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RESEARCH AND ANALYSIS

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Deep-sea nodules versus land ores

A comparative systems analysis of mining and processing wastes for battery-metal supply chains

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Abstract

To meet UN Sustainable Development goals, a clean-energy transition with minimal ecological impact from its raw-material supply chain is essential. Polymetallic nodules lying unattached on the abyssal seafloor of the Pacific Ocean's Clarion Clipperton Zone contain four critical metals (nickel, cobalt, manganese, copper) in large quantities, and the International Seabed Authority may soon enact regulations to allow their commercial exploitation. There are complex global ecological implications of doing so. Nodule exploitation would damage abyssal habitats and may impact midwater-column organisms; but in the absence of nodule exploitation, terrestrial mining's environmental and social impacts would intensify. This paper adds to the growing systems-based literature on nodule collection by contributing a preliminary material flow analysis of global-average cradle-to-gate waste streams using either nodules or terrestrial sources as part of a preliminary life cycle assessment, as well as integrated risk assessments of those waste streams. System endpoints are battery precursors (nickel sulfate, cobalt sulfate, manganese sulfate), copper cathode, and a 40% or 75% manganese product. Overburden, tailings, and processing and refining wastes from terrestrial mining are compared to the nodule industry's anticipated offshore and onshore wastes, including sediment disrupted by nodule-collection machines. Robustness to offshore technology assumptions is tested using Monte Carlo simulation, while onshore mass-flow scenarios incorporate a "negligible-waste" flowsheet and high-waste flowsheets where manganese is not recovered. A billion-EV scenario incorporates the effects of declining terrestrial copper and nickel ore grades. Results imply that metal production from nodules may produce less waste of lower severities, caveated by uncertain impacts of disrupted sediment.

KEYWORDS
battery metals, industrial ecology, metal production waste, nodules, sustainable supply chain, systems analysis

1 INTRODUCTION

The Clarion Clipperton Zone (CCZ) of the Pacific Ocean hosts approximately 21 billion dry metric tons of potato-sized polymetallic nodules on its abyssal seafloor. This is one of the world's largest known undeveloped deposits of critical metals. Over 6 billion dry metric tons of manganese, nickel, copper, and cobalt are contained in these nodules, which largely lie on the seafloor unattached (Petersen et al., 2016).

The CCZ habitat risks disruption, as industry experts predict that a clean-energy future will require billions of tons of metals (Ali et al., 2017; Arrobas et al., 2017; Hund et al., 2020). Substitution or recycling could offset some of this need (Månberger & Stenqvist, 2018), but not all, as a fivefold or more demand increase in some minerals is anticipated (Hund et al., 2020; Xu et al., 2020). This demand increase is partly driven by electric vehicle (EV) batteries, projected by some analysts to reach ∼1 billion passenger EVs by 2050 (Stanley, 2017; Habib et al., 2020). While any growth projection faces uncertainties, it is possible that a shortage of high-purity Class 1 nickel and cobalt could develop as soon as 2025 (Campagnol et al., 2017; Azevado et al., 2020), in addition to potential copper shortages, if enough new mining projects are not added (Desai, 2019; Deneen, 2020).

Under the International Seabed Authority (ISA), regulations may soon be adopted to enable commercial exploitation of CCZ nodules. Consisting of 167 Member States and the European Union (EU), the ISA was established by the United Nations Convention on the Law of the Sea (UNCLOS) and 1994 Implementation Agreement with a dual mandate: to regulate mineral-resources-related activities and to protect the marine environment from any harmful effects of doing so (ISA, 2021a). As of April 2021, 17 CCZ exploration contracts have been granted. Involved countries include China (2), Cook Islands, France, Germany, Jamaica, Japan, Kiribati, Korea, Nauru, Netherlands, Russia, Singapore, Tonga, United Kingdom (2), and an intergovernmental consortium (ISA, 2021b). Several exploration contract holders express strong environmental, social, and governance (ESG) commitment. Still, a number of NGOs and conservationists are concerned about potential irreparable harm to the seafloor, and they have objected to the ISA's plan for the CCZ (FFI, 2020; Chin & Hari, 2020; Cassan et al., 2019). Calls for moratoria on deep-sea mining recently gained support from BMW and Google (WWF, 2021).

Nodule "collection," so termed since nodules mostly sit loosely atop sediment, would typically follow this process: Nodules are removed from the seafloor via collector machines, entraining some underlying soft sediment. Most sediment is separated from nodules inside the collector and redeposited at the seafloor. Nodules are transported using seawater and compressed air inside 4–6 km rigid pipes to a surface vessel. There, nodules are dewatered and moved to transport vessels. Residual seawater, sediment, and nodule fines are returned to the ocean, either at some depth in the midwater column or at the bottom (Hein et al., 2020).

For a rough sense of scale, 30 operations each processing ∼4-5 dry metric megatons of nodules per year could supply battery metals for 1 billion EVs in about 30 years. This would theoretically impact ∼432,000 km^2 of CCZ seafloor (Paulikas et al. (2020b)): ∼10% of the CCZ, 2% of the North Pacific Ocean's abyssal floor, ∼0.2% of the global abyssal seafloor; or spatial equivalently, ∼1% of the world's agricultural land (World Bank, 2020), approximately the size of Iraq, or just ∼9% of global seafloor estimated to be trawled yearly by industrial fishers (Sala et al., 2021).

Within contracted areas, a majority of nodules, which act as substrates for abyssal life, may be removed. A substantial portion of nodules would also remain: some locations are non-traversable due to their slopes, substantial Preservation Reference Zones (PRZ) and Impact Reference Zones (IRZ) are to be set aside (Jones et al., 2020; Miller et al., 2018), and collector machines will not have perfect efficiency. Still, organisms attached to nodules formed over millions of years would be killed (Hein et al., 2020), disrupting food web integrity and reducing local benthic biodiversity (Stratmann et al. (2021)). Sediment plumes would also be generated. The potential impacts of plumes include smothering seafloor organisms, clogging feeding mechanisms of suspension feeders (Christiansen et al., 2020; Levin et al., 2020; Miller et al., 2018), harming animals in the midwater column (Drazen et al., 2019, 2020; Robison, 2009), and affecting ecosystem services (Armstrong et al., 2012; Le et al., 2017; Thurber et al., 2014).

On the one hand, amassing greater scientific knowledge about the CCZ is important for gaining social license prior to commencement (Komnitsas, 2020). Yet, if nodule collection is substantially delayed in order to collect such knowledge, terrestrial mining projects would expand to meet growing demand, and pronounced anthropocentric impacts from terrestrial mining would intensify (Koschinsky et al., 2018; WRI 2003). These impacts include disruption and fragmentation of land leading to biodiversity loss (Sonter et al., 2018); release of carbon sequestered in soil, living and dead vegetation, and detritus (Bradley, 2020); production of large amounts of overburden, waste rock (Agboola et al., 2020), and tailings—chemically processed rock, which can be toxic and must be managed in perpetuity (Cornwall, 2020; Sergeant & Olden, 2020); increased open-pit nickel-laterite mining which entails rainforest removal (Mudd, 2010; Sodol, 2006); and community harm through pollution, accidents, and manual labor in places such as the Democratic Republic of the Congo (DRC) (Mucha et al., 2018; Nkulu et al., 2018).

When policy decisions face complex ecological implications, a collaborative, science-based, systems approach for sustainable management can help engage stakeholders widely and assess impacts comprehensively (Støttrup et al., 2019; Figure 1). Systems-based tools such as life cycle assessment (LCA), material flow analysis (MFA), and integrated risk assessment (IRA) can help distill critical information and facilitate a structured, comprehensive discourse. Much peer-reviewed systems literature exists for metals produced from terrestrial ores (Agboola et al., 2020; Farjana et al., 2019; Kuipers et al., 2018; Nakajima et al., 2017; Nuss & Eckelman, 2014).

Such literature for nodule collection however is limited. Preliminary nodule LCA studies include McLellan (2015) (GWP and energy consumption: ammonia leach, no manganese recovery); Paulikas et al. (2020a) (GWP and carbon sequestration: pyrometallurgically processed nodules vs. terrestrial ores, dynamic ore grades); and Heinrich et al. (2020) (GWP: collection and transport only). Impact reviews include Hein et al. (2020)'s review

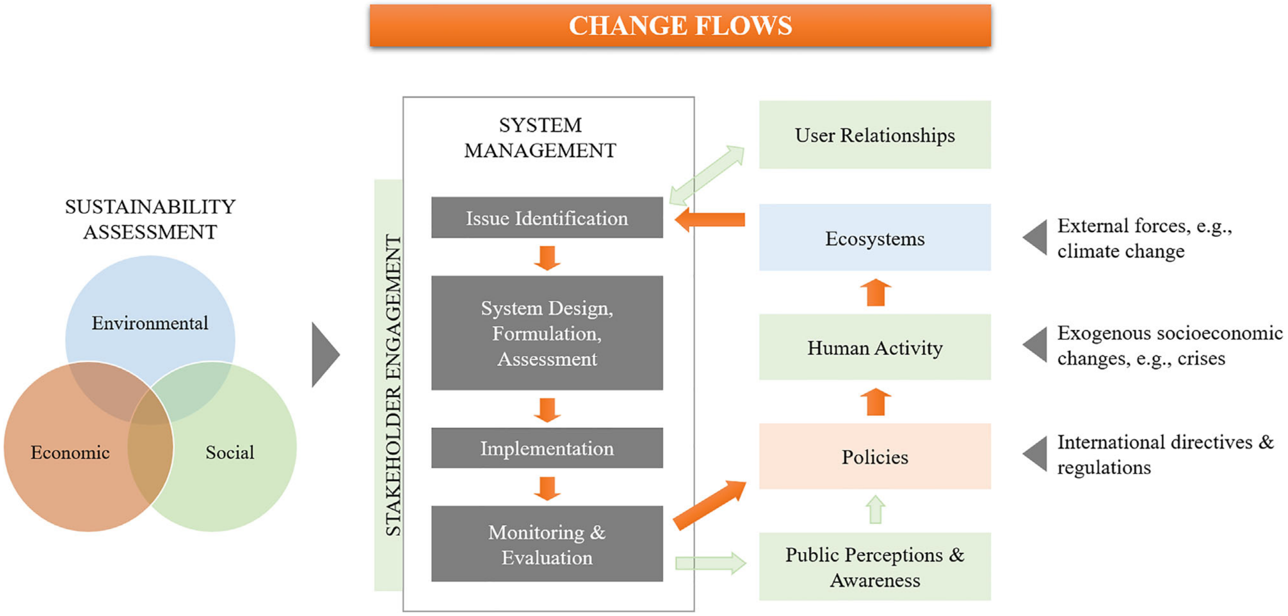


FIGURE 1 Framework for management of systems change with complex ecological implications. Adapted from Figure 2 (Støttrup et al., 2019)

