on the impacts of mining on environmental and social systems in the literature. For example, there is a dearth of evidence on these impacts on the Sami; a group of traditional people inhabiting a region spanning northern Norway, Sweden, Finland and Russia. Sami people are affected by a range of external pressures, one of which pertains to resource extraction and land rights, particularly in relation to nomadic reindeer herding. However, there is little published research on the topic [38]. Indigenous peoples reside in many other regions within Arctic and boreal ecosystems (e.g. the many Aboriginal communities in Canada [39]) and these systems have been shown to be equally limited in evidence on social impacts of resource extraction [40, 41]. There is thus a need for improved understanding of the consequences of mining on their lands, waters, and communities.

The evidence base for research on the environmental and social impacts of mining has grown over recent years. However, despite the clear importance of this topic, there has been little rigorous synthesis of research knowledge in Arctic and boreal regions (although see [42] for a review with high susceptibility to bias on the topic). This lack of rigorous synthesis represents a significant knowledge gap in the face of the continued promotion and expansion of resource extraction in the region. There is thus an urgent need for transparent and robust approaches to collate and describe the nature of research evidence on the environmental and social impacts of mining and its mitigation measures.

| Main metal mined | Number of mines |
|------------------|-----------------|
| Gold             | 144             |
| Iron             | 58              |
| Copper           | 45              |
| Nickel           | 39              |
| Zinc             | 27              |
| Diamonds         | 15              |
| Uranium          | 8               |
| Potash           | 7               |
| Silver           | 6               |
| Molybdenum       | 4               |
| Lead             | 4               |
| Chromium         | 3               |
| Titanium         | 2               |
| Tin              | 2               |
| Tungsten         | 1               |
| Palladium        | 1               |
| Nobelium         | 1               |
| Platinum         | 1               |
| Lithium          | 1               |
| Rare earth oxides| 1               |
| Antimony         | 1               |
| Manganese        | 1               |
| Aluminium        | 1               |
therefore felt to be beneficial in terms of identifying grey literature sources and the search string (see below).

Invitations to be included in this group were based on an initial stakeholder/rightsholder mapping process and soliciting expressions of interest (see Stakeholder Engagement Methodology Document, https://osf.io/cvh3u). This group included government ministries and agencies such as the Ministry of Enterprise and Innovation, the Mineral Inspectorate (Bergstaten) and County Administrative Boards, the mining industries’ branch organisation (Svemin) and individual companies such as LKAB Minerals and Boliden AB, Sami organisations, including the Sami Parliament, related research projects, and representatives of international assessment processes, such as activities within the Arctic Council. Stakeholders and rightsholders were invited to a specific meeting (held at Stockholm Environment Institute in September 2018) to help refine the scope, define the key elements of the review question, finalise a search strategy, and suggest sources of evidence, and also to subsequently provide comments on the structure of the final protocol [45].

Objective of the review
The broader 3MK project aims to develop a multiple evidence base methodology [46] combining systematic review approaches with documentation of Indigenous and local knowledge and to apply this approach in a study of the impacts of metal mining and impacts of mitigation measures. This systematic map was conducted in order to answer the question:

What research evidence exists on the impacts of metal mining and its mitigation measures on social and environmental systems in Arctic and boreal regions?

Definition of the question components
The review question has the following key elements:

Population Social, technological (i.e. industrial contexts, heavily altered environments, etc.) and environmental systems in circumpolar Arctic and boreal regions.

Intervention/exposure Impacts (direct and indirect, positive and negative) associated with metal mining (for gold, iron, copper, nickel, zinc, silver, molybdenum and lead) or its mitigation measures. We focus on these metals as they represent approximately 88% of Arctic and boreal mines (according to relevant country operating mine data from 2015 [36]), and contain the 5 most commonly mined minerals in the region (gold, iron, copper, nickel and zinc). Furthermore, these minerals include all metals mined within Sweden, the scope of a related workstream within the broader 3MK project (https://osf.io/cvh3u).

Comparator: For quantitative research; the absence of metal mining or metal mining mitigation measures—either prior to an activity or in an independent, controlled location lacking such impacts. Additionally, alternative mining systems are suitable comparators. For qualitative research; comparators are typically implicit, if present, and are thus not required.

Outcome Any and all outcomes observed in social and environmental systems described in the literature were iteratively identified and catalogued. Measured outcomes should be linkable to mining activities or their mitigation measures in the Arctic, irrespective of the scale of the intervention/exposure.

Data type Both quantitative and qualitative research were included.

Methods
The review follows the Collaboration for Environmental Evidence (CEE) Guidelines and Standards for Evidence Synthesis in Environmental Management [47] and it conforms to ROSES reporting standards [48] (see Additional File 1). The review was conducted according to the published protocol [45].

Deviations from the protocol
We made the following deviations from our published protocol. Several bibliography databases could not be used as planned:

- Worldwide Political Science Abstracts (via Proquest)—subscription lapsed
- JSTOR—an update to the search functionality meant that complex search strings are no longer accepted and a basic search was not functional at the time of conduct (error: ‘string too long’)
- AGRIS—advanced search and export not functional at the time of search conduct
- CAB Abstracts (via CAB Direct)—search facility not functional at the time of search conduct

Of the 104 proposed organisational websites, 19 sites could be searched: 9 were duplicate sub-organisations already included in other websites, 9 websites were unavailable at the time of searching, and 1 website could not be searched because of the departure of a Russian speaking colleague (n = 1). We chose not to search Google Scholar because of limited resources. Similarly, due to the COVID-19 pandemic and staff personal circumstances, we did not have resources available to perform a search update prior to publication.
Search for articles

**Bibliographic databases** Searches for relevant research evidence were conducted between 27 and 29th November 2018 using the 21 bibliographic databases shown in Table 2.

