WHERE SHOULD METALS FOR THE GREEN TRANSITION COME FROM?

Daina Paulikas, MSc | Steven Katona, PhD

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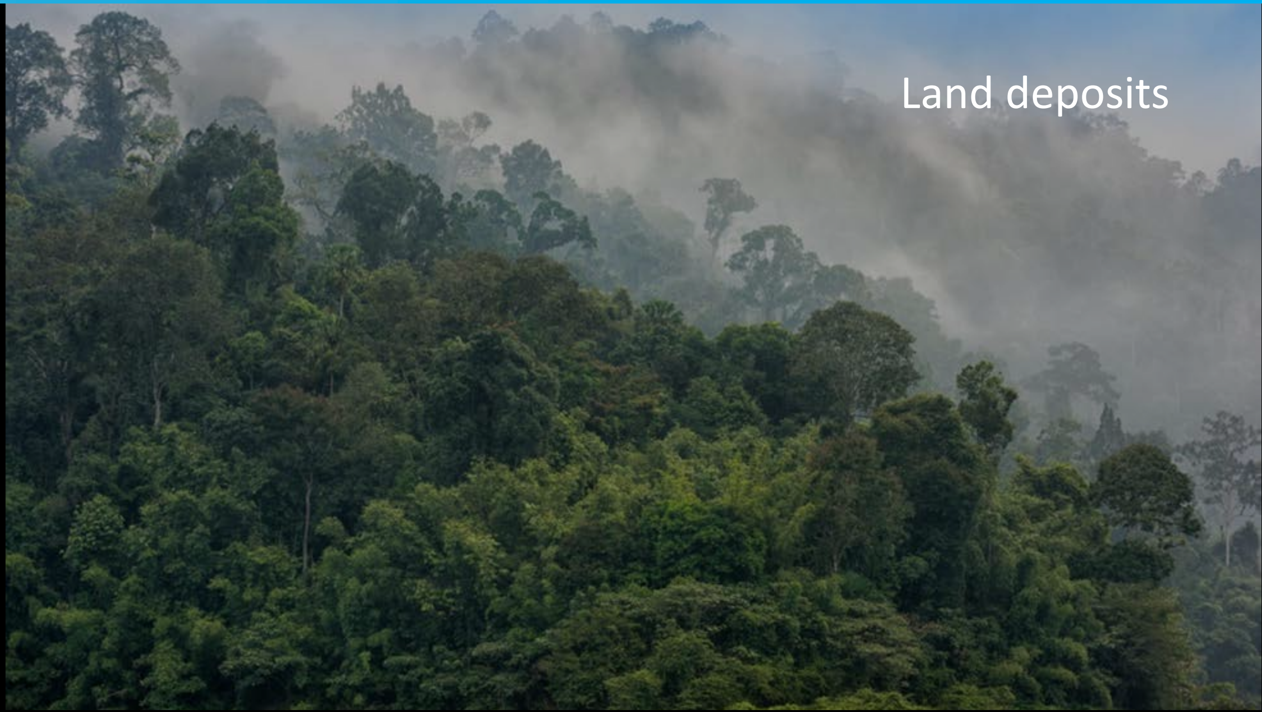
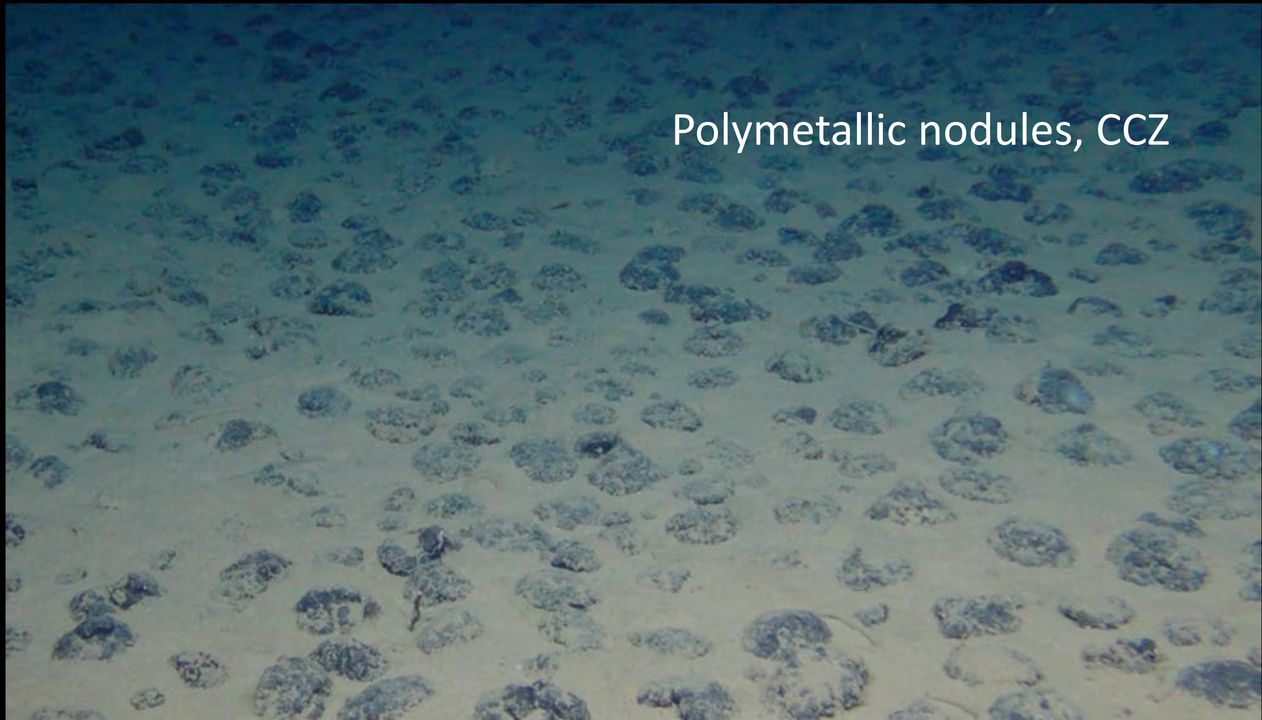




Today’s findings are based on 9 months of primary and secondary analyses by an inter-disciplinary team

WHERE SHOULD METALS FOR THE GREEN TRANSITION COME FROM?

Comparing Environmental and Social Impacts of Supplying Base Metals from Land Ores and Seafloor Polymetallic Nodules

Daina Paulikas, Steven Katona, Erika Ilves, Dr. Greg Stone, Anthony O'Sullivan

July 2019

Daina Paulikas

Strategic and analytical projects; large-scale systems engineering, international economic development, public policy design, human process improvements & artificial intelligence

Dr Steven Katona

Marine biology and ecology; global ecological systems; whale research; ocean health index co-founder; sustainability consultant

Erika Ilves

Strategy; innovation projects in land mining focused on reducing environmental and human impacts through automation, renewables, robotics & machine learning

Tony O’Sullivan

Geology; global base metal exploration on land, mining project development on land and in the ocean

Dr Greg Stone

Ocean conservation; ocean health index co-founder, ocean research and technology, marine protected areas design

The green transition will require millions of tonnes of base metals

CUMULATIVE REQUIREMENT by 2050

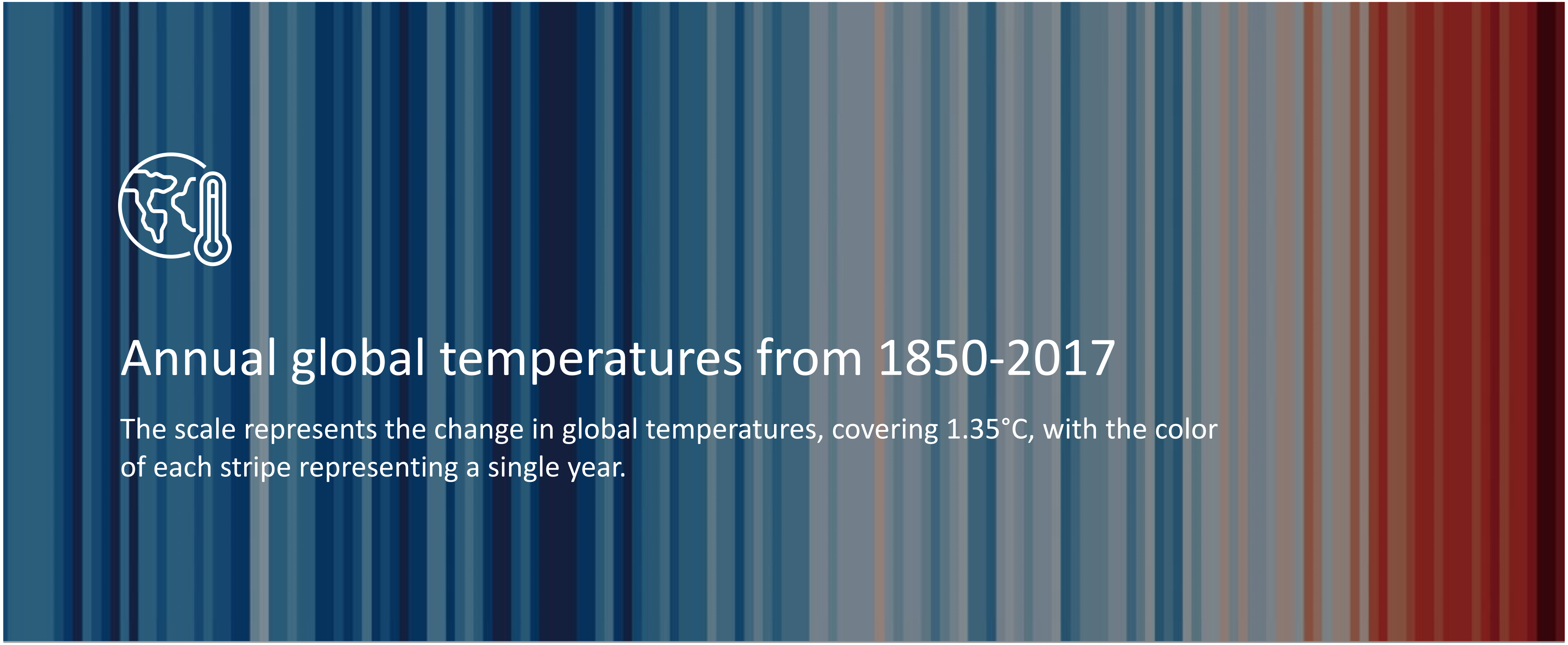
392 million tonnes of Copper

102 million tonnes of Manganese

67 million tonnes of Nickel

7 million tonnes of Cobalt

Understanding the impacts of supplying a new massive demand for metals is critical given the severity of climate crisis…



Annual global temperatures from 1850-2017

The scale represents the change in global temperatures, covering 1.35°C, with the color of each stripe representing a single year.