of chemistry, economic, and ecological impacts of exploiting deep-sea mineral deposits; Levin et al. (2020)'s review of deep-sea mining's alignment with SDG goals; and Koschinsky et al. (2018)'s interdisciplinary examination of deep-sea mining's environmental, legal, economic, and societal implications. Impact comparisons are limited; Hein and Koschinsky (2014)'s chapter on deep-sea ferromanganese resources was a first qualitative comparison between nodules and terrestrial ores, while The Metals Company (TMC, formerly DeepGreen Metals) commissioned a white paper showing a lower "sustainability footprint"—environmental, social, and economic impacts—using nodules (pyrometallurgical, negligible-waste processing, hydropower) (Paulikas et al., 2020b). Still, several nodule-only assessments conclude that environmental damage from nodule collection would be extreme, irreparable, and economically risky (Cassan et al., 2019; Chin & Hari, 2020; FFI, 2020). Investigations now underway by scientists, conservationists, and contractors (ISA, 2020) are attempting to baseline CCZt's abyssal and water-column biota and predict nodule collection's likely impacts.

Comprehensive systems-based analyses of both options will enable greater clarity on pros and cons of nodule exploitation. One critical aspect of systems studies is characterization of solid waste outputs. Terrestrial metal extraction is a leading source of industrial waste globally, with an estimated 189.8 Gt of mining waste managed in 2020 and 5% growth rate projected through 2027 (Global Industry Analysts, Inc., 2021). Resulting waste streams are a known significant driver of environmental and social harm from terrestrial mining (Agboola et al., 2020), causing acidification and toxic metal pollution of streams, rivers, lakes, ground water, and soil; toxic windblown dusts that pollute air and soil (Witten et al., 2019); and sudden, massive releases of toxic material when tailings impoundment dams collapse, damaging natural and human communities (Chambers, 2019; Earthworks, 2019; Lyu et al., 2019).

Since nodules lie unattached, no overburden or waste rock must be removed to access them. However, collection introduces a new "waste stream"—disturbed sediment. In addition to the harm from removing nodule substrates, there is concern about effects of disturbed sediment and plumes, with much research underway to characterize their effects on abyssal and midwater-column wildlife (Kulkarni et al., 2018; Gillard et al., 2019; Spearman et al., 2020). Hence, waste streams from either source would be valuable to understand, characterize, and compare.

This study combines several ecological systems analysis tools to quantify and characterize waste streams generated by battery-metal production from either source. We inventoried large wastes with potential to drive significant impact (excluding transport and indirect impacts), using MFA with a "cradle-to-gate" scope (material extraction through refined metal). MFA is an industrial ecology tool, originally applied to waste management, and specifically designed for the analysis of "process chains comprising extraction or harvest, chemical transformation, manufacturing … and disposal" (Bringezu & Moriguchi, 2002). This created a life cycle inventory (LCI), as part of an overall attributional LCA (ALCA) for quantifying the environmental footprint of a material. Since nickel and copper grades have shown a persistent downward trend (Norgate, 2010; Northey et al., 2014; van der Voet et al., 2018), consequently increasing the waste produced per kg of metal, we quantified and presented results according to an aggregate 1-billion-EVs scenario with projected ore grades. We also conducted a preliminary IRA, a standard tool that supports complex decision-making under uncertainty by assessing likelihoods and expected severities of a range of potential risks. Pausing at the MFA retained systems context and preserved dynamic relationships, enabling us to characterize the wastes, assess risks, and analyze possibilities for impact-risk reduction.

TABLE 1 Waste taxonomy for metal production from terrestrial sources and CCZ nodules

TERRESTRIAL ORES	
Mining Phase	
Overburden	The ecosystem, soil, and country rock overlaying an ore body. In open-pit mining, overburden must be removed in order to access economic ore. Sulfide-bearing overburden rock that is stacked and piled can generate acid and leach toxic metals into streams and ground water
Interburden	Discrete waste rock found between ore bodies
Mine waste or waste rock	Typically refers to overburden (mostly country rock) and interburden
Mine tailings	Material remaining after ore has been concentrated at the mine site (mechanically crushed and milled and/or chemically treated to extract economically valuable components); typically, processed ore waste; can often be toxic
Miscellaneous	Minor wastes from support activities including mine building, road building, and various operations, as well as from transport to processing plants
Processing and Refining Phases	
Process tailings and residues	Processed ore waste resulting from processing and refining metal ores or concentrates; can be toxic
Tailings as "deep-sea tailings placement" (DSTP)	Processed ore waste resulting from processing and refining metal ores or concentrates, stored in perpetuity in the deep sea rather than on land
Slags and inert byproducts	Often uneconomic byproducts; may be toxin free or may contain toxic elements like arsenic. Toxic slags require management. Toxin-free slags may be used and sold if regulations allow, or may be discarded as mines are generally remote from industrial centers that could utilize the material
Miscellaneous	Minor wastes from raw-material transport and personnel support
CCZ NODULES	
Collection Phase	
Displaced seafloor sediment	Sediment entrained by nodule collector's seawater jets, then separated from nodules inside the collector, and discharged at the back of the collector for redeposition on the seafloor; also, sediment moved or stirred by collector tracks. May bury or smother creatures at the seafloor
Riser material and fines	Residual sediment and nodule fines discharged in midwater or back on the seafloor. May harm creatures in the midwater column
Miscellaneous	Wastes from collector ship operations as well as ship transport to onshore processing plant, regulated by MARPOL requirements
Processing and Refining Phases	
Process tailings and residues	Processed ore waste resulting from processing and refining metal ores—significant levels, if aiming to recover only three of the four economic metals, or if pure hydrometallurgical flowsheet is employed
Inert byproducts	Toxin-free slags that may be used and sold or discarded, depending on processing-center proximity to industrial centers that could utilize the material, if regulations allow
Miscellaneous	Minor wastes from raw-material transport and personnel support

The nature and amount of allocated waste per metal yield depend on factors like ore and processing geographies, mineralogy, ore grades, presence of valuable coproducts, metallurgical flowsheet, proximity to markets, regulatory environment, and operational execution. Several typical or expected wastes using terrestrial ores or nodules are shown in Table 1. Impact severities range from benign to severe, with waste streams varying in toxicity.

Low levels of heavy elements in nodules enable low-waste optimization, such that processing and refining can produce negligible tailings, residues, or other solid processing waste (see Supporting Information S2). A negligible-waste flowsheet, designed and demonstrated by TMC with intent to commercialize (SEC, 2021) using pyrometallurgical processing and hydrometallurgical refining, is included in the study. Replicating this design requires collocation of processing and refining facilities; selection of material inputs and flowsheet such that refining residues are recycled into the pyrometallurgical step while byproducts are non-toxic and marketable; and physical proximity to byproduct markets, so that byproducts certified as inert are used rather than piled and discarded as uneconomic waste (Sommerfeld et al., 2018; von Schroeter et al., 2020).

Terrestrial waste streams were estimated using a combination of literature review and mass-flow modeling. Since no commercial nodule operations exist yet, estimates for nodules used a combination of published CCZ literature, pilot test results, technological and commercial developments in collector systems, and metallurgical flowsheets and concepts pursued by exploration contract holders. Monte Carlo simulation was used to estimate confidence intervals (CIs) of offshore wastes, while scenario analysis explored uncertainties in the onshore processing. Five theoretical processing flowsheets were modeled, with different market weights used to generate three scenarios: a baseline "expected" case, a hypothetical "best case" in which 80% of producers optimize for low waste, and a hypothetical "worst case" in which 80% of producers extract only three metals (all manganese becomes waste).

In summary, this papert's unique contributions include:

- Estimating dominant global-average allocated waste streams of battery-metal production from terrestrial ores, with dynamic nickel and copper ore grades
- Modeling dominant average waste streams expected from battery-metal production from CCZ nodules, including sediment plumes, with a Monte Carlo offshore sensitivity analysis
- Conducting preliminary IRAs of these waste streams
- Qualitatively and quantitatively comparing the waste streams of battery-metal production using terrestrial sources or CCZ nodules

2 | METHODS

Methods for quantitative estimation (preliminary MFA) are described in Section 2.1. Methods for qualitative evaluation (key impacts, driving characteristics, preliminary IRA, and impact-risk reduction opportunities) are described in Section 2.2.

2.1 | Quantitative estimation

MFA, a "systematic assessment of the flows and stocks of materials within a system" (Brunner & Rechberger, 2004), is a core tool of industrial ecology to support decisions in resource, waste, and environment management (Moriguchi & Hashimoto, 2016). It is optionally part of an LCA—a widely used scientific framework for quantifying and comparing environmental footprints of processes or products. Guided by ISO 14040/44 standards, LCA consists of four stages: goal and scope setting, LCI, impact assessment, and interpretation. As detailed in the next subsections, we followed the first two LCA stages and used MFA techniques to arrive at preliminary waste-stream inventories.