The following Boolean search string formed the basis of searches:

\[(\text{mine OR mined OR mining OR mines OR (extract* AND resource*) OR (extract* AND industr*) OR (extract* AND (mineral OR minerals))) AND (metal* OR iron OR copper OR nickel* OR lead OR zinc OR hematite OR haematite OR magnetite OR chalcopyrite OR digenite OR azurite OR malachite OR chrysocolla OR atacamite OR ore OR mineral* OR tailing OR pyrite OR ferric OR ferrous OR goethite OR limonite OR siderite OR ochre OR cupric OR chalcocite OR tenorite OR cuprite OR bornite OR covellite OR tetrahedrite OR tennantite OR pentlandite OR millerite OR galena OR kamacite OR taenite OR laterite OR garnierite OR boulangerite OR ...}

**Table 2** List of bibliographic databases and platforms searched for evidence along with the platform and subscription through which they were accessed

| Database/index                        | Platform/provider     | Date ranges | Date searched | Results | Search record link |
|---------------------------------------|-----------------------|-------------|---------------|---------|--------------------|
| Academic search premier               | EBSCOhost             | 1956-2018   | 27/11/2018    | 5753    | [Link](https://doi.org/10.1079/searchRxiv.20210350283) |
| Agricola                              | National agricultural library | 1700-2018 | 28/11/2018 | 7 | [Link](https://doi.org/10.1079/searchRxiv.202103505628) |
| Aquatic sciences and fisheries abstracts | ProQuest             | 1971-2018   | 28/11/2018    | 6835    | [Link](https://doi.org/10.1079/searchRxiv.20210350284) |
| DOAJ                                  | DOAJ                  | 2003-2018   | 29/11/2018    | 47      | [Link](https://doi.org/10.1079/searchRxiv.202103505629) |
| EconLit                               | EBSCOhost             | 1969-2018   | 29/11/2018    | 697     | [Link](https://doi.org/10.1079/searchRxiv.20210350285) |
| Greenfile                             | EBSCOhost             | Unclear     | 29/11/2018    | 877     | [Link](https://doi.org/10.1079/searchRxiv.20210350286) |
| International Bibliography of the Social Sciences (IBSS) | ProQuest             | 1951-2018   | 29/11/2018    | 1238    | [Link](https://doi.org/10.1079/searchRxiv.20210350287) |
| MEDLINE                               | Web of science        | 1950-2018   | 28/11/2018    | 1869    | [Link](https://doi.org/10.1079/searchRxiv.20210350288) |
| ProQuest dissertations and theses      | ProQuest             | 1861-2018   | 29/11/2018    | 33      | [Link](https://doi.org/10.1079/searchRxiv.202103505630) |
| PsycINFO                              | ProQuest             | 1806-2018   | 29/11/2018    | 213     | [Link](https://doi.org/10.1079/searchRxiv.20210350289) |
| Russian science citation index         | Web of science        | 2005-2018   | 28/11/2018    | 704     | [Link](https://doi.org/10.1079/searchRxiv.20210350290) |
| Scopus                                | Scopus                | 1966-2018   | 29/11/2018    | 15609   | [Link](https://doi.org/10.1079/searchRxiv.20210350291) |
| Sociological abstracts                | ProQuest             | 1952-2018   | 29/11/2018    | 266     | [Link](https://doi.org/10.1079/searchRxiv.20210350292) |
| Science citation index expanded       | Web of science        | 1945–2018   | 28/11/2018    | 11518   | [Link](https://doi.org/10.1079/searchRxiv.202103505625) |
| Social sciences citation index        | Web of science        | 1956–2018   |               |         | [Link](https://doi.org/10.1079/searchRxiv.202103505622) |
| Arts and humanities citation index    | Web of science        | 1975–2018   |               |         | [Link](https://doi.org/10.1079/searchRxiv.202103505624) |
| Conference proceedings citation index-science | Web of science | 1990–2018   |               |         | [Link](https://doi.org/10.1079/searchRxiv.202103505625) |
| Conference proceedings citation index-social science and humanities | Web of science | 1990–2018 |               |         | [Link](https://doi.org/10.1079/searchRxiv.202103505626) |
| Emerging sources citation index       | Web of science        | 2015–2018   |               |         | [Link](https://doi.org/10.1079/searchRxiv.202103505627) |
| DART-Europe E-theses portal           | DART-Europe           | Unclear     | 29/11/2018    | 0       | [Link](https://doi.org/10.1079/searchRxiv.202103505631) |
| EThOS                                 | British library       | Unclear     | 29/11/2018    | 0       | [Link](https://doi.org/10.1079/searchRxiv.202103505632) |
anglesite OR cerussite OR pyromorphite OR calamine OR smithsonite OR sphalerite OR hemimorphite OR wurtzite OR hydrozincite OR pb OR zn OR cu OR ni OR fe OR gold OR au OR silver OR ag OR argentite OR chlorargyrite OR galena OR calaverite OR sylvanite OR nagyagite OR petzite OR krenmerite OR molybden* OR wulfenite OR powellite OR mo