…and wildlife crisis

IPBES Global Assessment of Biodiversity & Ecosystem Services, May 2019

82%	~50%	1M
reduction in wild animal biomass	area loss for natural ecosystems	species at risk of extinction

Forest clearance in Indonesia. Deforestation destroys wild life habitats.

Photo credit: Ulet Ifansasti/Greenpeace

We focused on the specific case of supplying the electrification of the global passenger fleet…

1 EV

75KWh battery with NMC811 chemistry

85 Kg of Cu

56 Kg of Ni

7 Kg of Co

7 Kg of Mn

1 billion EVs

75KWh battery with NMC811 chemistry

85 million tonnes of Cu

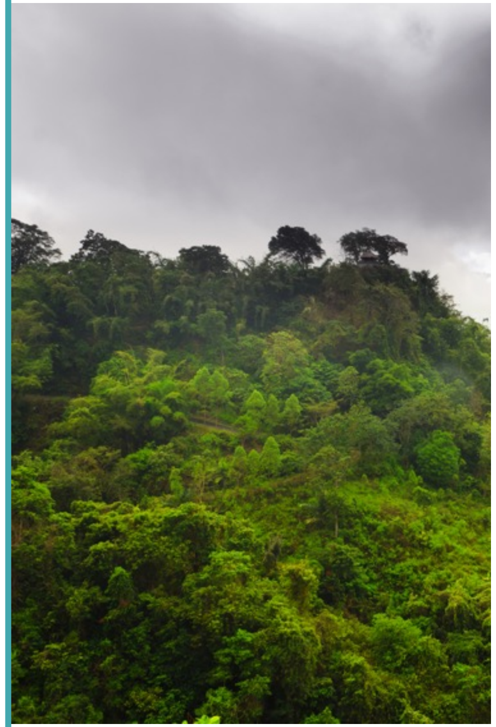
56 million tonnes of Ni

7 million tonnes of Co

7 million tonnes of Mn

…and compared impacts of producing required metal from two primary sources: land ores and ocean nodules

Land



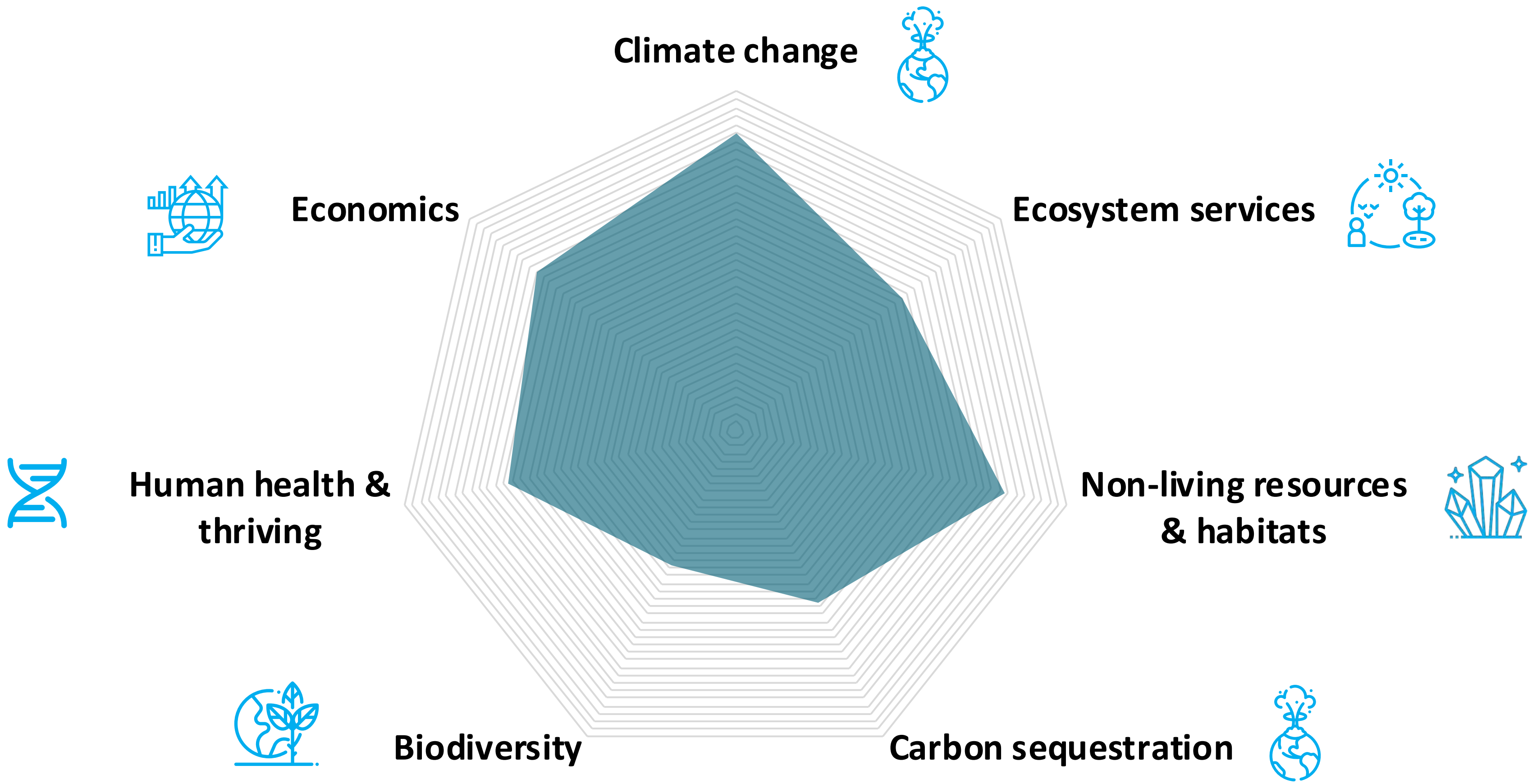
Ocean

Areas of higher biodiversity

Recycling

Insufficent stocks

We assessed seven major impact categories…



…across cradle-to-gate life cycle of four metal products that go into EV manufacturing

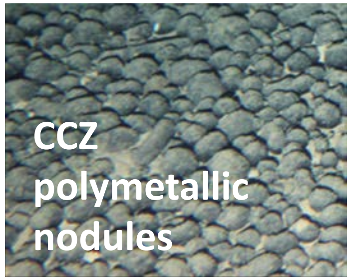
Life cycle assessment

"Cradle" "Gate"

Sources

Land

Ocean



Mining → Processing → Refining

Products

- NiSO4
- CoSO4
- MnSO4
- Cu cathode

Sources

For land ores we relied mainly on secondary research and for nodules we conducted primary analyses on climate change impact

Impact categories	Land ores	Ocean nodules
Climate change & carbon sequestration	Secondary research using peer-reviewed publications of life cycle assessments of nickel, cobalt, manganese, and copper, including van der Voet et al. (2018), Dai et al. (2018), Kuipers et al. (2018), Westfall et al. (2016), and Nuss et al. (2014). Relevant production paths for nickel laterite and sulfide trends from Mudd and Jowitt (2014), International Nickel Study Group (2018); USGS (2018) and Cobalt Institute (2019) for cobalt. Demand projections from Morgan Stanley (2017); ore degradation and fossil fuel projections from e.g., van der Voet et al. (2018) following UNEP GEO-4 and IEA.	**Primary analysis** to create life cycle inventory data for CCZ nodule collection. Sources include: Nori Area D resource assessment; preliminary economic assessments for all four metals; detailed engineering plans, on-land processing and refinery detailed design, input and output flow analyses, and site selection planning; materials and energy flows background database (Ecoinvent v2.2); Morgan Stanley (2017) scenarios for demand; and LCA and LCSA modeling literature such as UNEP (2016) and Guinee et. al. (2016).
Ecosystem services	Followed Pushpam (2010) and Millenium Ecosystem Assessment (2005) standards to collate known impacts across the four major ES categories using extensive literature sources.	Followed Pushpam (2010) and Millenium Ecosystem Assessment (2005) standards to collate known impacts across the four major ES categories using extensive sources such as World Ocean Review (2010).
Non-living resources & habitats	Observed impacts to air, land, water, habitats, and carbon sequestration from broad sources including Dai et al. (2018), ICMM (2012), Singh (2010), Sanamarina et al. (2019), Sauer and Miranda (2010), Blight (2011), EPA (2019), European Environment Agency (2015), and Blacksmith Institute (2007).	Predicted impacts to air, land, water, habitats, and carbon sequestration based on analyses of detailed engineering and nodule processing designs and site selection planning; literature sources e.g., World Ocean Review (2010), Jones et al. (2017); Woods Hole Oceanography Institution, and University of Virginia.
Biodiversity	Data on the number and diversity of species in common terrestrial mining settings from, e.g., Costello and Chaudhary (2017), Zhang (2017), Butler (2016), Royal Botanical Gardens (2019), Veron et. al. (2017), Webster (1977), Horak (2004). Mechanisms of potential and realized impacts from mining from, e.g., EPA (2014), Sonter et. al. (2017), Pena et. al. (2017), Woods (2016), 2019 Goldman Environmental Prize, Mongolia (2019), Miranda and Marques (2016), and Snow Leopard Trust (2018).	Data on the number and diversity of species on the deep-sea floor, particularly CCZ, from, e.g., Ramierz-Llondra et al. (2011), Miller et al. (2018), Simon-Lledo et al. (2019), Purser et al. (2016), Bardgett and van der Putten (2014). Mechanisms of potential impacts from nodule collection from, e.g., Varnreusel et al. (2016), Christiansen et al. (2019), Secretariat of the Pacific Community (2013), Robinson (2009), GSR (2018), Paul et al. (2018), Jones et al. (2017), and Danovaro et al. (2008).
Human health & thriving	Past impacts to human health and communities collected from Lang (2010), International Manganese Institute Risk and Policy Analysts (2015), Department of Mineral Resources, South Africa (2017), ENCA (2015), Mine Safety and Health Administration (2019), Seymour (2005), Pure Earth and Green Cross Switzerland (2016), World Bank Group (2005), Aldana and Abate (2016), and others.	Potential impacts to human health and communities isolated due to CCZ's remoteness from human communities. Impacts analyzed based on known attributes of the CCZ. Ship-related human health issues modeled using literature sources e.g., the European Marine Safety Agency (2018) and Allianz (2015).
Economics	Price impacts and national economy impacts based on analyses of C1 cost curves and future market projections for each metal, including position of individual countries' operations on the cost curve, metals' elasticity of demand, production volumes, GDP data, costs of mine reclamation, and risks of mine collapse.	Price impacts and national economy impacts based on analyses preliminary economic assessments and detailed engineering plans, C1 cost curves and future market projections for each metal, position of nodule metals on the cost curve, metals' elasticity of demand, production volumes, GDP data, and ISA's proposed royalties and sponsor-country contributions plan.