An LCA may prevent burden shifting and improve decision-making by comprehensively communicating impacts. Results must be thoughtfully compared, as each study may differ in scope, system boundaries, assumptions, and simplifications. In policy making, there may also be a bias to prioritize impacts to humans over animals or nature. LCA allows exposure of multiple indicators simultaneously, though bias may still be introduced by indicator selection, choice of normalization weights if used, and design of indicators which may still be anthropocentric (Koschinsky, et al., 2018).

In ALCA, direct and indirect material and energy flows across the supply chain are quantified, with impacts statically allocated. Consumption is a given, so any policy externalities, behavioral shifts, and other dynamics, benefits, or consequences of a decision are not explicitly considered (Yang, 2017). Consequential LCA may hence be more relevant for policy making, as its dynamic, marginal, context-specific approach estimates effects of an action (Curran et al., 2005; EC-JRC-IES, 2010; Plevin et al., 2014). However, since most LCA tools, databases, and available studies use ALCA (Finnveden et al., 2009; Zamagni et al., 2012), we followed this approach.

We therefore considered average impacts and defined system boundaries around each source type's supply chain. We implicitly assumed one unit of metal from nodules displaces one unit of metal from terrestrial sources, that is, in the absence of nodule collection, terrestrial mining would correspondingly increase at the margins (see Section S5 in Supporting Information S2 for discussion). In partial response to ALCA's limitations, we incorporated terrestrial ore-grade dynamics and extensive nodule-side sensitivity analyses. Relevant follow-on studies may include analyzing highest-cost terrestrial pathways most likely to be displaced by CCZ supply, and incorporating a quantification of potential undersupply of nickel and cobalt markets, that is, changing the one-for-one displacement assumption.

2.1.1 | Goal and scope

Our goal is to understand the critical waste streams of metal production from two different resource types. Intended audiences are scientists, systems analysts, supply-chain participants, policy makers, governments, NGOs, and others interested in sustainable metal production.

The study scope is cradle to gate. Terrestrial production paths within scope are those relevant to current and future supply chains for EV battery metals, globally. For nodules, the five modeled flowsheets span a range of potential production methods. Transport and indirect impacts are excluded.

System endpoints are refined nickel sulfate, cobalt sulfate, copper cathode (inputs to EV battery manufacture and assembly), and a manganese product. We accommodated varying nodule-processing flowsheets by allowing the manganese endpoint to vary: battery-grade manganese sulfate; 40% product as an input to manganese refining; 75% alloy; or (terrestrial) electrolytic manganese. Manganese wastes therefore represent coarse estimates which may be further refined, as differing endpoints equate to differences in contained metal and refining reagents; differences in endpoints are noted throughout.

In metal LCA literature, impacts are typically allocated economically, by multiplying each byproduct's price by its yield then dividing by total sales (Nuss & Eckelman, 2014). We used average 2025–2055 battery-metal price projections by CRU International (2019) (19.926 USD Ni; 51.007 USD Co; 0.390 USD Mn; 7.084 USD Cu), except where allocations were provided.

The unit of measure is 1 kg of contained metal. In addition, to interpret impacts at scale, we employed an aggregate demand scenario of building 1 billion EV batteries by 2047 (Stanley, 2017). The reference technology is a 75 kWh nickel–manganese–cobalt (NMC) 811 battery (metals in 8:1:1 proportion), used by Tesla Model 3. Every such battery requires 56.2 kg of nickel, 7.05 kg of cobalt, and 6.6 kg of manganese, plus ~85 kg of copper for harnesses and connectors. Realized demand will vary, so this is meant as a representative scenario for understanding relative impacts. Each battery also requires ~65 kg of lithium, but CCZ nodules do not contain commercially significant amounts, so lithium must be sourced from other sources regardless and its impacts are not considered here.

2.1.2 | Inventory

Terrestrial

Waste streams quantitatively estimated:

- Mining phase: waste rock, mine tailings
- Processing and refining phases: process tailings and residues, slags and inert byproducts

For each metal, we estimated waste streams using two methods: benchmark of comparables using literature review, and representative aggregate mass-flow model. To compile the benchmark, we sourced multiple point estimates from the literature for production paths within scope (see below), reflecting a variety of operations for each metal; calculated and applied economic allocation factors; and took weighted arithmetic means. In building the representative mass-flow model, we incorporated ore grades, reagents, byproducts, and other stated assumptions aligning to the relevant production paths; and calculated and applied economic allocation factors. Initial (static) waste-stream estimates for each metal are arithmetic means of the two individual estimates.

We focused on production paths relevant to battery-metal supply chains for which waste literature was available:

- Nickel sulfides and laterites are fundamentally different resources, with distinct mineralogies and processing characteristics. Sulfides are the traditional resource for class 1 nickel required for batteries, but their resources are declining. We modeled both, assuming 70% of battery-grade nickel comes from sulfides.
- For manganese, electrolytic manganese metal (EMM) is the typical intermediate product refined into battery-grade manganese sulfate. We primarily focused on this production path.
- The predominant copper deposit types are porphyries, sulfides, and stratiform. We modeled all three, and sourced comparables on a variety of deposits.
- Cobalt was calculated as a byproduct of three common ore types (nickel–copper sulfides, nickel laterites, and copper ores). We excluded unregulated artisanal mines from the study.

The decline of ore grades for nickel and copper directly impact their yields (i.e., the denominator of per kg waste ratios), impact allocations, and waste generated. Cobalt's allocated waste streams also increase when coproduct nickel or copper grade declines: (1) more waste is generated for the same cobalt output; (2) cobalt's relative yield with respect to other metals increases, hence increasing its allocation of wastes. These dependencies were built into the mass-flow model. Global-average ore-grade time series projections for copper, nickel sulfides, and nickel laterites were taken from several LCA studies which assessed effects of ore-grade decline on LCA indicators (van der Voet et al. (2018), Kuipers et al. (2018), and Verboon (2016)), linearly interpolated to 2017–2047 at 5-year intervals.

Static estimates in hand, we then calculated ore-grade scaling factors for each waste stream. These factors accounted for ore-grade effects by time averaging from 2017 to 2047 and weighting by metal-demand projections. First, ore-grade time series were applied to the mass-flow model, yielding a time series of waste-stream estimates per metal. Then, aggregate wastes for 1 billion EVs were calculated by summing per kg waste streams according to 2017–2047 metal-demand time series. These were divided by total metal demands to yield time-averaged waste streams, which were then divided by year 2017 waste streams to yield ore-grade scaling factors. (See Table S2 in Supporting Information S1.)

Applying ore-grade scaling factors to initial static waste-stream estimates gave static-equivalent comparisons. Average per kg scaled static estimates were then multiplied by billion-EV metal demand to yield scenario results. For sensitivity analysis, for each metal the upper/lower bound was estimated by selecting the higher/lower value among each static estimate pair, adjusting by the ore-grade scaling factors, and multiplying by billion-EV demand.

Nodules

Waste streams quantitatively estimated:

- Collection phase: displaced sediment at the seafloor, sediment and nodule fines returned to the ocean
- Processing and refining phases: process tailings and residue wastes, inert byproducts

Collection phase. For this phase, a simple model of mass flows through the collector, riser-pipe, and discharge-pipe system was needed. A key parameter to estimate was depth of sediment likely to be entrained by the collector. Entrained sediment per seafloor area is then this depth multiplied by sediment density. Dividing by dry nodule yield per seafloor area converts this to entrained sediment per kg of collected nodule. To finally obtain the "displaced sediment at the seafloor" waste stream, entrained sediment is multiplied by the collector's sediment separation efficiency—the percent of entrained sediment directly returned to the seafloor behind the collector machine (while any unseparated sediment travels up the riser pipe).

We report this sediment as its dry-mass equivalent. The sediment waste stream is unique in its high liquid content (the top layer of CCZ sediment has extremely high water content, often referenced as "semi-liquid"; Beaudoin & Baker, 2013), and in originating and terminating while submersed in water. Since the original waste stream is aqueous but our interest is solid waste streams, and since its moisture content is seawater (not an unnatural part of the environment) and the aqueous material is reintegrated into its original environment, the waste stream is reported as its solid contents, designated with "(dry)". Other moisture-containing waste streams such as tailings are not suspended in their natural aqueous environment, nor chemically unaltered, and the entire waste masses are managed separately; hence those waste streams are reported as is, without dry-mass conversion.

Unseparated sediment enters the riser pipe (along with nodules) and travels to the surface, then is assumed to return through a pipe to be discharged. Some nodule fines result from nodule breakage during transport and dewatering. Fines and unseparated sediment together comprise the second offshore waste stream. Fines were calculated by multiplying together average wet nodule density per seafloor area, nodule recovery efficiencies from seafloor to riser, and nodule mass attrition during transport and dewatering, then dividing by dry nodule yield per seafloor area.

Once these waste streams were calculated per kg dry nodule, they could be allocated to individual metals. We used CCZ-wide average ore grade and metal yield assumptions to determine most allocations (as noted). A Monte Carlo simulation then tested sensitivity to nine parameters, yielding 5% and 95% CIs per kg metal and per EV.

Data inputs included preliminary experiment and prototype results, combined with resource data. Calculations assumed an average wet nodule density of 15 kg/m^2, 85% nodule recovery efficiency from seafloor to riser, and additional parameters based on results of technical scoping studies by Halkyard and Smith (2015). We assumed most operators would employ hydraulic jet collectors (see Section S2 of Supporting Information S2). Greater use of the mechanical method is implicitly included by the sensitivity analysis. Conversion to dry mass assumed sediment wet weight (1.2 g/cm^3), water to dry-mass ratio (300%), and hence dry sediment contents (0.3 g/cm^3) (Bluefield Technology Group, 2019).