AND

("arctic OR boreal OR boreo* OR "polar OR "snow forest" OR tundra OR taiga OR alaska OR canada OR russia OR sweden OR norway OR finland OR greenland OR iceland OR faroe OR canadian OR swedish OR norwegian OR russian OR icelandic OR subarctic OR "northern latitude" OR "high latitude" OR yukon OR nunavut OR quebec OR "northwest territories" OR newfoundland OR labrador OR alaskan OR siberia OR ural OR volga OR caucasus OR lapland OR lappland OR norrbotten OR västerbotten OR ångermanland OR jämmtland OR medelpad OR härjedalen OR hälsingland OR daalarna OR gästrikland OR uppland OR västmanland OR värmeland OR ostrobothnia OR kainuu OR karelia OR savonia OR pirkkamaa OR satakunta OR tavastia OR kymenlaakso OR uusimaa OR äland OR Trondeig OR "kalaallit nunait" OR avannaa OR qeqertalik OR qeqqata OR serrnersoog OR kuvalleq OR aleutia* OR "british columbia" OR alberta OR saskatchewan OR manitoba OR "new brunswick" OR "prince rupert island" OR ontario OR "nova scotia" OR "north* europe" OR meadowbank OR ekati OR Meadowbank OR bellekeno OR "keno hill" OR minto OR tom OR raglan OR wolverine OR "pine point" OR "red chris" OR granduc OR thompson OR birchtree OR seabee OR "voisey's bay" OR dso OR "james mine" OR schefferville OR "flin flon" OR "triple seven" OR "snow lake" OR huckleberry OR carol OR scully OR wabus OR "bloom lake" OR "mont wright" OR elonore OR "gr gold" OR musselwhite OR gibraltar OR "mcleese lake" OR campbell OR "red lake" OR "rice lake" OR bralorne-pioneer OR "new aften" OR "highland valley" OR "detour lake" OR ming OR rambler OR "pine cove" OR "corner bay" OR "bachelor lake" OR "myra falls" OR "casa benua" OR vezza OR "copper mountain" OR similo OR langlois OR grevet OR trail OR "duck pond" OR hemlo OR williams OR "kidd creek" OR "david bell" OR hislop OR "bell creek" OR beaufor OR "black fox" OR glimmer OR holloway OR holt OR porcupine OR "fabie bay" OR "doyon division" OR laronde OR apa OR mishii OR macassa OR sigma OR lamaque OR goldex OR "eagle river" OR young-davidson OR "halfmile lake" OR coleman OR "nickel rim" OR fraser OR "mccready west" OR sudbury OR garson OR stobie OR "copper cliff" OR manitoba OR ontario OR creighton OR gertrude OR ellen OR lockerby OR totten OR dufferin OR bingo OR "bonanza ledge" OR bracenac-mcleod OR cochenour OR "ep gold" OR nunavik OR "fire lake" OR "hudson bay" OR island OR "lac herbin" OR "lalar lake" OR malartic OR morrison OR "mount milligan" OR phoenix OR rubicon OR "reed lake" OR shakespear OR "timmins west" OR mcgarry OR westwood-mooshla OR yellowjacket OR alexo OR monique OR "yellow giant" OR kittleil OR kevista OR pahtavaara OR hannukainen OR laiva OR talvivaara OR kokkola OR hitura OR pyhäsalmi OR pampalo OR kylylahti OR orivesi OR kutemajärvi OR vammala OR harjavalta OR jokisivu OR sydvaranger OR rana OR odda OR oktaybrsky OR talnakhskoye OR taimyrsky OR komsomolsky OR mayak OR kaula-kotselvaara OR kola OR zapoljarnoe OR zapoljarny OR ametistove OR "medvezhy rucheu" OR norilsk-1 OR skalisty OR zhdanovskoye OR maysky OR olenevorsky OR olengorskoye OR "15th anniversary of october" OR kovdorsky OR kupol OR korpanga OR kostomuksha OR kubaka OR ropyakh OR lunnaya OR susuman OR berelekh OR duktar OR omsukchan OR julietta OR natalka OR olimpiada OR sovetskoye OR blagodatnoye OR khakanja OR tarnjerskoye OR severnaya OR severoapeschanskoye OR vorontsovskoye OR "golets vysochaishy" OR kuranakh OR gusegovskoye OR pervenets OR goroblagodatsky OR bereznjakovskoye OR gorevsky OR voskogorsky OR rudnogorsky OR penvorualskoye OR berezovskoye OR tatiansky OR korshunovskoye OR safyanovskaya OR chermenshansky OR irkinda OR aginskoye OR bakalskoye OR talgansky OR berezitovy OR svetlinsky OR uchalinsky OR uchalisnky OR mulginskoye OR burlukskoye OR chebachej OR pionier OR mnogovershinnoye OR abakansky OR alexandrinisk OR pokrovskiy OR teysky OR sheregeshsky OR ozernoye OR tashtagolskoye OR sibay OR murzinskye-1 OR zun-holba OR mikhailovskoye OR asacha OR novoshokranskoye OR oktybrsky OR verninsky OR kyzyl-tashtyg OR rubtsovsk OR omen OR gaisky OR stepnoy OR korbalikhinsky OR stoylensky OR zarechenskoye OR lebedinsky OR stoylo-lebedinskoye OR letneye OR dzhusinskoye OR kimkanskye OR dalpolimetal OR urupsky OR sadonsk OR albasni OR ald-gold OR amazarkan OR "lena artelj" OR "tyva artelj" OR avlayakan OR albyn OR belaya OR birkan OR buryatoloto OR elderado OR festivanoye OR fevralskoye OR goltsovoyme OR gubkin OR karaleem OR kirovogorskye OR kochkarskoye OR komsomolsky OR kamaganskoye OR kazsky OR kommunarovsky OR lenzoloto OR "maly kuybas" OR malomir OR maulsky OR mikheevskoye OR mezhopochnoyoe OR "novogodnee monta" OR odenochnaya OR podtalvanoye OR pogromnoyoe OR samolazovskoye OR savkino OR shemurskoye OR sideritovaya OR yuzhno-kirovskoye OR sopka kvarcetsevaya OR sosnovskoye OR tabornoye OR tardan OR titimmukhta OR tsolok OR uzelginsky OR vasilevsky OR valunistsoye OR voskogorsky OR voskogorskye OR
These searches involved manual screening of each website for grey literature (metalminedrift; metalminedrift; minedrift) and Norwegian (stot effekter på gruvedrift av metal; metall gruvedrift; gruvedrift) as appropriate.

Supplementary searches In addition, we (Adrienne Smith [AS] and Brooke Etherington [BE]) hand searched reference sections of relevant included articles and 47 randomly selected relevant literature reviews which accounted for 30% of the relevant reviews identified in the searching (see Additional File 2).

Estimating the comprehensiveness of the search
A set of 49 articles known to be relevant were provided by the review team; the benchmark list (see Additional File 3). During scoping and development of the search string, the bibliographic database search results were checked to ascertain whether any of these studies were not found. We found 45 of the 49 benchmark based on search term presence in titles, abstracts and keywords (see Additional File 4). Four articles were not found because they lacked abstracts and/or keywords. This was deemed to be an appropriate retrieval level considering the complementary searching outlined above.

Article screening and study eligibility criteria
All articles were screened according to the established eligibility criteria developed in the protocol [45]. All inclusion criteria were used at title, abstract, and full text screening. However, data type and comparator were not considered useful at title and abstract screening since this information is often not well-reported in these fields.

Eligibility criteria
The following criteria were used to assess relevance (eligibility) of studies identified through searching.

Eligible population We included social, technological and environmental systems in Arctic and boreal regions based on political boundaries as follows (this encompasses various definitions of boreal zones, rather than any one specific definition for comprehensiveness and ease of understanding): Canada, USA (Alaska), Greenland, Iceland, the Faroe Islands, Norway (including Svalbard), Sweden, Finland, and Russia.