Land ores / production process

Producing metals from land-ores is an energy-intensive process with serious impacts at every step

Mineral Resources in Land or Ocean

Mining

Remove metal ores from the earth. May crush and/or concentrate boulders into higher grades.

Transport

Mineral Ores, Medium Grade Concentrates

Processing

Use water, heat or chemical based processes to separate out metal compounds.

Transport

Metal Intermediates

Refining

Refine metals from intermediary forms into pure metals or alloys.

Final Metals or Alloys ready for Manufacture

Key potential impacts

Mining:
- Tailings generation
- Risk to downstream communities
- Biodiversity loss
- CO_2 emissions
- SO_x and NO_x emissions
- Acid drainage
- Freshwater contamination
- Freshwater depletion
- Human death & illness
- Habitat loss and degradation
- Topsoil loss
- Deforestation
- Carbon sequestration impact
- Vulnerable pop. exploitation
- Community relocation
- Wasterock generation
- Marine water pollution
- Noise pollution

Processing:
- Fossil fuel-based electricity
- CO_2 emissions (direct)
- SO_x & NO_x emissions (direct)
- CO_2 emissions (materials)
- Tailings generation
- Residue, waste, slag generation
- Toxic chemicals release
- Acid drainage
- Freshwater depletion
- Freshwater contamination

Refining:
- Fossil fuel-based electricity
- CO_2 emissions (direct)
- SO_x & NO_x emissions (direct)
- CO_2 emissions (materials)
- Tailings generation
- Residue, waste, slag generation
- Toxic chemicals release
- Acid drainage
- Freshwater depletion
- Freshwater contamination

Ocean nodules / production process

Producing metals from polymetallic nodules has a different operational and impact profile both during mining as well as processing & refining

Polymetallic Nodules on Sea Floor

Mining

Collect nodules from the seabed floor and transport to the surface using a vertical lift system.

Ship Transport

Wet Nodules

Processing

Use heat and chemical based processes to separate out metal compounds.

Transport

Metal Intermediates

Refining

Refine metals from intermediary forms into metal products that go directly into EV battery production

Final Alloys ready for Manufacture

Key potential impacts

Mining	Processing	Refining
CO_2 emissions SO_x & NO_x emissions Biodiversity loss Nodule removal Sediment resuspension and deposition Compaction of surface sediment Discharge of sediment and water Underwater noise Surface vessel's noise, light & waste	CO_2 emissions (direct) CO_2 emissions (materials) SO_x emissions (direct) Disruption of carbon sequestration (land use)	CO_2 emissions (direct) CO_2 emissions (materials)

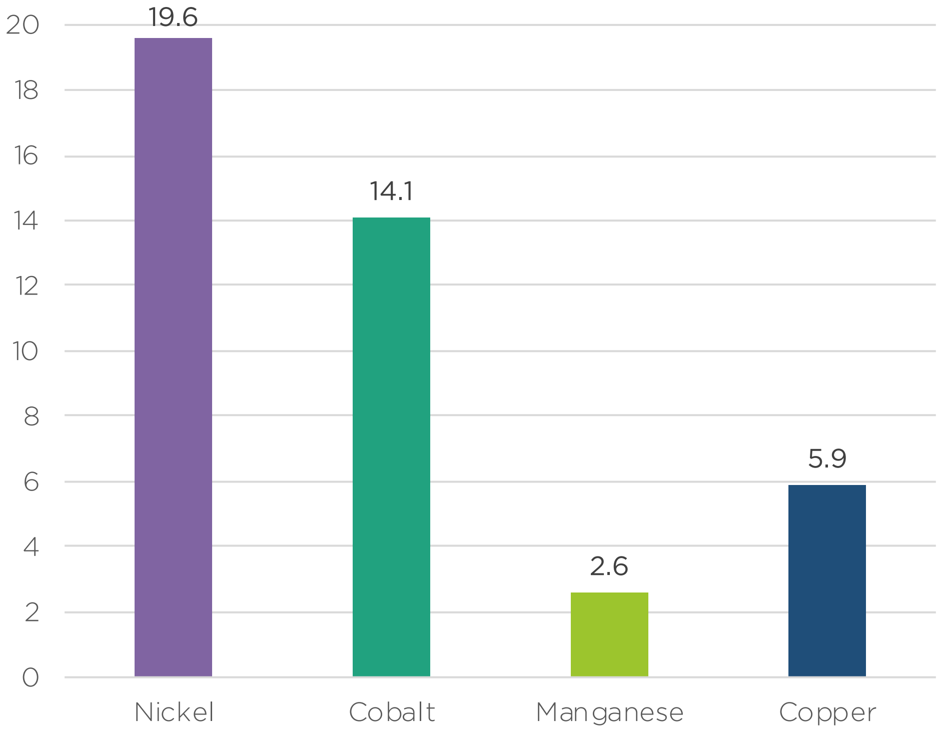
Climate change

‘Global Warming Potential’ or GWP

Cradle-to-gate, every kg of EV metals produced from land ores today generates 2-20 kg of greenhouse gas emissions

Climate change impact of metal production from conventional land ores

kg of CO_2e / per kg of metal



Business as usual scenario

Continuing current situation assuming:

- No depletion of the world's resources and no technology improvements
- Today's mix of electricity
- Today's production pathways
- Today's ore grades

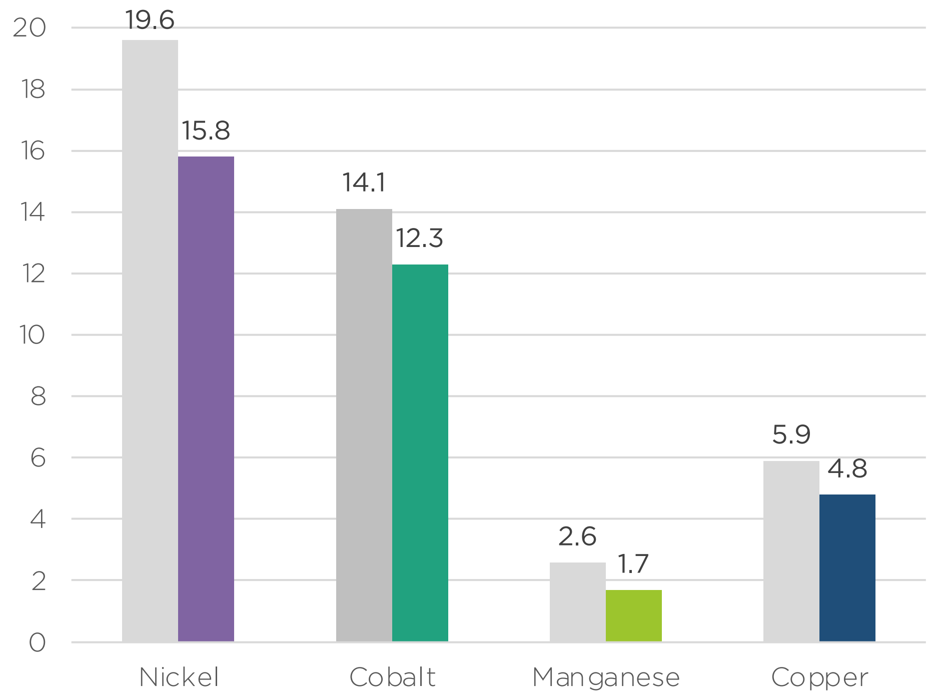
Emissions allocated based on the economic value of the product – the more valuable the product, the higher its CO_2 allocation

Land ores

It is possible for miners to invest in significant improvements but most of the gains will be offset by declining ore grades

Climate change impact of metal production from conventional land ores

kg of CO_2e / per kg of metal



Green mining scenario

Rapid and ambitious transformation assuming:

- Strong global policy actions to limit temp increase to 2 degrees C
- Reduction in fossil fuel share of electricity, from 70% in 2019 to 43% in 2047
- Energy efficiency gains in Cu production towards practical minimum
- Ore grade continue to fall – Ni from 1.25% to 1.0%, Cu from 0.7% to 0.45% by 2047. Increases energy needs, emissions & waste

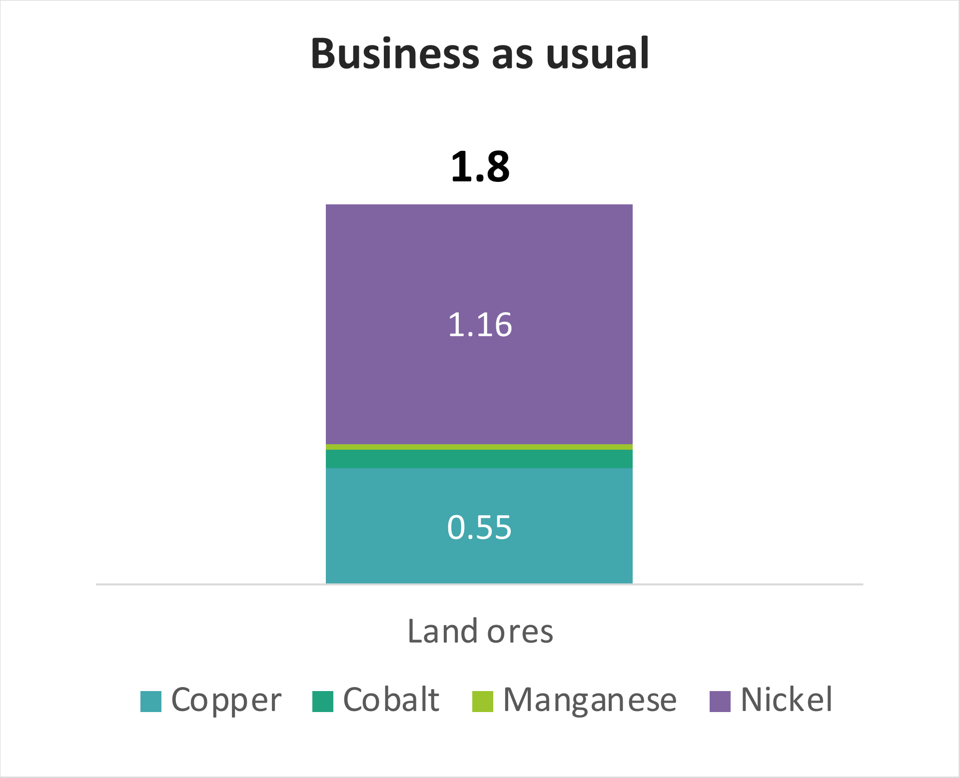
Scenario integrates IEA WEO “450 Scenario,” UNEP GEO-4 “Equitability First Scenario,” and literature on ore grades and production efficiency