Processing and refining phases. We first created mass-flow models for several potential flowsheet approaches, then estimated future market shares for each. Mass-flow modeling involved assumptions about ore grades, reagents, byproducts, and waste flows:

1. **Pyrometallurgical, negligible-processing waste**: Parameters based on TMC's demonstrated design (see Section S4 of Supporting Information S2). All byproducts are either sold, or recycled into the pyrometallurgical step. Ore grades are midway between NORI Area D grades and CCZ-wide averages. Endpoints are nickel sulfate, cobalt sulfate, copper cathode, a 40% manganese silicate product, ammonium sulfate (fertilizer), and an environmentally stable converter slag usable in local markets (as construction, road ballast, filler material).
2. **Pyrometallurgical, medium waste**: Negligible-waste optimizations are not made. Ammonium sulfate is not produced; the alternative, sodium sulfate, is identified as a waste. This case has two sub-cases: in the first, byproducts do not reach local markets, so converter slag simply becomes an unused "slag or inert byproduct" in the second, that same mass flow is classified as a processing waste/residue since intermediate nickel–cobalt–copper matte is not produced.
3. **Pyrometallurgical, three metals**: Nickel–cobalt–copper alloy is still separated, but manganese is not extracted.
4. **Hydrometallurgical, medium waste**: A leaching method is used, with reagents close to levels seen in terrestrial hydrometallurgical methods. All four metals are extracted, and the remainder of mass is assumed to become waste flow.
5. **Hydrometallurgical, three metals**: A method such as the Cuprion process is used to extract only three metals (nickel, cobalt, and copper). Manganese is not recovered. Reagents increase to 70% of ore mass.

Key differentiating attributes among these approaches include whether pyrometallurgical or hydrometallurgical processing is used; which metals are recovered; final formats of metal outputs; reagent levels; and whether negligible-waste optimization is used. Model and market-share assumptions may be revised once operators complete pilot processing plant programs and feasibility studies, and secure permits for onshore metallurgical plants.

Our future market-share scenarios span "realistic, best-case, worst-case" possible realities. In the worst case, we suggest manganese will not be extracted by 80% of operators. As manganese comprises ∼20% of nodule value (CRU International, 2019), its recovery is economically incentivized, and we are currently unaware of any contractor planning to extract only three metals; still, such a flowsheet is theoretically possible. In the best case, we assume nearly all operators converge quickly on negligible-waste processing. We are currently aware of only one contractor using this flowsheet, though the global trend in importance of ESG for brand along with other competitive pressures may lead others to follow. Since it seems unlikely that most producers would align on either extreme (extracting only three metals, or optimizing for no waste), we consider both to be improbable extreme cases.

The baseline market-share scenario is an educated guess of likely average market composition over time. As preliminary indicators, we looked to methods that have generated published research and/or are subjects of feasibility studies. We made three key assumptions:

1. Pyrometallurgical approaches will represent a majority (71%) of production, as they have been most extensively studied since the 1970s and are preferred by numerous research groups (e.g., by Inco/Vale, Sumitomo, Kennecott/Rio Tinto, Germany, Korea, and others; AMC, 2019b).
2. Negligible-waste processing will comprise a non-trivial share (16%), as at least one contractor (TMC) which is piloting a negligible-waste flowsheet (SEC, 2021) has commercial rights to three areas totaling 1.6 billion Mt (wet) on two of them (TOML, NORI).
3. Economic incentives will lead almost all producers to extract manganese; only a small number (5%) will choose not to recover manganese, using a simple (pyrometallurgical) flowsheet.

Billion EVs. Billion-EV waste estimates for nodules were generated by simply multiplying static metal-specific estimates by billion-EV metal-demand quantities, then summing across metals. Sensitivity analyses for offshore and onshore phases were again considered separately. For the collection phase, since metal-specific Monte Carlo simulation results cannot simply be summed, as metal-specific waste streams from nodules are not independent (e.g., they are all impacted by changes in nodule density, efficiencies, processing yields), the Monte Carlo model was augmented to calculate and sum wastes at billion-EV metal quantities, and CIs were estimated on those totals. For processing and refining, the scenario analysis was straightforwardly scaled: for each scenario, metal-specific results were scaled to billion-EV metal quantities, and total wastes were summed.

2.2 | Qualitative evaluation

A preliminary IRA was performed to survey and highlight key impact risks from waste streams. This is typically part of an overall risk management process of risk identification, assessment, response, communication, and monitoring. Since nodule-collection risk discussions tend to focus on geographically specific organism or human groups, we focused the IRA on harm to categories of ecosystems (marine, water supply, land, atmosphere) or stakeholders (ocean, freshwater, terrestrial organisms, humans), representing both human and non-human interests. While a more complete risk management process may benefit from additional focus on highest-impact risks or more-granular stakeholder groupings (Levin et al., 2020), our coarser approach is useful for broadly landscaping impact drivers and vulnerable subsystems and stakeholders.

For each waste stream and subsystem/stakeholder pair, we assessed (1) the likelihood the waste stream would have a detrimental effect on that subsystem or stakeholder (from rare to very likely), and (2) the expected severity of such detrimental effect should it occur (from trivial to extreme). Using a standard lookup table, each likelihood/severity pair mapped directly to an overall risk assessment (from very low to very high). Note that correlations and interdependencies were not directly addressed in this IRA.

To aid in assessing severities and likelihoods, we conducted brief literature-based summaries of impact characteristics of each waste stream. We also qualitatively classified each waste stream along a set of dimensions that may drive impact, including:

- Factors that cause direct environmental harm, for example, toxicity, corrosivity
- Other physical properties that may harm animals, for example, ability to smother
- Operational process characteristics, including whether the material can be returned to its natural habitat, the degree to which the material has been altered, ease of mitigation or management of potential ongoing impacts, and whether extensive and/or ongoing operations are required to discard and/or manage the waste.

Finally, we highlighted a set of opportunities for impact reduction.

3 | RESULTS

3.1 | Quantitative results

3.1.1 | Terrestrial

Terrestrial waste-stream results using the two estimation methods are shown in Table 2. The first portion shows comparables from the literature, while the second outlines mass-flow assumptions and resultant waste streams. All values reflect the economic allocations listed.

With the exception of nickel laterites, the dominant wastes from terrestrial ores are waste rock and mine tailings in the mining phase. Large mine wastes (overburden) reflect the dominance of surface mines for most of these metals, though a minority of underground mines are included, particularly for nickel sulfides and copper. Large quantities of tailings are seen in the mining phase when concentration is performed, as is the case for most nickel sulfides, copper ores, and cobalt. Reagents added in concentration and in processing further increase the mass that results in tailings and other processing wastes. These can be quite large, especially for hydrometallurgical processing (e.g., high-pressure acid leaching [HPAL]) of nickel laterites.

Note nickel laterites are generally not concentrated; mined ore is typically fed directly into a collocated processing plant. Hence, tailings from laterites are categorized as process-phase wastes. (Occasionally laterite ores are pre-sorted or "upgraded" at the mining site, and the removed ore becomes mine waste. Metal recovery can be lower, resulting in more total waste mass per metal yield, though slightly less of it becomes tailings.)

3.1.2 | Nodules

Depth of entrained sediment

Sediment disturbance and entrainment are complex to model and likely to fluctuate. They depend on specific local geotechnical conditions (e.g., thickness of the semi-fluid top layer of sediment) as well as collector jet performance attributes (e.g., pressures, flows, stand-off distance). This leads to difficulties in predicting depth of displaced sediment. At present, there is little published experimental data justifying an expected range; depths will be better understood once deep-sea CCZ pilot tests are completed in 2021 (GSR) and 2022 (NORI). Given this, we attempted to estimate industry-wide bounds.

At the higher end, sediment profiles within NORI Area D of the CCZ indicate that around 15 cm, the semi-fluid layer transitions to firmer clay, making entrainment by seawater jets more difficult, suggesting an upper displacement limit (AMC, 2019a). Literature often cites 10–15 cm as expected displaced depth (Aleynik et al., 2017; Cuvelier et al., 2018; Hund et al., 2020), though without clear experimental justification or citation, and ranges may include nodule protrusions.

At the lower end, 91% of sampled nodule mass in NORI Area D sat atop sediment or had top surfaces in the upper 1 cm (AMC, 2019b). There are economic, environmental, and political incentives to minimize the additional sediment entrained. Experimental lab test results by Allseas (2020a, 2020b), using an analogue with similar compressive strength to CCZ sediments but lower water content, suggested sediment disturbance depth as low as 2 cm with hydraulic jets, leading to engineering estimates of 2–5 cm likely to be entrained operationally.

Considering these inputs, for the baseline scenario we estimated an industry-wide average depth of 5 cm. For the worst-case scenario, considering the upper limit and the possibility of mechanical design, we assumed an average of 10 cm. For the best-case average, we assumed 2.5 cm, suggesting collectors converge on optimal designs which approach the lower test bound.

Collection phase

Mass-flow assumptions and results are shown in Table 3. Consistently, sediment redeposited at the seafloor was the dominant waste stream, typically three to six times greater than the returned material.

The 5% and 95% CIs determined by Monte Carlo simulation show a large range of potential variation for both waste-stream types (see Supporting Information S1 for additional detail). These align closely to the range of potential sediment displacement depths, suggesting this is the key driver.

Returned material comprised both sediment and nodule fines in substantial quantities. In over 40% of simulation runs, fine content in this waste stream was greater than sediment. The simulation also yielded a 90% confidence range of seafloor area to produce metals for 1 billion EVs: 381,000 to 582,000 km^2.

Processing and refining phases

Key mass-flow assumptions, waste outputs, and market-share assumptions for the five modeled nodule-processing approaches are shown in Table 3 (see also Table S10 of Supporting Information S1). Percentages indicate mass flow with respect to 1 kg of dry nodule.