Eligible intervention/exposure We included all impacts (positive, negative, direct and indirect) associated with any aspect of metal mining and its mitigation measures. We included research pertaining to all stages of mining, from prospecting onwards as follows: prospecting, exploration, construction, operation, maintenance, expansion, abandonment, decommissioning, reopening and repurposing. Eligible mines included those of gold, iron, copper, nickel, zinc, silver, molybdenum and lead.
| Organisation                                                                 | URL                                                                 |
|----------------------------------------------------------------------------|----------------------------------------------------------------------|
| Alaska department of natural resources                                      | http://dnr.alaska.gov                                                  |
| Alaska Division of Geological and Geophysical Surveys                      | http://dggs.alaska.gov/                                               |
| All-Russian Geological Research Institute. A.P. Karpinsky                   | http://www.vsegei.ru/                                                 |
| Arctic Centre (University of Lapland)                                       | http://www.arcticcentre.org                                           |
| Arctic Council                                                             | http://www.arctic-council.org                                         |
| Arctic Health                                                              | https://arctichealth.nlm.nih.gov                                      |
| Arctic Health (Finland)                                                    | http://www.oulu.fi/arctichealth/                                     |
| Arctic Monitoring and Assessment Programme (AMAP)                           | https://www.amap.no/                                                 |
| Arctic Research Centre                                                      | http://arctic.au.dk/                                                 |
| Aurora Research Institute                                                   | http://www.arcticnet.ulaval.ca/                                      |
| Bureau of Land Management, US Dept. of the Interior                        | http://www.blm.gov                                                   |
| Canadian Institute of Health                                               | http://www.chr-irsc.gc.ca/e/193.html                                 |
| Centre for Indigenous Peoples' Nutrition and Environment (CINE)            | http://www.mcgill.ca/cine/                                            |
| Centre for Saami Health Research                                           | http://en.uit.no/ansatte/organisasjon/hjem?p_menu=42374&p_dimensjon_id=88182 |
| Conservation of Arctic Flora and Fauna (CAFF)                              | http://www.caff.is                                                   |
| Copper Alliance—The International Copper Association                       | http://copperalliance.org/                                            |
| Cultural Survival                                                          | https://www.culturalsurvival.org/                                    |
| Environment and Climate Change Canada                                       | http://www.ec.gc.ca                                                  |
| European Commission                                                        | http://ec.europa.eu/                                                 |
| European Environment Agency                                                | http://www.eea.europa.eu/                                            |
| Faroese Geological Survey: Jarðfeingi                                      | http://fjlo/                                                        |
| Federal Agency for Mineral Resources                                        | http://government.ru/en/department/53/                                |
| Finnish Environment Institute                                              | http://www.environtment.fi/                                          |
| Finnish Game and Fisheries Research Institute                               | http://www.rktl.fi                                                  |
| Fridtjof Nansen Institute                                                    | https://www.fni.no/                                                 |
| Geological Survey of Denmark and Greenland (GEUS)                          | http://www.geus.geus.dk/                                             |
| Geological Survey of Finland                                               | http://engtik.fk/                                                   |
| Geological survey of Norway                                                | https://www.ngu.no/en                                                |
| Greenland Institute for Circumpolar Health Research                        | http://www.pi.gl/da                                                  |
| Greenland Institute of Natural Resources                                    | http://www.natur.gl                                                 |
| Greenland Institute of Natural Resources                                    | https://education.uarctic.org/universities/greenland/23857/greenland-institute-of-natural-resources |
| GRID Arendal                                                               | http://www.grida.no                                                 |
| Institute of Arctic Biology                                                | http://www.iab.uaf.edu/                                             |
| International Arctic Research Center (IARC)                                | http://www.iarc.uaf.edu/                                            |
| International Arctic Social Sciences Association (IASSA)                   | http://www.iassa.org/                                               |
| International Copper Study Group                                           | https://www.wicsg.org/                                              |
| International Iron Metallics Association                                    | https://www.metalsolics.org/                                         |
| International Lead and Zinc Study Group                                     | http://www.ilzsg.org/static/home.aspx                               |
| International Lead Association                                              | https://www.iila-lead.org/home                                       |
| International Molybdenum Association (IMOA)                                | https://www.imoa.info/index.php                                      |
| International Nickel Study Group                                           | http://www.insg.org/                                                |
| International Resource Panel                                               | http://www.resourcepanel.org/                                       |
| International Union for Conservation of Nature                             | http://www.iucn.org                                                 |
| International Zinc Association                                             | https://www.zinc.org/about/                                          |
| Isaaffik                                                                   | http://www.isaaffik.org/                                            |
| Luleå University of Technology                                             | https://www.ltu.se/?i=en                                             |
Eligible comparator For quantitative research; the absence of metal mining or metal mining mitigation measures—either prior to an activity or in an independent, controlled location lacking such impacts. For qualitative research; comparators are typically implicit, if present and thus were not required.

Eligible outcome Any and all outcomes (i.e. measured impacts) observed in social, technological and environmental systems were included.

Eligible data type We included quantitative, qualitative and mixed methods research.

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**Table 3** (continued)