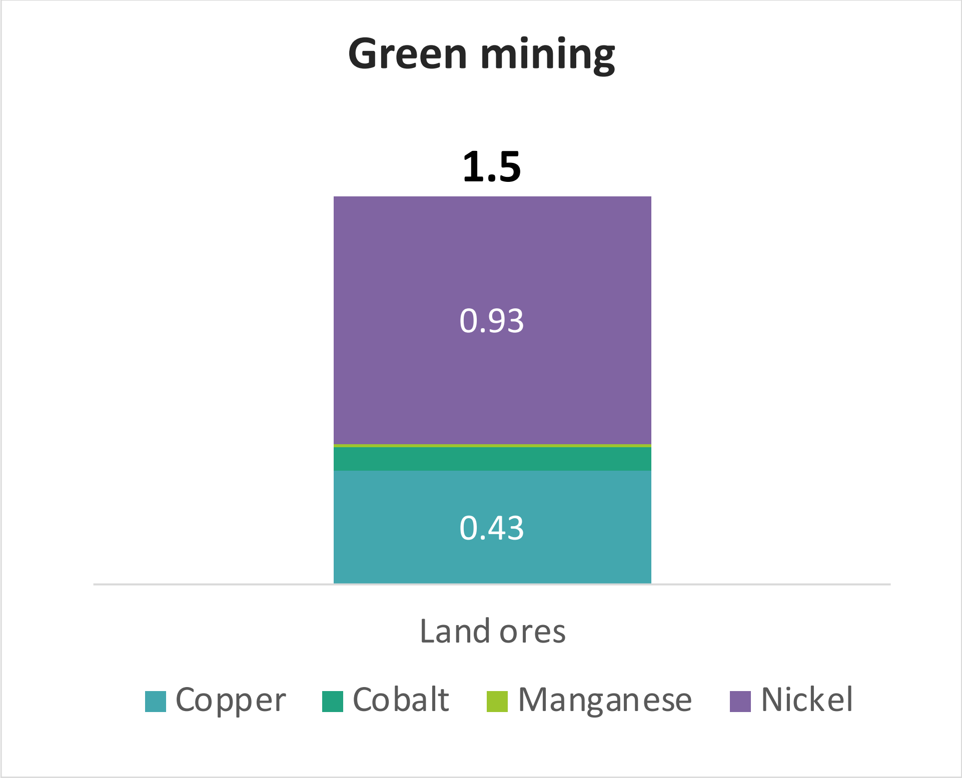
Land ores

Supplying 1 billion EVs with metals produced from land ores will add gigatons of CO_2e even in the most ambitious green scenario

Electrifying 1 billion vehicles

Gigatonnes of CO_2e attributable to production of battery cathode metals and copper 2018-2047



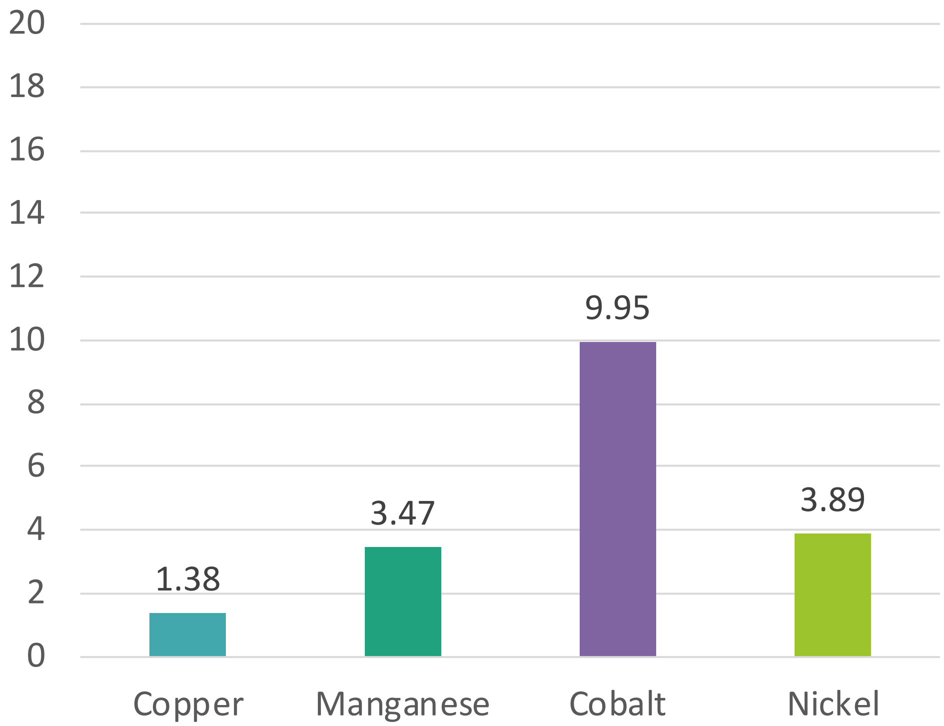


Ocean nodules

Cradle-to-gate, every kg of EV metals produced from nodules will produce 1-10 kg CO_2e

Climate change impact of metal production from ocean nodules

kg of CO_2e / per kg of metal



Base case scenario

Based on planned concepts of operations and independent preliminary economic analysis

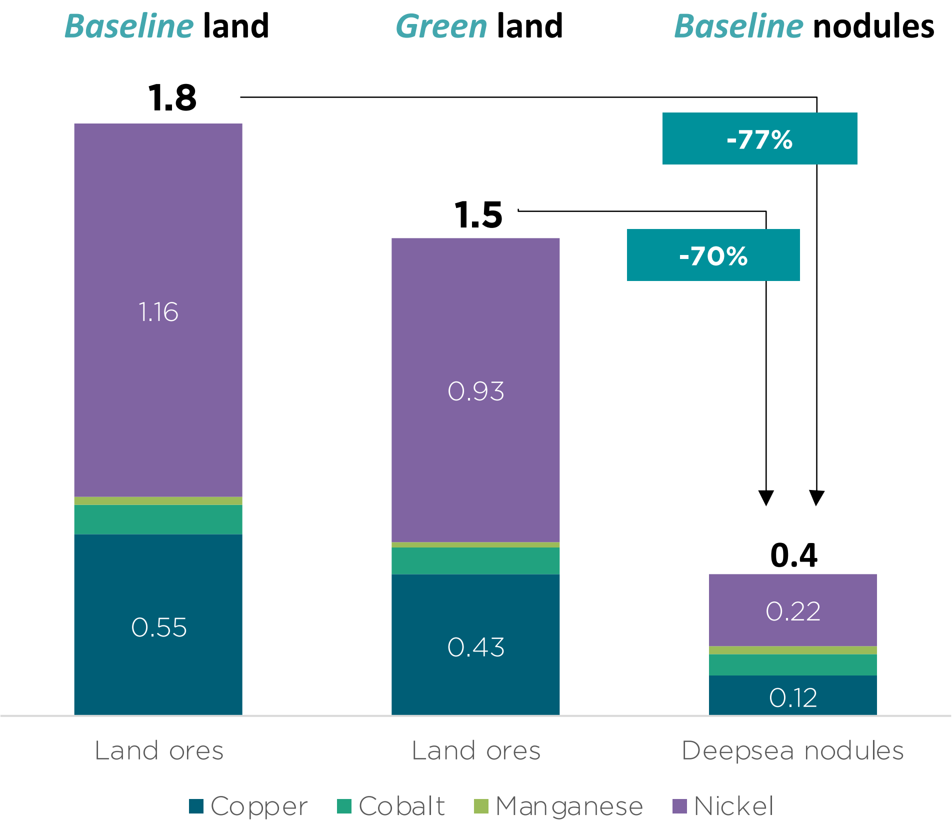
- High-volume offshore nodule collection system using tracked seabed harvesters with hydraulic collection tools, sediment separation and vertical lift system (riser) to the surface
- Processing & refining flowsheet designed for zero solid waste
- Onshore sites selected based on proximity to customers and access to hydropower

Emissions allocated based on the economic value of the product – the more valuable the product, the higher its CO_2 allocation. If, instead, allocating by mass, Cobalt and Nickel drop < 2 kg CO_2e.

Supplying 1 billion EVs with metals produced from ocean nodules will save 1-1.5 gigatonnes of CO_2e—with options to get to ‘net zero’

Electrifying 1 billion vehicles

Gigatonnes of CO_2e attributable to production of battery cathode metals and copper 2018-2047



Pathways for nodules to get to net zero CO_2e emissions

- Using excess power from oversized renewable plants to produce zero-CO_2 fuels to power offshore operations
- Using excess renewable power to produce alternates (e.g., hydrogen) for use as a reductant in place of coal – the largest single CO_2e driver in nodules processing
- Other ongoing exploration of technologies and pathways to get to net-zero CO_2 onshore operations as the industry matures

Ecosystem Services

Ecosystem services

Land-mining negatively impacts most ecosystem services

Ecosystem Service Category	Land ores		Ocean Nodules	
Provisioning				
Food	red	Habitat cleared. Erosion. Toxins	grey	Low or none
Water	red	Excessive withdrawal. Pollution	grey	Little water for processing
Raw materials (e.g., wood, fiber)	orange	Loss of trees and vegetation	grey	Low second order effects
Genetic resources	orange	Potential loss of endemic species	orange	Possible, but uncertain
Medicinal Resources	orange	Potential loss of endemic species	orange	Possible, but uncertain
Ornamental Resources	orange	Damage to vegetation and species	grey	Low or none
Regulating				
Air Quality Regulation	red	Blasting and toxic dusts, particulates, emissions	orange	Some from vessel, refining
Climate Regulation	orange	Loss of soil and vegetation	grey	Low or none
Moderation of Extreme Events	orange	Loss of soil and vegetation	grey	Low or none
Regulation of Water Flows	red	Water drawdown and pollution	orange	Water for processing
Waste Treatment	orange	Loss of soil and vegetation	grey	Low or none
Erosion Prevention	orange	Loss of soil and vegetation	grey	Low or none
Maintenance of Soil Fertility	red	Toxic dusts, polluted water, vegetation	grey	Low or none
Pollination	orange	Vegetation loss, toxic dusts and water	grey	Low or none
Biological control	orange	Harm to vegetation and aquatic life	orange	Possible, but uncertain
Habitat				
Habitat for Resident/Migr Species	red	Noise, pollution, vegetation loss, tailings dams	orange	Noise, light, substrate loss
Maintenance of Genetic Diversity	orange	Potential loss of endemic species	orange	Possible species loss
Cultural				
Aesthetic Information	red	Excavation, noise, species loss	grey	Low or none
Opp. for Recreation & Tourism	red	Exclusion areas, fish kills, noise	grey	Low or none
Inspirational Culture, Arts, Design	green	Jewelry, tools, lore, books, films	grey	Low or none
Spiritual Experience	red	Harm to/exclusion from sacred sites	grey	Low or none
Info. for Cognitive Development	green	Has stimulated technological developments	green	Science, knowledge, tech growth

green: May positively impact an ES
orange: May have moderate negative impact on an ES
red: May have serious negative impact on an ES
grey: Low or no impact on an ES