TABLE 2 Terrestrial waste-stream estimation using two methods

METHOD 1: LITERATURE COMPARABLES								
Description	**Type**	**Average grade**	**Allocation factor applied**	**Mine waste (kg / kg)**	**Mine tailings (kg / kg)**	**Process waste (kg / kg)**	**Slags (kg / kg)**	**Sources**
Nickel sulfides								
General pyro-processed	Open pit	0.26%	70%[1]	175	337[2]	37[2]	–	Verboon (2016); Classen et al. (2009)
Mid/higher-grade nickel sulfides	Underground	1.13%	58%	30	56[2]	6[2]	–	Verboon (2016); Classen et al. (2009)
Vale (Canadian mines)	45% Underground	1.90%	45%	21[3]	54[2]	6[2]	–	SEC (2019); Vale (2021)
Norilsk	Both	2.47%	35%	48[4]	24[4]	3[4]	7[4]	Nornickel (2019)
Average slag waste per processed Ni	–	Various	70%[1]	–	–	–	7	Zhang et al. (2020a)
Nickel laterites								
Vale New Caledonia 1.42% grade	Open cut	1.42%	85%	95	0	81	–	SNL (2019); NS Energy (2020)
Ambatovy (Madagascar)	Open cut	1.13%	82%	89	0	98	–	SNL (2019); USGS (2020a)
Ramu in Papua New Guinea	Open cut	1.00%	82%	48	0	160	–	Ramu (2020); Highlands Pacific (2018)
Manganese								
Mamatwan (South Africa)	Open pit	38%	100%[5]	14	0	–	–	Credit Suisse (2015)
Manganese alloy LCA: mining waste	Both	Various	100%[5]	37[6]	9[6]	–	–	Westfall et al. (2016)
Electrolytic Mn - China; concentrated	–	19%	100%[5]	–	4	0	–	Zhang et al. (2020b)
Electrolytic Mn - China	–	18%	100%[5]	–	0	7	–	Peng et al. (2012)
Electrolytic Mn - South Africa	–	44%	100%[5]	–	0	2	–	Peng et al. (2012)

(Continues)

TABLE 2 (Continued)

Copper								
Duluth Gabbro deposit (Ni/Cu)	Open pit	0.4%	50%	200	126	–	–	Black et al. (2018); Trethewey (1977)
Ok Tedi Mine (Cu/Au)	Open pit	0.64%	53%	77	196	–	–	WRI (2003); WWF (2020); USGS (2020c)
Island Cu Mine Vancouver Island	Open pit	0.52%	90%	–	111	–	–	Skei et al. (2019); Fluor (2020)
Antofagasta (Chilean mines)	Most open pit	Various	80%[1]	266	98	–	–	Chigumira et al. (2019)
KAZ Minerals (Kazakhstan)	Most open pit	0.4-2.3%	70%	34	46	–	–	Chigumira et al. (2019)
First Quantum	Most open pit	Various	80%[1]	161	–	–	–	Chigumira et al. (2019)
El Teniente	Underground	0.8%	80%[1]	4	111	–	–	Codelco (2020)
Global avg tailings, wastes US, slag	–	Various	80%[1]	304	154	3	2	Ayres et al. (2002), EPA (2020), Sanchez and Sudbury (2013); Gorai et al. (2003)

METHOD 2: STATIC MASS-FLOW MODEL

	Class 1 Nickel Ni sulfides (Komatiite)	Class 1 Nickel Ni sulfides (Tholeiite)	Class 1 Nickel Ni laterites	Cobalt Ni-Cu-Co sulfides	Cobalt Ni laterites	Cobalt Stratiform (CACB)	Manganese Carbonite or oxides	Copper Poryphyries	Copper Ni-Cu-Co sulfides	Copper Stratiform (CACB)
Coproducts	Cu, Co	Cu, PGE	Co	Ni, Cu	Ni	Cu	None	Mo, Au, Ag	Ni, Co	Co
Weighting	42%	28%	30%	25%	15%	60%	100%	80%	5%	15%
Processing methodology	pyromet	pyromet	HPAL	pyromet	HPAL	pyromet	acid leach	pyromet	pyromet	pyromet
Average ore grade	0.59%	1.4%	1.5%	0.06%	0.08%	0.47%	35.0%	0.46%	0.35%	2.4%
Total valued metals grade	0.89%	2.9%	1.6%	1.0%	1.6%	2.9%	35.0%	0.47%	1.1%	2.9%
Average recovery	83.1%	83.1%	92.2%	49.0%	81.0%	56.0%	83.3%	89.2%	81.9%	89.2%
% surface mines (remainder underground)	100%	10%	100%	20%	100%	95%	95%	87.5%	100%	95%

(Continues)

TABLE 2 (Continued)

METHOD 2: STATIC MASS-FLOW MODEL	Class 1 Nickel Ni sulfides (Komatiite)	Class 1 Nickel Ni sulfides (Tholeiite)	Class 1 Nickel Ni laterites	Cobalt Ni-Cu-Co sulfides	Cobalt Ni laterites	Cobalt Stratiform (CACB)	Manganese Carbonite or oxides	Copper Poryphyries	Copper Ni-Cu-Co sulfides	Copper Stratiform (CACB)
Average strip ratio	0.8	0.8	1.0	0.8	1.0	2.0	5.0	2.0	0.8	2.0
% mines concentrating	95%	95%	0%	95%	0%	95%	10%	95%	95%	95%
Average concentrate grade	10%	10%	0%	1%	0%	4%	40%	26%	6%	26%
Mass removed in conc	95%	88%	0%	95%	0%	91%	64%	98%	95%	91%
Added reagents	15%	15%	60%	15%	60%	10%	10%	10%	15%	10%
Allocation factor applied	74.5%	57.4%	89.3%	13.2%	10.7%	45.1%	100.0%	77.3%	13.1%	51.8%
Mine waste (incl underground) (kg/kg)	123	4	65	54	165	326	16	330	37	45
Mine tailings (kg/kg)	145	48	0	336	0	196	0	180	43	24
Process tailings and waste (kg/kg)	8	2	96	17	246	12	2	10	2	2
Slags (kg/kg)	7	6	0	16	0	9	0	2	2	1
Total allocated waste & slags (kg/kg)	283	60	161	424	411	542	19	522	84	72

[1]Economic allocation reflects estimated global mineral average. [2]Assumes 90% of tailings attributable to mining phase and 10% to processing and refining phases. [3]Average of open-pit and underground mines; assigns zero waste rock to underground mines, and assumes strip ratios of 1.3 for open-pit mines. [4]Norilsk reports approximately 36 Mt of waste (∼1 Mt hazard level 1–4) per annum and approximately 166.3 kt of nickel generated yearly, or ∼212 kg of waste per kg Ni produced (unallocated). Assumes 37% of wastes are tailings or other wastes that cannot be reused, mineral-average slag production, and 90% of tailings in mining phase. [5]Manganese allocation reflects typical lack of marketable byproducts, or byproducts as other manganese products or low-value slags. [6]Assumes total reported waste represents 80% overburden and 20% tailings. Method 1 notes: Overburden, tailings, processing waste, and slags have been scaled by indicated allocation factors. Cobalt's waste streams are derived from representative nickel and copper ore comparables containing cobalt as a coproduct. Wastes generated by the refining phase are not explicitly shown, and in some cases may be subsumed in "process wastes" or may be additional. For nickel, cobalt, and manganese, product-wide averages were attained by using an unweighted arithmetic mean of literature data points; for copper, estimates were weighted by production output then averaged with global/US averages. Method 2 notes: Shown are several key assumptions and results of terrestrial mass-flow model. Status quo ore grades are assumed. Overburden, tailings, processing wastes, and slags have been scaled by indicated allocation factors. Full mass-flow calculations, assumptions, and detailed allocation calculations are available in Supporting Information S1.

TABLE 3 Nodule waste stream assumptions and results by phase

1. COLLECTION PHASE[1]				
Assumptions varied	**Units**	**Baseline**	**Minimum**	**Maximum**
Wet density of sediment	g/cm^3	1.2	1.02	1.38
Water content	%	300	255	345
Sediment depth displaced	cm	5	2.5	10
Nodule density	kg/m^2	15	12.75	17.25
Nodule entrainment efficiency	%	90	80	98
Concentrator nodule recovery	%	95	85	99
Concentrator mud rejection	%	92	80	98
Dewatered nodules water content	%	80	80	80
Dewatering sediment to product	%	7.5	1	20
Static assumptions				
Wet nodule water content	%	20		
Impact allocation to nickel	%	47.1516		
Impact allocation to cobalt	%	18.322		
Impact allocation to manganese	%	21.4416		
Impact allocation to copper	%	13.08		
Results per seafloor area	**Units**	**Baseline**	**5% Conf. Interval**	**95% Conf. Interval**
Sediment redeposited (dry)	kg/m^2	13.8	7.5	27.2
Returned material—nodule fines	kg/m^2	1.3	0.35	2.4
Returned material—sediment	kg/m^2	1.1	0.40	4.1
Returned material—total	kg/m^2	2.4	1.3	5.7
Collection phase total	kg/m^2	16.2	9.7	31.3
Results per kg dry nodule	**Units**	**Baseline**	**5% Conf. interval**	**95% Conf. interval**
Sediment redeposited (dry)	kg / kg	1.5	0.84	3.3
Returned material—nodule fines	kg / kg	0.14	0.04	0.29
Returned material—sediment	kg / kg	0.12	0.04	0.48
Returned material—total	kg / kg	0.26	0.14	0.68
Collection phase total	kg / kg	1.8	1.1	3.8