| Organisation | URL |
|--------------|-----|
| Ministry of Natural Resources of the Russian Federation | http://www.mnr.gov.ru |
| Natural Resources Canada | http://www.nrcan.gc.ca |
| NGO Mining Working Group | https://miningwg.com/ |
| Nickel Institute | https://www.nickel institute.org/ |
| Nordic Council of Ministers | http://www.norden.org |
| Northern Research Institute (NORUT) | http://www.norut.no |
| Norwegian Directorate for Nature Management | http://www.dirnat.no |
| Norwegian Environment Agency | http://www.miljodirektoratet.no/en/ |
| Norwegian Institute for Nature Research (NINA) | http://www.nina.no |
| Norwegian Institute for Water Research (NIVA) | http://www.npolar.no |
| Norwegian Polar Institute | http://www.nri.ru.ca/ |
| Nunavut Research Institute | https://eu-interact.org/field-sites/polar-environment-atmospheric-research-laboratory-pearl/ |
| Polar Environmental Atmospheric Research Laboratory (PEARL) | https://del.s.edu/prb |
| Polar Research Board | https://www.rand.org/topics/russia.html |
| RAND Corporation | http://www.rand.org/topics/russia.html |
| Resource Extraction and Sustainable Arctic Communities project (REXSAC) | http://www.rusrec.ru |
| Russian Regional Environmental Centre | https://www.saamicouncil.net/ |
| Saami Council | http://www.samediggi.fi |
| Sámediggi (Finnish Sami Parliament) | http://www.samediggi.fi |
| Sámediggi (Norwegian Sami Parliament) | http://www.sametinget.no |
| Stockholm Environment Institute | http://www.sei.org/ |
| Strategic innovation programme for the Swedish mining and metal producing industry | https://www.sipstrim.se/ |
| Swedish Agency for Marine and Water Management | http://www.havochvatten.se |
| Swedish Environmental Protection Agency (SEPA) | http://www.swedishepa.se/ |
| Swedish Geological Survey | https://www.sgu.se/en/ |
| Swedish University of Agricultural Sciences (SLU) | http://www.slu.se |
| The Arctic Institute: Center for Circumpolar Security Studies | http://www.thearticinstitute.org/ |
| The European Network for Sustainable Quarrying and Mining | https://ensqm.weebly.com/ |
| The World Bank | https://www.worldbank.org/ |
| Thule Institute | http://www.oulu.fi/thuleinstitute/ |
| United Nations Environment Programme | http://www.unep.org |
| United States Environmental Protection Agency | http://www3.epa.gov/ |
| United States Fish and Wildlife Service | http://www.fws.gov |
| University of Alaska Anchorage | http://www.uaa.alaska.edu |
| University of Eastern Finland | http://www.uef.fi/en/etusi vu |
| Uppsala University Department of Earth Sciences | https://www.geo.uu.se/research/geophysics/ongoing-research/mineral-exploitation/ |
| World Gold Council | https://www.gold.org/ |
| World Steel Association | https://www.worldsteel.org/ |
| Yukon Research Centre | http://www.yukoncollege.yk.ca/research |
**Eligible study type** We included both primary empirical research and secondary research (reviews were catalogued in a separate database). Modelling studies and commentaries were not included.

**Screening process**
Articles found by searches in databases were combined and screened at three distinct stages: (1) title (2) title and abstract, and (3) full-text. Articles found by other means (i.e., organisational websites and review references) were screened at title and abstract and full-text but were not included in consistency checks.

Any doubt over the presence of a relevant inclusion criterion (or if information is absent) resulted in the articles being retained for assessment at a later stage.

Titles were screened by three reviewers (NRH, JJT, CA). This stage was not subject to consistency checking—it was conducted as a preliminary stage to remove all clearly irrelevant records that could be obviously discerned as ineligible based on titles. Records for which any doubt remained were included to be conservative.

Prior to screening abstracts, all reviewers conducted a consistency checking procedure in EPPI-Reviewer to ensure consistent and repeatable decisions were being made among reviewers in regards to which records were deemed eligible. A total of 1,655 abstracts were screened by 4 reviewers as follows. In the first round, the agreement level achieved was 369/510 abstracts (NRH vs CA). Following discussion, the second round increased slightly to 205/271 (NRH vs JJT) and 216/271 (CA vs JJT). A third round resulted in a 372/510 (NRH vs JJT), 384/510 (JJT vs CA), and 370/510 (NRH vs CA) agreement level. A final round indicated a further increase in agreement, with 292/364 agreements (NRH vs CA). At this point, we felt consistency was as high as possible, and a continued conservative approach was applied to screening of the remaining abstracts. Reviewers did not screen articles (at title and abstract or full-text) for which they were an author.

A consistency check was also conducted prior to screening articles at full-text on 69 articles. Full-texts were screened by four reviewers [NRH, JJT, AS and Amanda Jeansen (AJ)], with a first round of screening resulting in 18/30 article agreement across all four coders. Disagreements were discussed at length and related primarily to uncertainty in this round. Consistency checking on a further set of 39 articles, resulting in only 7 disagreements (κ=0.62). Following this consistency checking, the remaining articles were split between the two reviewers (AS and AJ) and allowed to proceed. Any query made by a reviewer was discussed with the review team (NRH, JJT, AS and AJ) and a consensus decision made, and conferred to all reviewers. Lists of all articles excluded on the basis of full-text assessment with the reasons for exclusion, and unobtainable articles are provided in Additional File 5. A list of articles that could not be retrieved at full text is available in Additional File 6.

**Study validity assessment**
No formal in-depth critical appraisal was made of study validity after their inclusion in the systematic map, since it is an optional part of systematic mapping methodology [49]. However, meta-data referring to study setting and design were extracted that could aid future study validity assessments and synthesis of studies on sub-topics of interest identified from our systematic map exercise. We have synthesised these variables along with other meta-data.

**Data coding strategy**
Following full-text screening of articles, relevant studies were extracted from the included articles: where multiple studies were reported within one article they were entered as independent lines in the database. Here, we define a study to be an experiment or observation that was undertaken at a particular mine site, mitigation or ex-situ experiment with mine-specific treatments. Studies were separated by line if the intervention impacted different systems (populations) within the same article.

The following key data domains were identified through scoping activities and discussion with the review team and advisory group: (1) bibliographic information; (2) mine location and details (e.g., geographic location, metal extracted, type, stage, etc.); (3) broad objectives of the study; (4) study design and setting; (5) system affected; (6) impact/mitigation; (7) measured outcomes; (8) data type and location. Coding variables and meta-data within these domains were then compiled in a partly iterative process, expanding the range of options as they were encountered during scoping and extraction.

Where data are missing they were coded as ‘NR’ (not reported). Where coding is not applicable, ‘NA’ was recorded.

We adapted an outcome coding schema designed within an ongoing environmental and social impact assessment synthesis project [50]. The coding schema was developed to a small degree during trial data extraction. Our impact coding schema (including editions relative to the source) is outlined in Table 4.