Non-living resources

Non-living resources

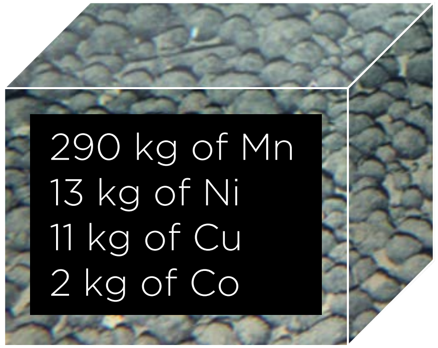
3.4 times more ore needs to be dug out on land to get at the metals contained in 1 tonne of nodules

Land

3,440 kg

Ocean nodules

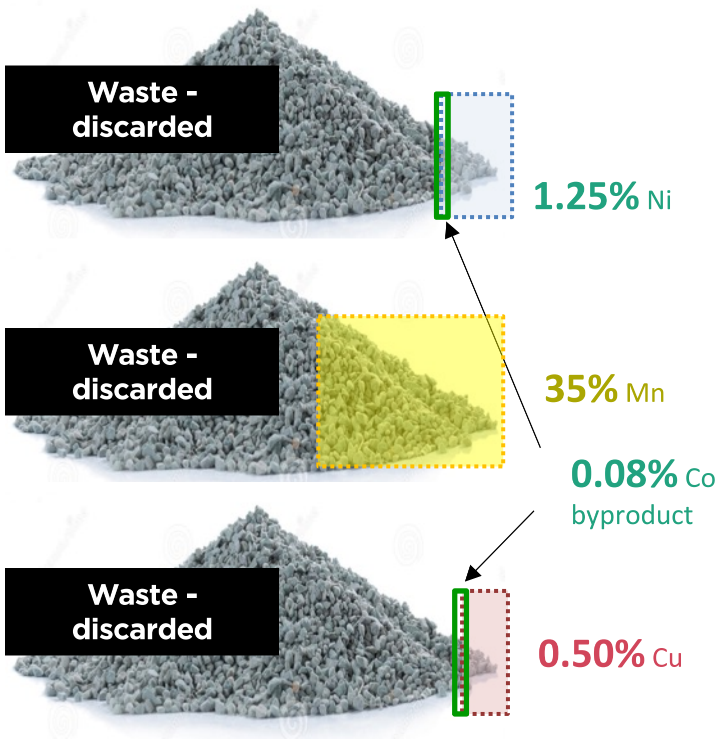
1,000 kg



This is because three types of ore bodies need to be mined on land to get at metal contained in nodules

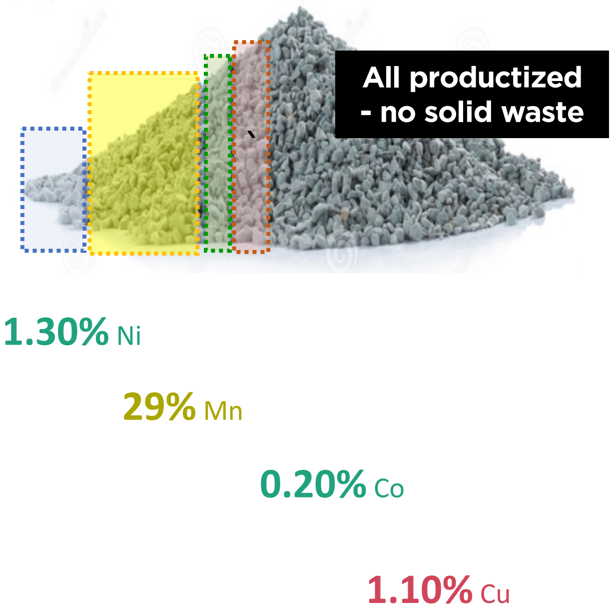
Land

Average grades of mined ores
% of mined tonnage



Ocean nodules

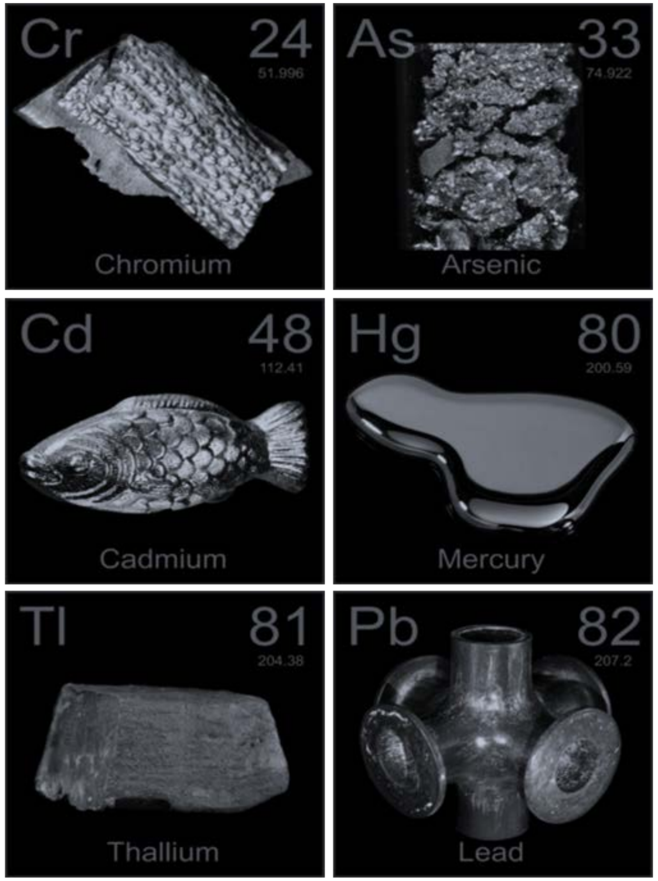
Average grades of CCZ nodules
% of total tonnage



Non-living resources

Land ores typically contain heavy metals in toxic concentrations—not found in nodules

Land



Ocean nodules

Contain non-toxic trace amounts of heavy metals (parts per million) that don’t require removal

Non-living resources

As a result, land mining generates toxic tailings and waste streams that can contaminate local and regional habitats

Land	Ocean nodules

0 tonnes

for 1 billion EVs

Non-living resources

Depletion of freshwater is a major issue for land mining, less critical for nodules

Land

- Milling, flotation, separation of ores
- Hydraulic / slurry transport
- Dust suppression
- Leaching
- Heating and cooling
- Electro-refining
- Tailings management
- Granulation
- Revegetation
- Wastewater
- Employee needs

Ocean nodules

- Heating and cooling
- Granulation
- Employee needs

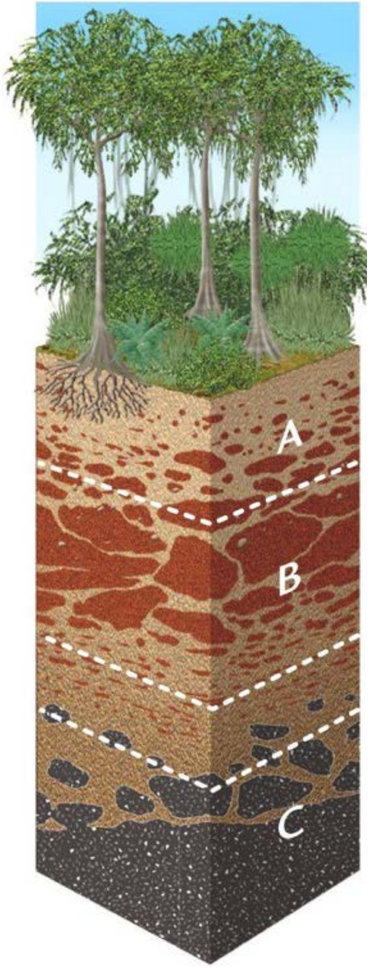
5 km³

for 1 billion EVs

Carbon Sequestration

Carbon sequestration

To understand impacts on carbon sequestration, we need to understand where carbon is stored



2,300 gigatons

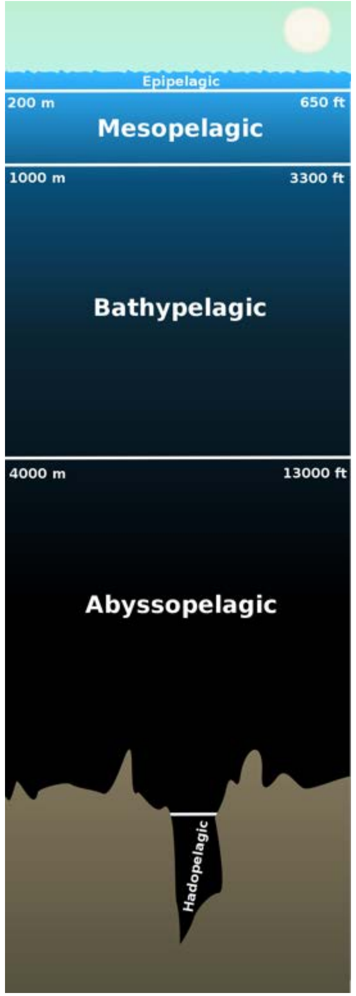
of carbon stored in vegetation, soil & detritus on planet Earth

130 million km^2

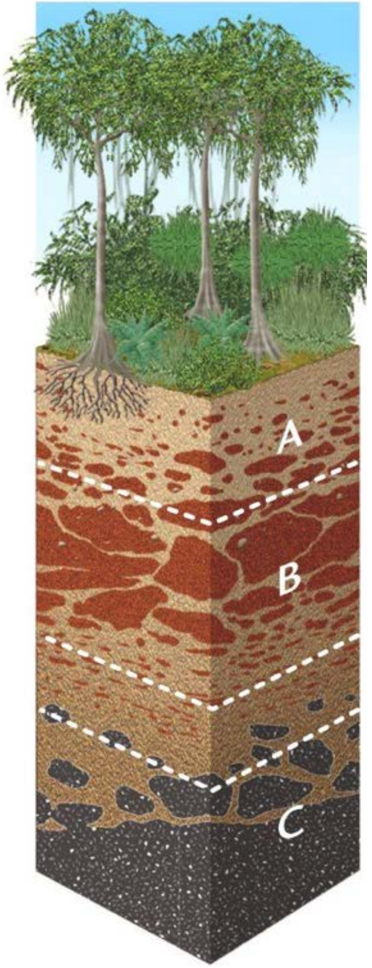
150 gigatons

of carbon stored in seabed surface sediments on planet Earth

354 million km^2



Sourcing metals for 1 billion EVs from land ores will put 2.2 gigatons of stored carbon at risk (=potential release of 8.1 Gt CO_2)