2. PROCESSING AND REFINING PHASES ***(Percentages are with respect to dry nodule mass)***					
	1. Pyromet, neglig. waste	**2. Pyromet, medium waste**	**3. Pyromet, 3 metals**	**4. Hydromet, medium waste**	**5. Hydromet, 3 metals**
Reagents + coal ash added	11.3%	11.1%	0.6%	50.0%	70.0%
Oxygen mass reduced	10.6%	10.2%	10.2%	10.2%	5.0%
SO_2 off-gas	0.2%	0.2%	0.0%	0.0%	0.0%
Non-free water released	6.6%	6.6%	6.6%	6.6%	6.6%
Reagents recycled	0.6%	0.0%	0.0%	0.0%	0.0%
Yield—nickel in sulfate	1.22%	1.21%	1.21%	1.21%	1.21%
Yield—cobalt in sulfate	0.15%	0.18%	0.18%	0.18%	0.18%
Yield—Mn final product[2]	72.7%	37.4%	0%	37.4%	0%
Yield—Copper	0.97%	0.94%	0.94%	0.94%	0.94%
Yield—ammonium sulfate	4.2%	0.0%	0.0%	0.0%	0.0%
Waste output: Inert byproduct	**14.7%**	**25.0%**	**0.0%**	**16.4%**	**0.0%**
Waste output: Residues/tailings	**0.0%**	**29.7%**	**82.7%**	**77.6%**	**156.6%**

(Continues)

TABLE 3 (Continued)

2. PROCESSING AND REFINING PHASES *(Percentages are with respect to dry nodule mass)*	**1. Pyromet, neglig. waste**	**2. Pyromet, medium waste**	**3. Pyromet, 3 metals**	**4. Hydromet, medium waste**	**5. Hydromet, 3 metals**
Market Shares by Scenario *(Percentages indicate share of global industry assumed to use this approach)*					
Baseline scenario	17%	50%	5%	29%	0%
Low-waste scenario	80%	10%	0%	10%	0%
High-waste scenario	0%	10%	40%	10%	40%

1. Impact allocations were determined by multiplying per-metal price assumptions by final metal yields per kg of dry nodule. Allocations and ore grades were assumed not to vary for the purposes of sensitivity analysis. Baseline results were calculated directly using static baseline assumptions. CI results were calculated using Monte Carlo simulation, assuming independent random variables uniformly distributed between minimum and maximum bounds given for each parameter. Each CI value reflects the arithmetic mean of 30 simulation runs each estimating the proportion of 5000 iterations in the bottom or top 5%. CI values do not directly sum because some waste streams are correlated: for instance, when below-average sediment is redeposited, above-average sediment must be sent up the riser, so their minima cannot coincide. 2. Mn product endpoint in medium-waste approaches #2 and #4 are assumed to be an alloy containing approximately 75% Mn; the remainder of mass may include Fe, Si, and additional elements in small quantities. In approaches #2 and #4, the 16.4% of inert byproduct is attributable to refinement of 40% Mn into 75% Mn and as such is allocated directly to Mn. Mn product endpoint in approach #1 is a 40% marketable product containing approximately 75% MnO and SiO_2; once refined, the non-Mn-alloy mass plus any additional reagents may become an inert byproduct or waste, and would be directly allocated to Mn.

Compared to the first three pyrometallurgical approaches, higher wastes typically resulted from using hydrometallurgical methods, primarily due to greater amounts of reagents entering the mass flow. Additionally, the second hydrometallurgical case compounded this with the absence of manganese recovery.

Manganese endpoints for each approach are indicated in the footnote. To attain comparable manganese endpoints, the low-waste flowsheet would add refinement of 40% product into ~75% alloy, with the added waste flow fully allocated to manganese.

3.1.3 | Quantitative comparison

A side-by-side summary of baseline results is shown in Figure 2. The figure shows that per kg quantities of roughly comparable wastes tend to be lower when nodules are used. For both sources, per kg waste streams from cobalt are largest in part due to its low ore grades and higher price.

Ore-grade dynamics are expected to increase the time-averaged waste streams by 32% for nickel and 23% for copper, as well as 18% for cobalt due to its increased allocation and slightly increased waste mass when nickel and copper ore grades decrease. (Detailed calculations shown in Supporting Information S1.)

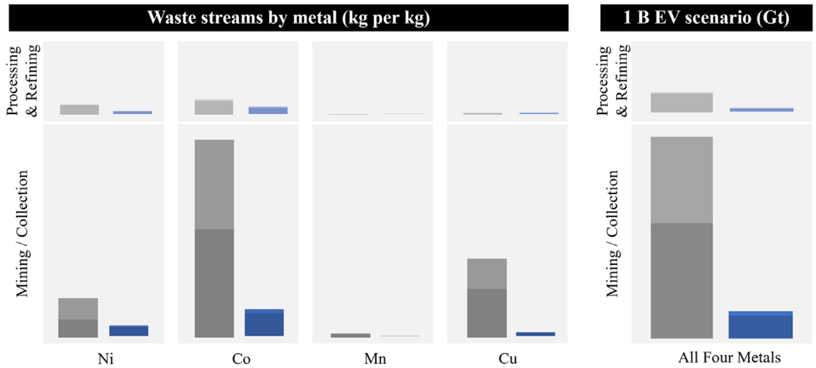
The billion-EV scenario reflects significant impact contributions from nickel, cobalt, and copper. Augmenting this scenario by the total flow of manganese from nodules would increase allocated wastes by approximately 26% in accordance with manganese's allocation ratio, plus any additional mass flow from refining the 40% manganese product into a manganese sulfate or alloy.

3.2 | Qualitative results

Detailed descriptions of all waste streams are presented in Appendix S2 of Supporting Information S2. Their key high-level characteristics are highlighted below. Each description also indicates any medium or high risks from the IRA assessment, which follows.

3.2.1 | Impacts of land-ore waste streams

- **Overburden (ecosystem and soil)**. Ecosystem overburden and soil overburden are relatively smaller waste streams with potentially significant impacts. Their removal degrades and fragments habitats, causes deforestation, and biodiversity loss, and potentially releases carbon sequestered in soil, living and dead vegetation, and is detritus to the atmosphere (Bradley, 2020; Sonter et al., 2020). Restoration timelines can span hundreds to thousands of years (Liebsch et al., 2008). *High risk: terrestrial organisms, humans; land, atmosphere. Medium risk: freshwater organisms; water supply*.
- **Overburden (country rock)**. Country-rock overburden is the largest waste stream and has potentially significant impact. It requires extra land use for storage, and can lead to acid rock drainage which cannot be easily stopped (Sumi & Gestring, 2013) and causes significant pollution to



Terrestrial			Ni (kg/kg)	Co (kg/kg)	Mn (kg/kg)	Cu (kg/kg)	1B EV (Gt)
Proc. & Ref.		Slags	4.4 [4.3, 4.5]	9.4 [8.3, 10.6]	0.0 [0.0, 0.0]	1.7 [1.6, 1.7]	0.5 [0.4, 0.5]
		Tailings & Waste	46.7 [38.0, 55.5]	66.4 [55.2, 77.5]	2.6 [2.4, 2.8]	6.9 [3.8, 10]	3.7 [2.9, 4.5]
Mining		Mine Tailings	122 [105, 139]	512 [244, 780]	1.8 [0.2, 3.3]	174 [162, 185]	25.3 [21.4, 29.1]
		Mine Waste	101.1 [96.3, 106]	618 [271, 966]	20.8 [16.3, 25.3]	277 [217, 337]	33.6 [25.8, 41.4]

Nodules			Ni (kg/kg)	Co (kg/kg)	Mn (kg/kg)	Cu (kg/kg)	1B EV (Gt)
Proc. & Ref.		Inert Byproducts	2.6 [5.0, 0.3]	6.7 [12.9, 0.9]	0.19 [0.13, 0.2]	0.94 [1.8, 0.1]	0.3 [0.5, 0.04]
		Tailings & Waste	11.6 [2.9, 50.5]	29.7 [7.5, 129.2]	0.33 [0.09, 0.45]	4.1 [1.0, 17.9]	1.2 [0.3, 5.3]
Collection		Returned Material	10.1 [5.3, 26.7]	25.9 [13.6, 68.5]	0.2 [0.1, 0.5]	3.6 [1.9, 9.5]	1.1 [0.6, 2.8]
		Displaced Sediment (Dry)	58.3 [32.8, 129]	149 [83.9, 329]	1.1 [0.6, 2.5]	20.7 [11.6, 45.7]	6.1 [3.4, 13.4]

FIGURE 2 Solid waste streams from producing battery metals using terrestrial ores or nodules (with ore grade dynamics). Stacked bars indicate baseline waste streams per kg of metal produced (left) or per 1 billion EVs (right) for either terrestrial ore sources (gray) or nodule source (blue). Results reflect economic allocation. Ore-grade dynamics are reflected in terrestrial results. 1-billion-EVs scenario represents cradle-to-gate waste streams for 56.2 metric Mt of nickel, 7.05 metric Mt of cobalt, 6.6 metric Mt of manganese, and 85 metric Mt of copper. Not included are wastes from transport, support operations, indirect impacts, and final refinement of terrestrial metals or of nodule-derived manganese into sulfates. Sensitivity analyses indicated within "[,]" brackets correspond to (terrestrial) baseline, minimum, maximum values for each metal; (nodule collection phase) baseline, 5% CI, 95% CI Monte Carlo results; and (nodule processing and refining phases) baseline, low-waste, high-waste processing reflecting three static scenarios with different weightings of the modeled flows, with scenario allocations as shown in Table 3

streams, freshwater, drinking water, and human infrastructure (USGS, 2020b). *High risk: water supply. Medium risk: freshwater organisms, terrestrial organisms; land, atmosphere.*