To ensure that data were extracted in a consistent and repeatable manner, three reviewers (AS, JJT and NRH) piloted the extraction form by independently coding information from 10 articles at the beginning of the process. All disagreements were discussed, and additional, more detailed guidance was added to the extraction codebook to improve clarity. Coding and meta-data
| System affected     | Component affected          | Factor affected |
|---------------------|-----------------------------|-----------------|
| Soil/geology        | Soil surface                | Structure       |
|                     |                             | Quality         |
|                     |                             | Relief          |
|                     | Soil (other)                | Quantity\(^a\)  |
| Water               | Surface water               | Surface drainage (run-off patterns) |
|                     |                             | Quality         |
|                     |                             | Quantity        |
|                     | Groundwater                 | Aquifers recharge|
|                     |                             | Quality         |
|                     |                             | Quantity        |
|                     | Ice                         | Ice\(^a\)       |
|                     | Sediment                    | Quality\(^a\)   |
| Air                 | Climate                     | Climate         |
|                     | Atmosphere                  | Air quality     |
|                     |                             | Noise           |
|                     |                             | Vibrations\(^a\) |
|                     |                             | Light           |
| Biodiversity        | Flora                       | Habitat         |
|                     |                             | Species groups  |
|                     |                             | Individual species|
|                     |                             | Species distribution |
|                     | Fauna                       | Habitat         |
|                     |                             | Species groups  |
|                     |                             | Individual species|
|                     |                             | Species distribution |
|                     | Ecosystems                  | Quality         |
|                     |                             | Protected areas |
| Human environment   | Landscapes                  | Scenic resources|
|                     |                             | Change of land use|
|                     |                             | Other qualities |
|                     | Economic                    | Jobs (new employment) |
|                     |                             | Local business (e.g. local shops) |
|                     |                             | Traditional livelihoods |
|                     |                             | Property\(^a\)  |
|                     |                             | Migration\(^a\) |
|                     |                             | Other\(^a\)     |
|                     | Service and infrastructure demand | Water   |
|                     |                             | Energy          |
|                     |                             | Waste           |
|                     |                             | Consumables/subsistence |
Data synthesis and presentation

We have summarised the review process in a ROSES flow diagram, using the ROSES flow diagram R package [51]. Our primary outputs are a searchable and filterable systematic map database provided as a CSV file (Additional File 8) along with an interactive evidence atlas (geographical information system) provided as a web-based app and downloadable HTML file (Additional File 9). All interactive files and visualisations are provided through the dedicated project website; https://3mkproject.github.io/.

We summarise the evidence base using bar plots, focusing first on the publications (e.g. article publication year), then on the study systems (i.e. the mines), the mitigation measures investigated, the study designs (e.g. data type), and the measured outcomes. We then describe the affected systems using our three-layer hierarchy (system, component, factor) to describe the social or environmental context that was reported to have been affected by the mining. We have visualised this using a bespoke radial bubble plot that clusters outcomes across the hierarchy and show the volume of evidence at each level. Finally, we have produced heat maps that visualise two coding factors (categorical variables) along with the volume of evidence found across combinations of levels of each factor. The interactive plots are available online (https://3mkproject.github.io/) and the code to produce them has been converted into an R script (Additional File 10). All data, code and functions are available on GitHub as an Open Source/Open Data resource here; https://github.com/nealhaddaway/3mk.

Knowledge gaps and clusters are highlighted by visually analysing cross tabulations and discussing candidate groups amongst the review team.

No team member was permitted to review their own work. Team members conducting screening, data extraction and coding were not publishing in this field.

Review findings

Review descriptive statistics

The review process is depicted in a ROSES flow diagram (Fig. 1). We obtained a total of 44,870 records from bibliographic database searching. Following deduplication,
32,342 unique records were screened at title level and 5079 at abstract level. A total of 247 records could not be retrieved, leaving 2342 records screened at full text level. Following full text screening, 538 articles were retained. We included a further 47 articles from pre-screened resources (websites and review bibliographies). A final 585 articles were included in the map, corresponding to 902 outcome lines. We differentiate here between articles—the manuscripts in which data are presented—and outcome lines—the smallest independent data point in our map, corresponding to a measured outcome from a research article corresponding to a specific mine or mining area.

The evidence base
The interactive evidence atlas is available online (https://3mkproject.github.io/research.html) and as a downloadable HTML file (Additional File 9). We also present an exemplary screenshot in Fig. 2. The evidence atlas shows the location of each study system examined, displaying details of the system and the article describing it in a popup box that includes a hyperlink to the article on Google Scholar.

The articles
Figure 3 shows the publication dates of the included articles, suggesting a linear increase in the number of publications annually. This is in contrast to many other topics that seem to be experiencing a near exponential increase in published articles; perhaps because of the long and consistent history of mining relative to other topics, such as fossil fuel extraction. Although the environmental impacts of mining have a longer history [e.g. 52], the social impacts of mining is a fairly new research topic, and we may observe an increase in research attention overall in coming years.

Figure 4 displays a choropleth for the number of articles included in the map from across eligible countries. The majority of articles focused on Canada (n = 317), followed by Russia (n = 84) and Sweden (n = 72). No research was identified from Iceland.

Mines investigated
A total of 177 unique mines were described across the 585 articles: these are described in a database in Additional File 11. They were distributed across countries as follows: Canada, 97; Russia, 28; Sweden, 18; USA, 12; Finland, 9; Norway, 9; Greenland, 4; Iceland, 0.

Copper was the most commonly reported metal (n = 208), followed by gold (n = 162) and zinc (n = 141) (see Fig. 5). The metals extracted were not stated in 32 articles. Some articles stated only the principal metal mined, whilst others reported all metals encountered and extracted—the data are therefore representative of the articles and may not reflect precisely the state of metals mined across the Arctic and boreal regions.

The most commonly reported mine type was open pit (n = 218), with less than half this number underground (n = 80) and surface (n = 72), and only 22 articles focused on placer mines (Fig. 6). Some 218 articles did not report the type of mine.

Extraction stage
The most commonly studied extraction stage was operation (n = 276), followed by abandonment (n = 164), post-closure (n = 114), and remediation (n = 60) (see Fig. 7). Prospecting, exploration, construction, expansion, and decommissioning/closure were studied far less frequently (n = 1–7).

Figure 8 shows the articles reporting multiple extraction stages, demonstrating that the most commonly co-reported stages were post-closure and remediation (n = 21), followed by operation and abandonment (n = 17). Articles more commonly reported multiple stages following resource extraction activities (decommissioning/closure, post-closure, remediation and abandonment), than earlier stages. No articles reported more than three stages together.

Mitigation measures
A relatively small number of articles investigated mitigation measures (n = 105/585). The systems, components and factors these mitigation measures were used to ameliorate are listed in Table 5. Groundwater quality was the most common factor mitigated (n = 57), followed by soil surface quality (n = 13) and flora species groups (n = 11). Full descriptions of the mitigation measures encountered are provided in the map database (Additional File 8).