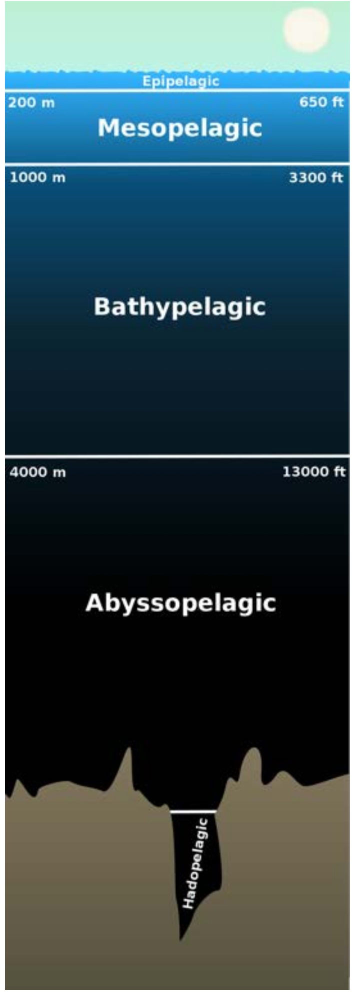
8.1 gigatons

of CO_2 is at risk of release from removing vegetation & soil ("overburden")

135,000 km^2
land area impacted by mining for 1B EVs

~15,700 tonnes of organic carbon
stored on average per km^2 of soil & vegetation across all terrestrial biomes

Sourcing same amount of metals from nodules will risk near zero carbon offshore and ~0.16 Gt C onshore (=potential release of 0.6 Gt CO_2)



~0 gigatons

of CO_2 at risk from pumping water or disturbing the seabed sediments

~0.00016 gigatonnes of CO_2

at risk of from depressurization of deep seawater pumped to surface for 1B EVs

470,000 km²

seabed impacted by mining for 1B EVs (0.1% of global seabed)

~424 tonnes of organic carbon

stored on average per km2 of seabed surface sediments – but, these carbon-containing sediment particles do not reach the surface …

0.6 gigatons

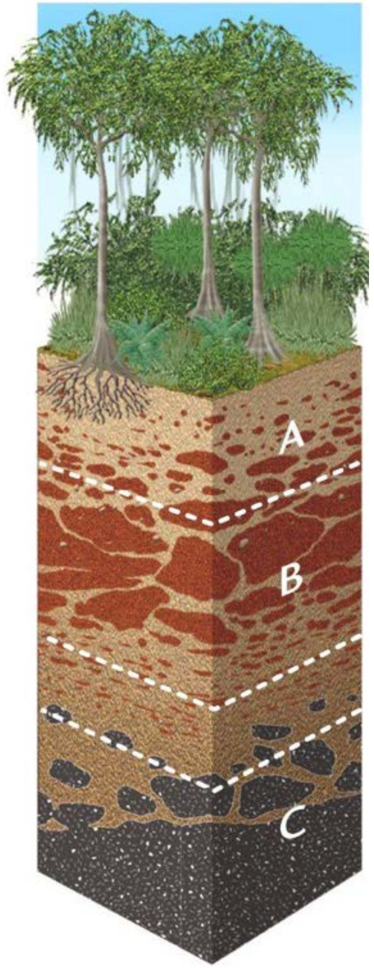
of CO_2 at risk from land use for processing & refining nodules

10,000 km²

land area impacted by processing and refining nodules for 1B EVs

~15,700 tonnes of organic carbon

stored on average per km2 of soil & vegetation across all terrestrial biomes



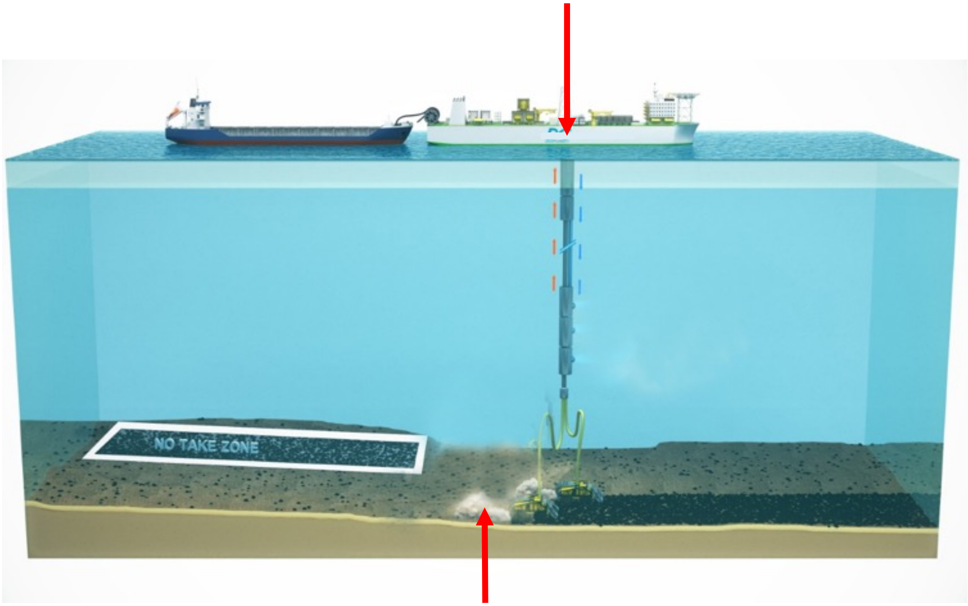
This is because carbon-bearing seabed sediments resettle on the seabed, carbon at risk of release from pumped deep seawater is negligible

Carbon in solution in deep seawater

Stored in ocean: **28 tons/** km^3

At risk by nodule transfer to the surface: **0.00016 gigatons of CO_2**

Why: deep seawater (higher carbon) pumped to the surface, exposed to atmosphere for up to 5 min before it is reinjected in midwater



Carbon in sediments

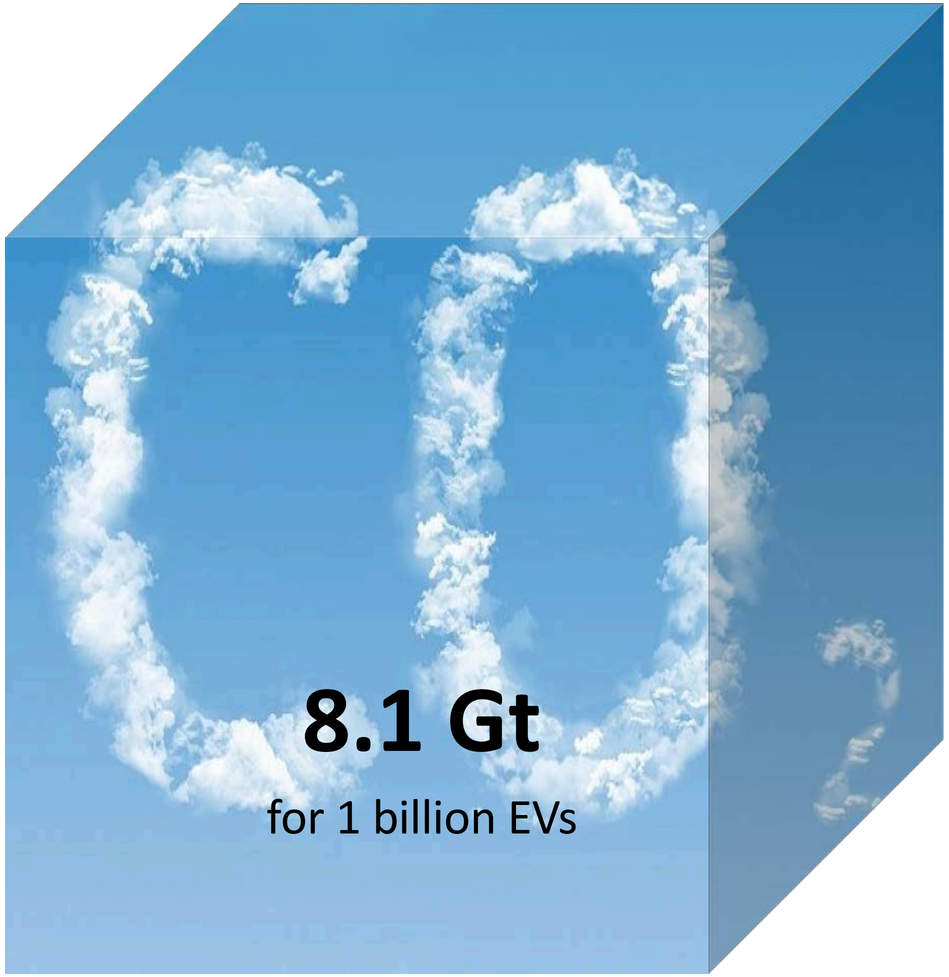
Stored in 470,000 km^2**: 0.2 gigatonnes**

At risk from nodule collection: **close to zero**

Why: sediment rises max 200m above seabed and resettles

Carbon sequestration

Land mining risks 14x more CO_2 release into the atmosphere from disturbing stored carbon than nodules