- **Dusts**. Airborne dusts represent a low-volume waste stream, but with significant effects on morbidity and mortality for miners and those exposed in surrounding communities, especially in arid or semi-arid environments (Entwistle et al., 2019; Mucha et al., 2018; Nkulu et al., 2018). *High risk: humans. Medium risk: terrestrial organisms; land, atmosphere.*
- **Mine tailings and processing tailings**. Tailings account for the second largest waste type from land ores. They typically require special infrastructure, for example, dams, to separate them from the environment, or to remediate polluted water (Pozo-Antonio et al., 2014; Skousen et al., 1998), and often need to be managed in perpetuity. Fallout from tailings-dam failures can have a pollution radius of hundreds of kilometers (Chambers, 2019; Lyu et al., 2019; Palmer, 2019; WISE, 2020); non-catastrophic groundwater pollution from seepage can impact rivers and ecosystems for hundreds to thousands of years (Sergeant & Olden, 2020). *High risk: freshwater organisms, terrestrial organisms, humans; water supply, land. Medium risk: ocean organisms; marine, atmosphere.*
- **Tailings as deep-sea tailings placement (DSTP)**. A relatively small waste stream of growing use as an alternative to tailings dams; where employed, ecological concerns include suspended sediments, turbidity, toxic metals and chemicals, bio-uptake and biomagnification, benthic habitat alteration, harm to benthic species, populations, and biodiversity, and changes to primary productivity (Hughes et al., 2015; Morello et al., 2016; Vare et al., 2018). *High risk: ocean organisms; marine. Medium risk: water supply.*
- **Slags and inert byproducts**. A medium-sized waste stream which may vary in degree of inertness or toxicity. Long-term environmental effects of some slag disposal can include toxic metal pollution of soil, surface water, and groundwater (Parsons et al., 2001; Potysz et al., 2016; Reuter et al., 2004). *Medium risk: ocean organisms, freshwater organisms, terrestrial organisms, humans; marine water supply, land, atmosphere.*

3.2.2 | Impacts of nodule waste streams

Substantial, long-lasting habitat degradation and ecological damage are expected from offshore wastes. Considerable variations in impact, resilience, and recovery time are expected—whether among geographic areas, taxa, size classes, or functional groups.

While we do not cover impacts of actual nodule removal, as it is not a waste stream, there is research which indicates removal of the nodule substrate itself may be one of the strongest negative environmental impacts of nodule collection (Vanreusel et al., 2016; Stratmann et al., 2021).

- **Sediment returned to seafloor**. This large waste stream can harm organisms and habitats in three main ways: (1) as sediment moved at the seafloor, (2) as a temporarily suspended plume, and (3) as resettled plumes. Impacts will vary by taxon, mode of life, degree of disturbance, and other factors (Gollner et al., 2017; Jones et al., 2017; Simon-Lledó et al., 2019a; Thiel & Schriever, 1989). Plumes have been predicted to rise as high as 100–200 m in the poorly characterized benthic bottom layer (BBL), though in recent tests of the 1:3 scale Patania II collector (Belgian/German licensed areas), the dense sediment plume only rose 5–6 m (BGR, 2021). Temporarily suspended plumes will contain sequestered organic carbon, though there are currently no known mechanisms for this carbon-carrying plume to rise through 4–6 km of water to reach the atmosphere (Atwood et al., 2020; Paulikas et al., 2020a). Overall, the extent and severity of impacts are still uncertain (Levin et al., 2020); sessile megafauna may recover more slowly, primarily due to loss of nodule habitat (Gollner et al., 2017; Simon-Lledó et al., 2019a, 2019b). *High risk: ocean organisms; marine.*
- **Riser material returned as plumes**. This is many times smaller than sediment returned to the seafloor, as only a small percentage of entrained seafloor sediment enters the riser pipe. Impacts on deep-sea wildlife will depend on riser-water discharge depth as well as sediment load, turbulence, and sensitivity of organisms to turbidity (Muñoz-Royo et al., 2021). The waste also contains nodule fines, which on average contain higher metal concentrations than nodules or seawater (Kim et al., 2021). Serious toxic effects may be unlikely, since seawater is oxic and any free metal ions are scavenged by organic matter (Koschinsky et al., 2018). The full set of properties of sediment and fines that have traveled to the surface and are redeposited in the ocean are not yet known, and their impacts still need to be characterized (Drazen et al., 2020; Schriever & Thiel, 2013). *Medium risk: ocean organisms; marine.*
- **Process tailings and residues**. Depending on choice of processing flowsheets, these solid waste streams may vary. Quantities are generally much smaller than terrestrial counterparts (in large part due to higher overall grades of nodules), except in the worst-case scenario where the industry converges on the highest-waste flowsheet. *High risk: freshwater organisms, terrestrial organisms, humans; water supply, land. Medium risk: ocean organisms; marine, atmosphere.*
- **Inert byproducts**. Impacts are expected to be less severe than terrestrial-ore counterparts, given the absence of toxic levels of deleterious elements, such that benign or inert byproducts rather than slags or toxic wastes can be created with greater ease. *(Inert byproducts show no high- or medium-risk evaluations.)*

3.2.3 | Driving characteristics

A summary of driving characteristics of the waste streams is depicted in Table 4. For nodules, the main challenges may lie in measuring, managing, and mitigating impacts across an expansive and remote area. For terrestrial ores, the main challenges may be the safe management of large quantities of wastes (e.g., tailings) separately and permanently away from nature.

3.2.4 | Preliminary IRA

Preliminary IRA results are presented in Figure 3. Any entry with an “Impact Risk Assessment” marked as medium, high, or very high deserves greater attention and detailed mitigation strategies. As illustrated, key risks frequently discussed for nodules are concentrated for “marine” and “ocean organisms,” and the waste type “tailings and residues”; for terrestrial ores, medium to high risks are seen more broadly.

3.3 | Combined summary view

Figure 4 combines qualitative and quantitative results into a single view, using the billion-EV scenario. Impact risks are indicated by color and presented alongside waste-stream quantities, with scenario or sensitivity analysis results shown in subsequent columns. Problematic waste streams likely have large quantities, an indication of significant risk (medium or higher), or both.

3.4 | Opportunities

For terrestrial ores, waste quantities can be fundamentally challenging to reduce; when ore grades are low, large amounts of excess mass tend to result. Opportunities for impact reduction may focus on innovatively treating or managing them. For instance, soil stripped during mining is typically

TABLE 4 Characteristics of cradle-to-gate direct solid waste streams using terrestrial ores or CCZ nodules

	Mining Phase					Processing & Refining Phase	
Land Ores	**Ecosystem overburden**	**Soil overburden**	**Country-rock overburden**	**Dusts**	**Mine/process tailings**	**Tailings as DSTP**	**Slags and inert byproducts**
Potential to harm	Non-toxic	May become toxic	Some toxic	Some toxic	Some toxic	Toxic	Some toxic
Habitat destination	Original setting or burned	Stored/returned or buried	Relocated similar setting	Resettles	Artificially kept separate	Artificially kept separate	Relocated or kept separate
Relocation effort	Little	Little	Moderate	None	Moderate	Moderate	Moderate
Transformation	May be burned	May acidify	May acidify	None	Mech + chem	Mech + chem	Mech + chem
Ease of mitigation	Standard processes	Standard processes	Standard processes	Windblown, difficult	Large-scale ops, challenging	Remote mgmt. challenging	Can be simple
Operations	None	Monitoring	Monitoring	Monitoring	Perpetual ops	Perpetual ops	None

	Collection Phase		Processing & Refining Phase	
CCZ Nodules	**Displaced sediment**	**Returned material**	**Tailings and residue**	**Inert byproducts**
Potential to harm	May smother	May harm	Some toxic	Non-toxic
Habitat destination	Resettles	Relocated similar setting	Artificially kept separate	Nearby markets
Relocation effort	None	None	Moderate	Short dist.
Transformation	None	None	Mech + chem	Mech + chem
Ease of mitigation	Remote mgmt. challenging	Impact mgmt challenging	Requires active management	Simple
Operations	Monitoring	Simple ops	Perpetual ops	None

stacked for rehabilitation purposes. This can lead to rapid decrease in topsoil quality and quantity—losses of organic carbon, available nitrogen, potassium, and phosphorus, and microbial populations, compounded by compaction and loss of soil structure. Instead, miners can opt for immediate placement of topsoil elsewhere if options exist (Block et al., 2020; Ghose, 2001). Impacts from tailings could be reduced by using new dry stacking technology, or potentially by reprocessing, reusing, or revalorizing them (Benzaazoua & Taha, 2020; Kinnunen et al., 2019, 2021). Some tailings could even be put to good use, as preliminary laboratory-scale tests show ultramafic mine tailings from Cu–Ni–platinum group elements (PGE) could be used to sequester CO_2 (via acid leaching, reaction with elevated concentration of gaseous CO_2, and optimization of tailings pore water saturation) (Hamilton et al., 2020). Additional efforts are underway to reduce the impacts of wastes from terrestrial mining, including improved management of wastes and toxins and restoration of removed and degraded habitats(Service, 2020). Rigorous application of best practices along with new technological development will likely continue to reduce impacts of some terrestrial waste streams.

For nodules, there are opportunities to both reduce wastes and mitigate impacts. Focusing on offshore, collector machines can be optimized to generate much less waste—by using hydraulic collectors instead of mechanical systems, by optimizing hydraulic jet controls to maximize nodule pickup while minimizing sediment disruption, and by discharging sediment in a way that maximizes particle aggregation but minimizes plume spread (more possible for benthic (Spearman et al., 2020) than midwater (Muñoz-Royo et al., 2021) plumes). Sediment waste impacts might also be mitigated through technological innovations, such as artificial substrates and artificial eutrophication (their effectiveness and economy require further study), or through spatial, temporal, and adaptive management of nodule-collection patterns and operations (Cuvelier et al., 2018). The amount of riser material can be reduced by increasing collector sediment separation efficiency, so that most entrained sediment is returned directly at the seafloor; or by filtering out sediment and fines on the collector ship, disposing of them separately. The impact of returned material can also be lessened by choosing an optimal discharge point to minimize disturbance. Determination of this optimal point is the subject of ongoing ecological studies, with a discharge well below the mesopelagic/bathypelagic transition (below ~1000 or 1500–2000 m depth) currently recommended (Drazen et al., 2019, 2020). This depth would minimize harm to human seafood supply and other ecosystem services provided by mesopelagic fauna; reduce plume exposure for most known diurnal or seasonal vertically migrating species; and avoid the oxygen minimum zone, where toxic metals could be remineralized. Near-seafloor discharge would also accomplish those goals, though it would compound the impacts of sediment discharge. In addition, onshore wastes can be reduced by following the principles of negligible waste: with metallurgical designs which use fewer reagents, internally recycle residues, and create locally usable inert byproducts.