Study design
Most articles in the map used a ‘control-impacts’ study design (n = 396), with a substantial number employing correlative designs (n = 142) (see Fig. 9). Only 5 articles examined just the impact/affected site with no real study design.

Related to this, the precise type of comparator is elaborated in Fig. 10, demonstrating that the most common comparator was a reference site/population (n = 254), followed by background values (n = 149). Full BACI designs (before after control impacts) were least common (n = 5).

The most commonly reported study setting was collection from the field and analysis in the laboratory...
Fig. 1 ROSES flowchart for the systematic map, showing the number of records retained at each stage of the review process. Produced using the R package 'ROSES_flowchart' [51]
(n = 358), followed by social science (n = 102) and laboratory experiments (n = 86) (see Fig. 11).

Similarly, the context of the included articles’ studies was predominantly in situ (n = 459), with a smaller number using ex situ methods (n = 118) and very few employing mesocosms (n = 8) (see Fig. 12).

The great majority of articles reported quantitative data (n = 545), with a very small number collecting qualitative data (n = 40). Similarly, a total of 473 articles reported data from environmental systems, whilst 112 reported data from social systems.

Only 7 articles reported both social and environment data (Table 6). The most commonly co-reported social factor was health/safety (n = 5), which was the core focus of several articles measuring environmental health impacts. For several other articles, the social impacts related to economics for otherwise environmental studies. One article [53] reported across a suite of 7 affected factors.

The measured outcomes/systems
Across all articles, the most commonly reported outcome category was metal concentration (n = 357), followed by water quality (n = 104) and species biomass or distribution (n = 102) (see Fig. 13). The most commonly reported social outcome was ‘community’ (i.e. community level social outcome measures) (n = 68), followed by ‘cancer rates/disease/mortality’ (n = 57). The least frequently reported outcome was hydrological flow or landscape change (n = 16).

Affected system/component/factor
The systems, components, and factors affected by the mines across included articles is visualised in Fig. 14 and available as an interactive plot on the project website (https://3mkproject.github.io/research.html). This shows that the most commonly reported system was biodiversity (n = 352), followed by water (n = 310), societies (n = 178), and soil/geology (n = 52), with air the least common (n = 10).

Within biodiversity, the most common component was fauna (n = 214), followed by flora (n = 125) and eco-systems (n = 40). Within water, surface, sediment and groundwater were approximately equal (n = 114, 104, and 87 respectively), with ice rather infrequent (n = 5).

For societies, health and wellbeing was most common (n = 106), followed by economic (n = 46), service and infrastructure (n = 12), landscapes (n = 8) and culture and history (n = 6). Soil surface was the only component reported for soil/geology articles (n = 52). Within air, atmosphere was most common (n = 9) and climate reported rarely (n = 1).

The most commonly reported factors were individual fauna species (n = 116), water sediment quality (n = 104) and surface water quality (n = 104).
Country-vs-stage

Figure 15 shows how the evidence in the map is distributed across countries and extraction stages, demonstrating that the majority of evidence focuses on operation of mines in Canada. Operation was the most commonly reported stage in Canada, Finland, Russia, Sweden and the USA. In Greenland and Norway post-closure was most frequent. In Russia, the majority of articles focused on operation, with very few on post-closure or remediation relative to Canada and Sweden.

Limitations of the map

Although our systematic mapping spanned 8 countries across the Arctic and boreal regions, we were restricted in the resources available for screening non-English articles from bibliographic databases (although grey literature searching and screening was performed across multiple languages; Finnish, Swedish, Norwegian, and Danish). A total of 307 full texts could not be screened for this reason (see Additional File 5).

Due to a lack of resources and time during the COVID-19 pandemic, we were unable to perform a search update as planned. As a result, the systematic map represents a snapshot of research from the end of 2018. An updated search of Web of Science Core Collection databases (see Table 2) in June 2021 revealed 2440 records from 2019 to
2021. Assuming the same spread of results across databases, this would have resulted in a total of >9500 records to screen: almost 25% of the original set of results. Despite this lag from searching to publication, we believe our map is still a valuable assessment of the state of the evidence base, particularly since our assessment of publication rates herein suggested a linear rather than exponential increase in relevant publications over time.

Our screening and data extraction/coding was performed initially using a subset in an attempt to ensure consistency, before proceeding in full with single screening. This is a standard practice amongst systematic reviews and maps published in this journal, and generally considered necessary given the large volumes of evidence common to non-health fields. If we had used full dual screening and data extraction we would have been able to minimise the risk of erroneously excluding some records. However, we believe our methods were both pragmatically necessary and sufficient for the purposes of this mapping exercise.

**Limitations of the evidence base**
We identified a large evidence base with a long history. The distribution of studies across outcome measures was relatively even (see Fig. 15), indicating few biases in

| System > Component > Factor | Number of articles |
|-----------------------------|--------------------|
| Water > Groundwater > Quality | 57 |
| Soil/geology > Soil surface > Quality | 13 |
| Biodiversity > Flora > Species groups | 11 |
| Water > Surface water > Quality | 5 |
| Biodiversity > Flora > Individual species | 4 |
| Biodiversity > Fauna > Individual species | 2 |
| Biodiversity > Flora > Habitat | 2 |
| Water > Sediment > Quality | 2 |
| Air > Atmosphere > Vibrations | 1 |
| Biodiversity > Fauna > Species distribution | 1 |
| Biodiversity > Fauna > Species groups | 1 |
| Biodiversity > Flora > Species distribution | 1 |
| Human environment > Economic > Jobs (new employments) | 1 |
| Soil/geology > Soil surface > Structure | 1 |
| Water > Groundwater > Quantity | 1 |
| Water > Surface water > Quantity | 1 |
| Water > Surface water > Surface drainage (runoff patterns) | 1 |
research attention across the evidence base as a whole. Studies were spread across eligible regions, but a heavy bias in Canada was evident (317/902 data points; 35%). Any further synthesis of these research studies should be sensitive to this bias.

The majority of study designs compared impacted and control samples (396/585 articles, 68%), followed by correlative studies (142/585 articles, 24%), with very few BACI designs (before-after-control-impacts: 6/585 articles, 1%) and no experimental designs. Although this is to be expected, perhaps, given the systems studied, the causal inference of these designs is poor and could be strengthened with randomised control trial study designs—particularly for impact evaluations of mitigation measures which were completely lacking.