0.6 Gt

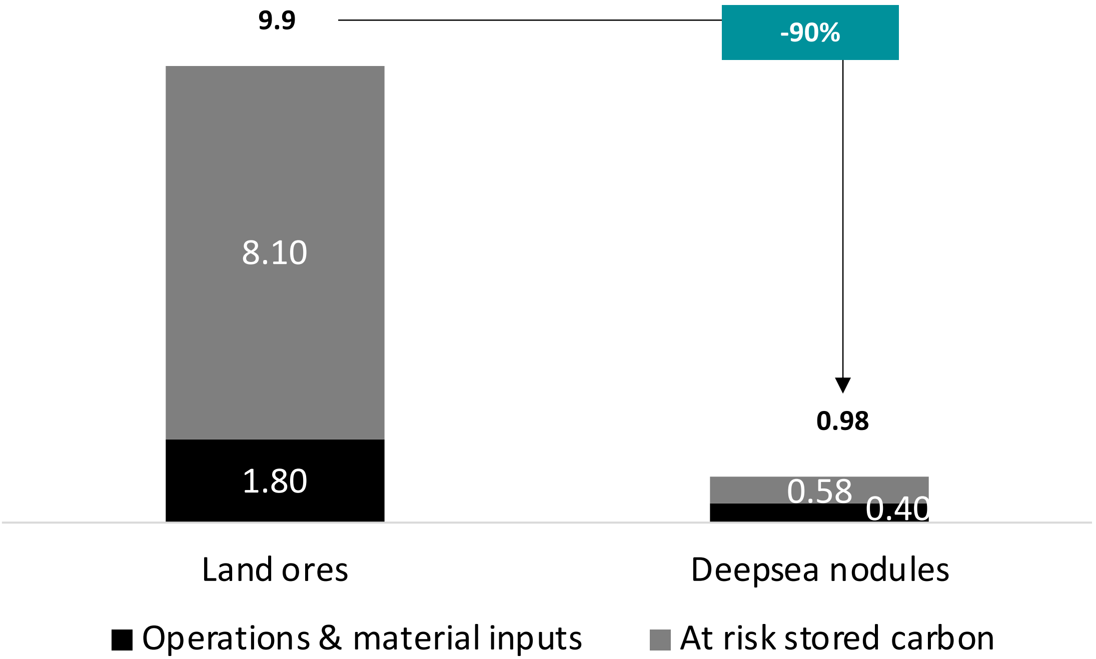
for 1 billion EVs

Climate change & disruption of carbon sequestration

In total, sourcing metals from nodules could reduce CO_2e impact by 90%

Electrifying 1 billion vehicles

Gigatonnes of CO_2e attributable to production of battery cathode metals and copper 2018-2047



Biodiversity

Despite the vastness of the ocean, there are six times more species on land, most still to be scientifically described

9-20 million species on Earth

~1.8 million species described scientifically

Land

29% of the surface area

Est. 8-17 million species

~6x more species than in the ocean

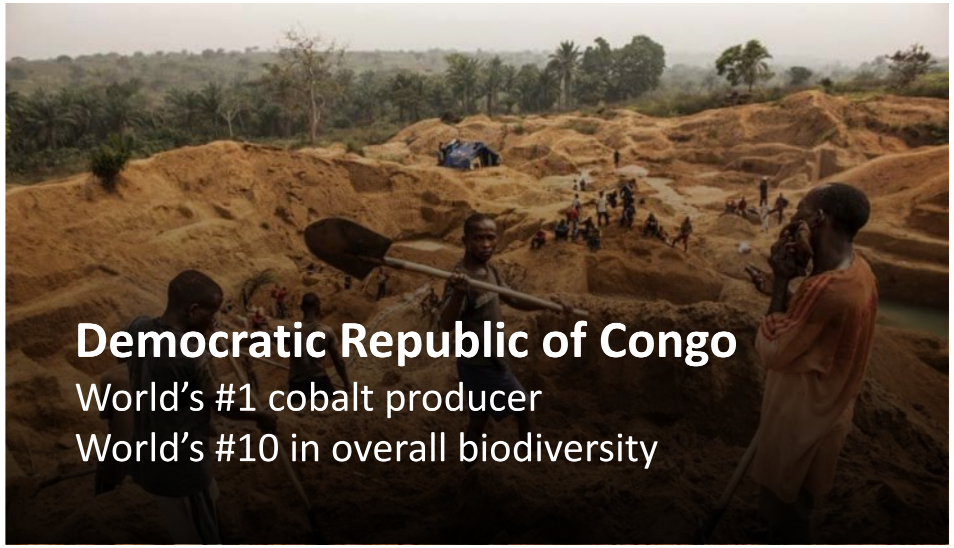
Ocean

71% of the surface area

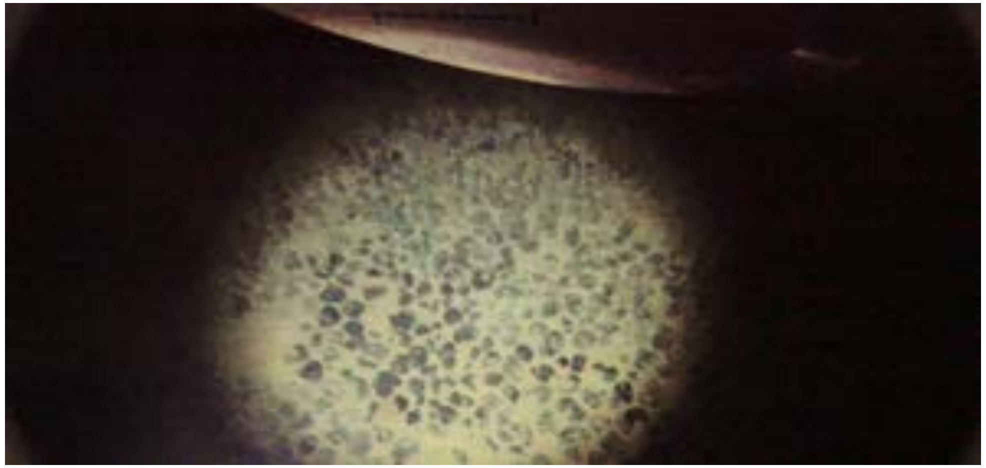
Est. 1-3 million species

Biodiversity

Mining of base metals on land has moved to some of the most biodiverse places on planet Earth



Exploration for nodules is currently taking place in a harsh, slow-changing and food-poor environment



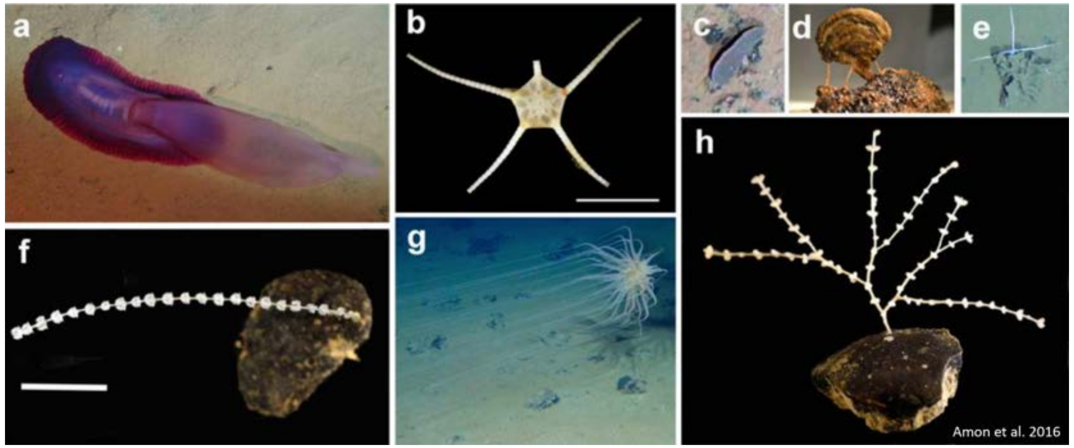
Physical environment

- 3,800-5,500 meters depth
- Intense pressure (5,700-8,500 psi)
- Vast sedimentary seabed, oxic to 200 cm
- Gentle depressions, troughs, ridges,
- No sound or light except made by animals
- Variable coverage of nodules (avg. ~15 wet kg/m^2)

Ecological environment

- Stable, food-poor, dependent on particles sinking from oligotrophic surface waters

Fascinating species have been discovered in the CCZ



Megafauna

a. Holothurian
b. Serpent star
c. E Multi-nucleate, test-building single-celled organisms
d. Soft coral
e. Relicanthus, new order of Cnidaria
f. Soft coral

Credit: Amon et al. 21016

Meiofauna

Meiofauna include many tiny species that live in between grains of sediment or sand.

Credit: C.R. McClain. 2010. An empire without food. Amer. Sci. 98(6)

Biodiversity

Wildlife impacted by mining on land is very different from wildlife that would be impacted in the deep sea

Megafauna definitions

>40-45 kg	>2 cm
weight	size

Individual organisms per m^2

~232,000

- min estimated number of organisms per m^2 of soil
- Estimate includes nematodes, enchytraids, colembolans, mites, isopods, diplopods, and Earthworms
- Estimate excludes prokaryotes, fungi, arbuscular mycorrhizal species, protists

600

median organisms per m^2 of abyssal sediments

Biodiversity

How do we trade off lives of different species?

Tarsius Tarsier

The Danagat-Caraga Tarsier, discovered in

the 1970s, lives only on Danagat Is., Philippines,

and is threated by 10 companies mine nickel ore

Photo credit: Futurity.org

Sea cucumber

Photo credit ROV Kiel 6000, GEOMAR Helmholtz Centre for Ocean Research Kiel

Biodiversity

Biodiversity impacts are not easily quantifiable but species extinction is a risk for both land and nodule mining

Land

Mining - land → Processing → Refining

Mining - land	Processing / Refining
Species extinction risk Habitat removal Habitat degradation	**Species extinction risk** Habitat degradation from chemical pollution Indirect impact from worsening climate change through CO2e emissions from operations and risking release of sequestered carbon

Nodules

Mining – deep sea → Processing → Refining

Mining – deep sea	Processing / Refining
Species extinction risk Habitat removal Habitat degradation	**Species extinction risk** Indirect impact from worsening climate change through CO2e emissions from operations and risking release of sequestered carbon