TERRESTRIAL ORE WASTE STREAMS / **CCZ NODULE WASTE STREAMS**

SUBSYSTEM RISKS

IMPACT LIKELIHOOD / SEVERITY IF OCCURS (Terrestrial ore waste streams)

	Ecosystem Overburden	Soil Overburden	Country-Rock Overburden	Dusts	Mine & Process Tailings	Tailings as DSTP	Slags and Inert Byproducts
Marine	Unlikely	Unlikely	Unlikely	Rare	Unlikely	Likely	Unlikely
	Minor	Minor	Minor	Minor	Moderate	Moderate	Moderate
Water Supply	Moderate	Likely	Moderate	Unlikely	Unlikely	Unlikely	Moderate
	Moderate	Minor	Major	Minor	Extreme	Moderate	Moderate
Land	Moderate	Moderate	Moderate	Likely	Unlikely	Unlikely	Moderate
	Major	Minor	Moderate	Minor	Extreme	Minor	Minor
Atmospheric	Very Likely	Moderate	Moderate	Moderate	Moderate	Unlikely	Moderate
	Moderate	Minor	Minor	Moderate	Minor	Trivial	Moderate

IMPACT LIKELIHOOD / SEVERITY IF OCCURS (CCZ nodule waste streams)

	Seafloor Sediment	Returned Material	Tailings & Residues	Inert Byproducts
Marine	Likely	Likely	Unlikely	Rare
	Moderate	Minor	Major	Minor
Water Supply	Rare	Rare	Unlikely	Rare
	Trivial	Trivial	Extreme	Minor
Land	Rare	Rare	Unlikely	Rare
	Trivial	Trivial	Extreme	Minor
Atmospheric	Rare	Rare	Moderate	Rare
	Trivial	Trivial	Minor	Minor

IMPACT RISK ASSESSMENT (Terrestrial ore waste streams)

	Ecosystem Overburden	Soil Overburden	Country-Rock Overburden	Dusts	Mine & Process Tailings	Tailings as DSTP	Slags and Inert Byproducts
Marine	Low	Low	Low	Low	Medium	High	Medium
Water Supply	Medium	Medium	High	Low	High	Medium	Medium
Land	High	Medium	Medium	Medium	High	Low	Medium
Atmospheric	High	Medium	Medium	Medium	Medium	Low	Medium

IMPACT RISK ASSESSMENT (CCZ nodule waste streams)

	Seafloor Sediment	Returned Material	Tailings & Residues	Inert Byproducts
Marine	High	Medium	Medium	Low
Water Supply	Very Low	Very Low	High	Low
Land	Very Low	Very Low	High	Low
Atmospheric	Very Low	Very Low	Medium	Low

STAKEHOLDER RISKS

IMPACT LIKELIHOOD / SEVERITY IF OCCURS (Terrestrial ore waste streams)

	Ecosystem Overburden	Soil Overburden	Country-Rock Overburden	Dusts	Mine & Process Tailings	Tailings as DSTP	Slags and Inert Byproducts
Ocean Organisms	Rare	Rare	Rare	Rare	Unlikely	Likely	Unlikely
	Trivial	Trivial	Minor	Minor	Moderate	Major	Moderate
Freshwater Org.	Moderate	Moderate	Unlikely	Unlikely	Unlikely	Rare	Unlikely
	Minor	Minor	Moderate	Minor	Extreme	Moderate	Moderate
Terrestrial Org.	Very Likely	Very Likely	Moderate	Moderate	Unlikely	Rare	Unlikely
	Moderate	Moderate	Moderate	Moderate	Extreme	Moderate	Moderate
Human Inhabitants	Likely	Unlikely	Unlikely	Likely	Unlikely	Unlikely	Unlikely
	Moderate	Moderate	Minor	Moderate	Extreme	Minor	Moderate

IMPACT LIKELIHOOD / SEVERITY IF OCCURS (CCZ nodule waste streams)

	Seafloor Sediment	Returned Material	Tailings & Residues	Inert Byproducts
Ocean Organisms	Likely	Likely	Unlikely	Rare
	Moderate	Minor	Moderate	Minor
Freshwater Org.	Rare	Rare	Unlikely	Rare
	Trivial	Trivial	Extreme	Minor
Terrestrial Org.	Rare	Rare	Unlikely	Rare
	Trivial	Trivial	Extreme	Minor
Human Inhabitants	Rare	Rare	Unlikely	Rare
	Trivial	Trivial	Extreme	Minor

IMPACT RISK ASSESSMENT (Terrestrial ore waste streams)

	Ecosystem Overburden	Soil Overburden	Country-Rock Overburden	Dusts	Mine & Process Tailings	Tailings as DSTP	Slags and Inert Byproducts
Ocean Organisms	Very Low	Very Low	Low	Low	Medium	High	Medium
Freshwater Org.	Medium	Medium	Medium	Low	High	Low	Medium
Terrestrial Org.	High	High	Medium	Medium	High	Low	Medium
Human Inhabitants	High	Medium	Low	High	High	Low	Medium

IMPACT RISK ASSESSMENT (CCZ nodule waste streams)

	Seafloor Sediment	Returned Material	Tailings & Residues	Inert Byproducts
Ocean Organisms	High	Medium	Medium	Low
Freshwater Org.	Very Low	Very Low	High	Low
Terrestrial Org.	Very Low	Very Low	High	Low
Human Inhabitants	Very Low	Very Low	High	Low

IMPACT-RISK LOOKUP MATRIX

LIKELIHOOD \ SEVERITY	Trivial	Minor	Moderate	Major	Extreme
Rare	Very Low	Low	Low	Medium	Medium
Unlikely	Low	Low	Medium	Medium	High
Moderate	Low	Medium	Medium	High	High
Likely	Medium	Medium	High	High	Very High
Very Likely	Medium	High	High	Very High	Very High

FIGURE 3 Likelihoods, severities, and impact-risk assessments of solid waste streams terrestrial ores or CCZ nodules. Likelihood and impact severities were estimated for each waste stream and correspond to impact discussions in the text. For each waste stream, the assigned likelihood (from rare to very likely) and assigned severity (from trivial to extreme) directly map to an impact rating (from very low to very high) via simple lookup, according to the key shown at bottom. For example, the fourth column near the top shows that terrestrial dusts' impact on marine subsystems is rare, and minor if it occurs, leading to a low (green) impact-risk assessment

4 | CONCLUSION

The global challenge ahead—building a new decarbonized energy and transport system—likely means expanding our inventory by billions of tons of metal. Given the anticipated time gap before reaching a circular economy, it is society's duty to be engaged in mid-term supply-chain decisions until we completely cease resource extraction. Understanding the least damaging metal sources requires a comprehensive assessment of impacts across the life cycle. Here we have quantified and analyzed one aspect of a systems-based assessment using terrestrial ores or CCZ nodules—cradle-to-gate direct waste streams.

Comparison of waste tonnage and impacts shows that for most waste streams, use of CCZ nodules may reduce waste quantities and impact-risk severities. Both heavy-metal emissions and the disposal and prolonged management of wastes may be lessened. This result is robust to most sensitivity tests performed, although actual waste profiles of nodule producers will not be known for years.

Substantial uncertainty still surrounds impacts of sediment plumes. The harm imposed by this waste stream would likely be significant, with many investigations underway to understand and mitigate its effects. These results must also be interpreted within an overall systems framework which aggregates various sources of impact to ecosystems, humans, and biodiversity across life cycle stages.

Efforts are underway to improve terrestrial waste and toxin management, reduce release of stored carbon, reduce water consumption, restore habitats, even valorize and productively use some waste streams. Tailings dams can be made safer by compaction, liners, and contingency planning

FIGURE 4 Qualitative and quantitative comparison of solid waste streams for billion-EV scenario. Summary of impact-risk assessment evaluations juxtaposed against 1 billion-EV waste stream quantifications alongside sensitivity analysis results. Terrestrial waste streams include ore-grade dynamics

of downstream communities. In situ leaching techniques reduce solid wastes, though they can also exacerbate groundwater contamination risk. Global adoption of best practices is challenging, as they increase costs in an industry already stressed by falling ore grades, and terrestrial ores' structural characteristics limit impact-mitigation potential. Additional difficulties result from variations in regulatory content and enforcement amongst mining countries, particularly in developing nations.

While the physical characteristics of terrestrial ores and their proximity to human habitation make their risk profile to humans challenging to address, deep-sea mining risks are more directly linked to non-human biodiversity. For nodules, the central challenge may lie in balancing scientific knowledge development with other timing pressures. It is critical to ensure the development and evolution of adequate and adaptive environmental safeguards, while difficult to balance stakeholder priorities within a single inter-governmental institution with limited resources and managed by consensus. Onshore process optimizations will evolve under differing pressures with country-to-country variations in regulatory practice, perhaps closely linked to constituents' appetites for prioritizing ESG.

Comparison of impacts is not straightforward when the ecosystems, impacted humans or wildlife, and impact mechanisms differ greatly. Metal production from nodules would kill creatures attached to nodules, degrade abyssal ecosystems over a large area, and risk harming creatures in the overlying water column. Metal production from land ores currently removes terrestrial habitats over a smaller area with greater depth, releases sequestered organic carbon, and exposes humans and animals to toxins, within highly biodiverse places. With this incongruence of comparisons on biodiversity impacts, waste data can provide an important metric for comparative analysis of impacts from an industrial ecology perspective.

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CONFLICT OF INTEREST

We have inserted a short section in the manuscript that states the source of funding and some expertise as The Metals Company.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supporting information of this article.

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SUPPORTING INFORMATION

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