Analysis of the validity of studies was not possible in this map, given the wide diversity of data types and study designs (spanning social and environmental science). Internal validity should be assessed in subsequent systematic reviews.

**Conclusion**

**Implications for research**

Our systematic map database and visualisations of the evidence in heat maps allow readers to gauge gaps and clusters, but here we suggest some areas of the evidence base that are sufficient in number to perhaps be suitable for synthesis in full systematic reviews. This list is based on frequently studied higher level categories (the top 3 affected components and factors). This list is indicative only and should not be taken as a priority list of topics for systematic review.

1. On mine operation (n = 428)

   1.1. Health/safety (n = 59)
1.2. Air quality (n = 45)

1.3. Fauna individual species (n = 45)

2. On post-closure activities (n = 176)

2.1. Fauna individual species (n = 27)

2.2. Surface water quality (n = 22)

2.3. Water sediment quality (n = 20)

3. On abandonment (n = 167)

3.1. Fauna individual species (n = 47)

3.2. Surface water quality (n = 40)

3.3. Water sediment quality (n = 39)

4. Articles focusing on groundwater quality mitigation measures (n = 60)

Based on our analysis of the evidence base, we also suggest the following topics where there appear to be evidence gaps that warrant further primary research:

1. Studies on earlier stages of resource extraction prior to operation—from prospecting to construction

2. Research on the effectiveness of mitigation measures (including ‘how’ things function)

3. Research employing quasi-experimental (e.g. BACI) and experimental (e.g. randomised control trials) designs for stronger evidence of causality

4. Migration and demography

5. Cumulative impacts and multiple pressures, including effects related to a changing climate
6. Impacts on local and Indigenous communities, especially social, cultural, and health-related

**Implications for policy/management**

This systematic map demonstrates that there is a large body of evidence on the impacts of metal mining in Arctic and boreal regions. Many topics within the map constitute potential areas for further synthesis or primary research on the impacts of particular types of mining on certain outcomes (described in **Implications for Research**, above). Relevant funders and decision-makers should ensure they are aware of these gaps and clusters, and commission further research as necessary, making the most of the available evidence. Where large bodies of evidence exist (e.g. operation of mines in Canada), research commissioners should consider whether funding and resources are best placed filling gaps than providing more research on a well-studied topic. Given the inherent connection between mineral development and the Indigenous rightsholders of the north it is also important to ensure that research and synthesis activities are done in ways that involve them and respect their sovereignty, knowledge systems, and cultures.

With efforts to move away from fossil fuels, demand for minerals to support “green” energy technologies is expected to increase. In many parts of the Arctic, these expectations have led to increasing prospecting for minerals and a push for opening new mines. However, mining is often met by protests, especially when new mines or
expanded mining activities come into conflict with other land uses and with efforts to protect ecologically valuable nature [60–63]. Furthermore, the process for assessing the impacts of mining have been criticised, with calls for more holistic assessment processes that include meaningful engagement by rightsholders and stakeholders [64] and the whole mining industry is facing increasing distrust [65]. An essential aspect of transparent assessment processes is access to relevant scientific information on all aspects on the implications of mining, and the mapping provided in this paper shows that information on many aspects is limited, especially impacts related to social wellbeing and the interactions between social and environmental factors. Such studies will require approaches that take the whole social-ecological-technological system into account [66], while filling such more holistically-oriented studies with details on specific aspects will require the types of research reviewed in this paper. In addition to identifying critical knowledge gaps, the mapping and potential updates of the map thus serve as an important resource for more holistic environmental and social impact assessment that will be essential for (1) protecting the environment, (2) ensuring that the local social consequences of mining are indeed positive also in the longer term, and (3) helping ensure that the mining permit processes do not stall in drawn-out conflicts due to limited (or contested) knowledge about potential impacts. Better assessment processes will not solve conflict over land use but would at least make decisions about acceptable risks and opportunities more transparent.

Whilst it is expected that most mitigation measures will address the construction and operations phases of a mining project, since this is typically what an Environmental and Social Impact Assessment focuses on, the gaps identified in this systematic map point not only to research gaps but problems with the EIA process itself. For example, EIA legislation is rarely applied to the exploration and development phases of mining, which we found evidence of impacts for. This highlights that there should probably be some legal requirement for analysis and addressing these risks in impact assessments in the future. Policy-makers should be aware that the social impacts from mining in particular begin early on in a project’s lifetime. There is a clear need for more research, and more mitigation, to address these issues.

It is also interesting we found no research examining the EIA process itself, including its effectiveness, and no explicit examination of the proposed mitigation measures from EIAs. Monitoring and evaluation of impact assessments are large gaps in mining legislation and research, and this should be addressed with a clear demand for impact assessment evaluation from decision-makers.

Fig. 15 Heat map showing the number of articles across countries and extraction stages
**Supplementary Information**

The online version contains supplementary material available at https://doi.org/10.1186/s13750-022-00282-y.

**Additional file 1:** Roses Form

**Additional file 2:** Relevant reviews used for bibliographic checking

**Additional file 3:** Benchmark articles used for search comprehensiveness checking

**Additional file 4:** Benchmark checking results

**Additional file 5:** List of records excluded at full text screening with reasons

**Additional file 6:** List of articles not obtainable at full text

**Additional file 7:** Meta-data extraction and coding form

**Additional file 8:** Systematic map database

**Additional file 9:** Interactive evidence atlas

**Additional file 10:** R script for producing the visualisations

**Additional file 11:** Database of unique mines

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**Author contributions**

Conceptualisation—NRH; methodology—NRH; software—NRH; formal analysis—NRH; investigation—JIT, AS, CA, NRH; data curation—JIT, NRH; writing—original draft—NRH; writing—review and editing—NRH, AS, JIT, CA, SJC, ARN, PL; visualisation—NRH; supervision—JIT; project administration—NRH, JIT; funding acquisition—NRH, AEN. All authors read and approved the final manuscript.

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**Availability of data and materials**

All data are available as supplementary information and via the Open Science Framework project site for 3MK: https://osf.io/cvh3u.

**Declarations**

**Ethics approval and consent to participate.**

Not applicable.

**Consent for publication**

Not applicable.

**Competing interests**

The authors declare that they have no competing interests.

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