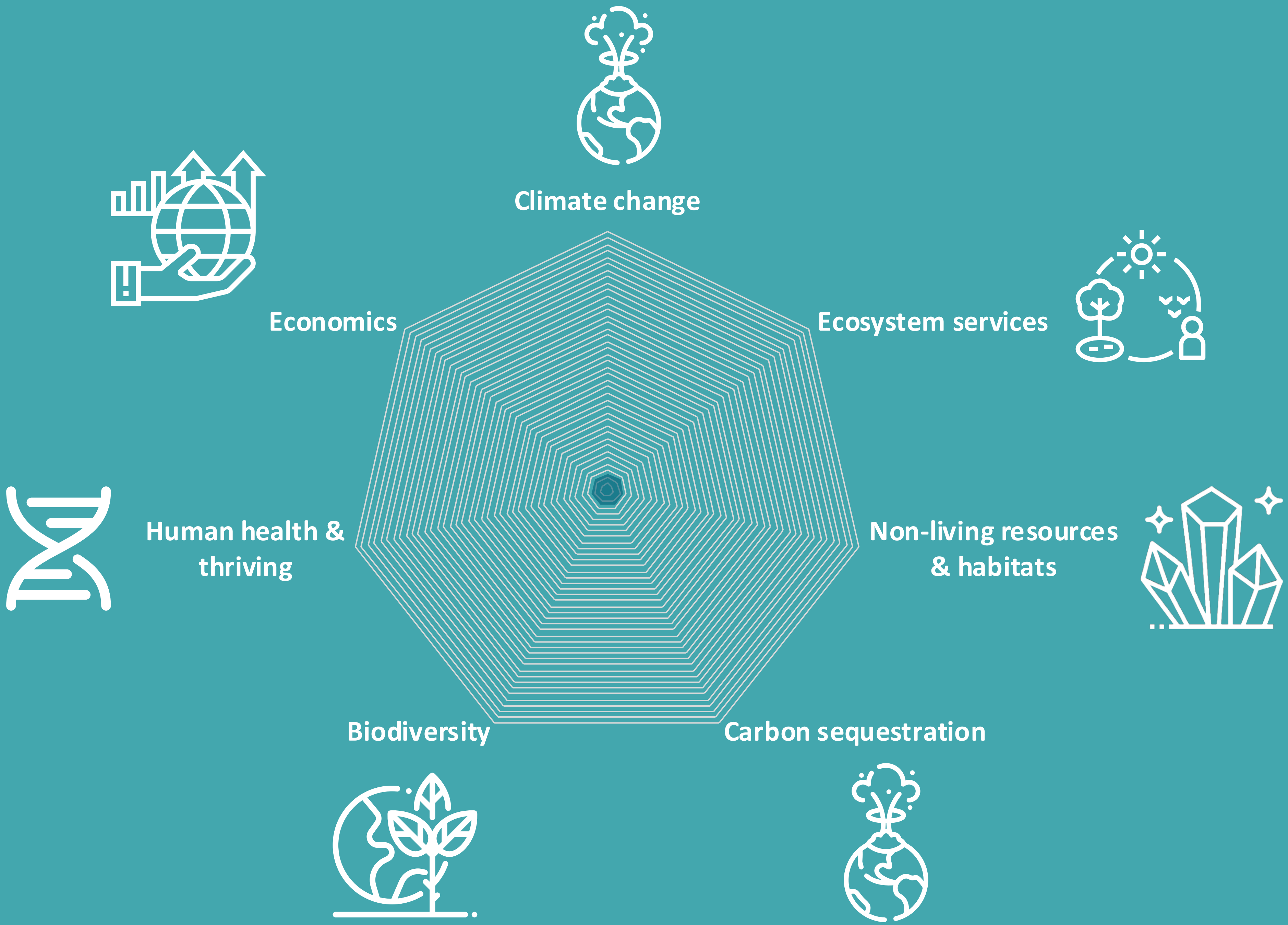
Human health & thriving

Human health & thriving

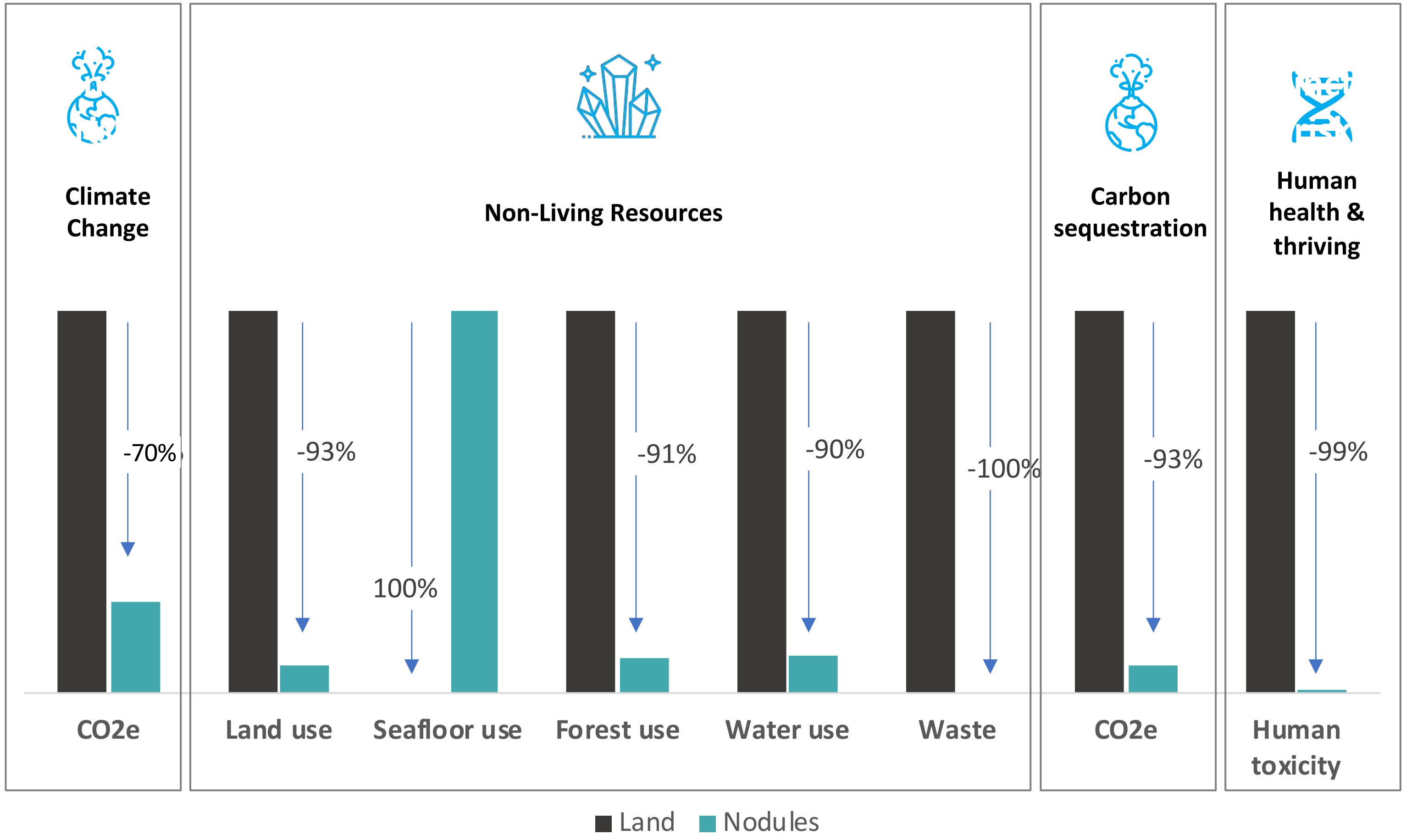
Land mining for equivalent metals causes hundreds of human deaths per year due to rock falls, terrace collapses and other accidents

Human health & thriving

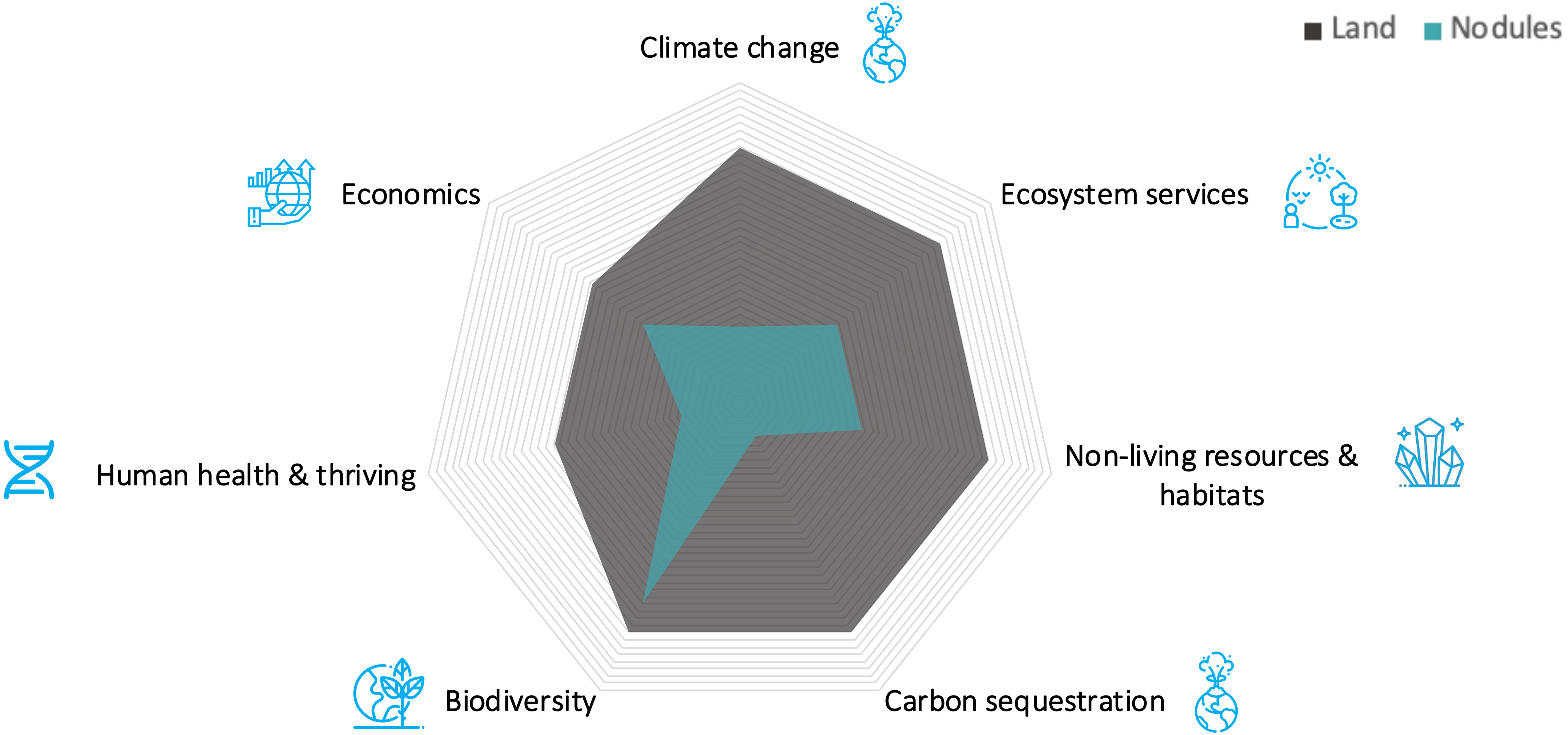
Artisanal cobalt mining in the DRC where 60% of cobalt is sourced can involve child labor


Climate change
Ecosystem services
Non-living resources & habitats
Carbon sequestration
Biodiversity
Human health & thriving
Economics

Quantitative comparison of several impacts of metal production for 1 billion EV batteries sourced from land vs. nodules



Comparing the impacts of EV metal production across all major impact categories



Zero impact mining is not possible, anywhere.

Unfortunately.

The question we should be asking:

Where can we source metals with the least harm?

Think whole Earth.

Think life cycle analysis.

Across major impact categories.

THANK YOU

Daina Paulikas, MSc | Steven Katona, PhD

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