2.6 Ga old BIF, Tom Price Mine WA

Natural History Museum

Exploring for truly net positive outcomes

Professor Richard Herrington

Science Lead, Resourcing the Green Economy
The Natural History Museum
Cromwell Road
London SW7 5BD, UK

Geological Collections

- Collection of >185,00 mineral specimens – many types
- Systematically collected
- Library of natural materials - variable chemistries and properties
- Actively studied and used as a reference collection

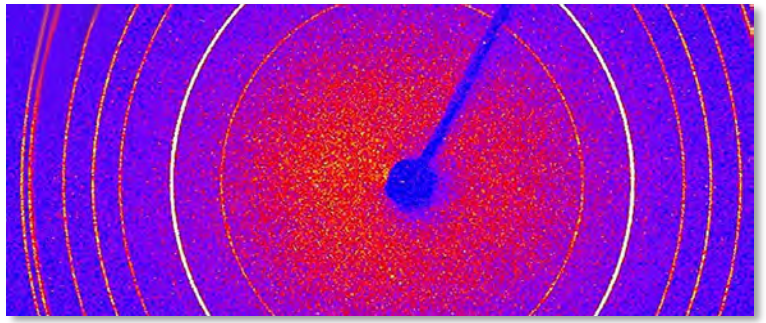
Ga-rich sphalerite ZnS

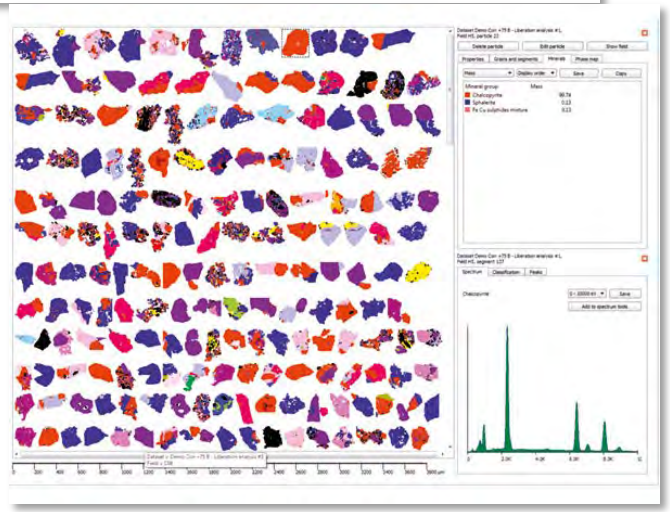
Jadarite $LiNaSiB_3O_7(OH)$

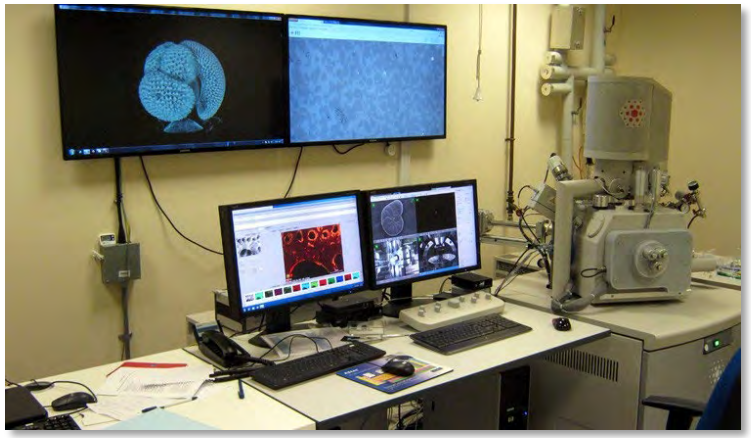
Kunzite $LiAl(SiO_3)_2$

- Meteorites
- Minerals
- Ore and rock collections

Advanced Geological Analytical Infrastructure







Projects - Mining related project portfolio

Minerals-related research projects (ca. £50 million in last 5 years - >£6.5 million to NHM)

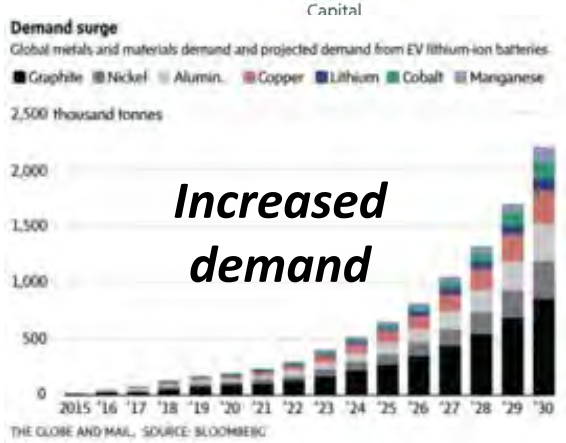
- £500k *Innovate UK* Li4UK – investigating potential UK lithium sources – **future positive mining**
- £2.5 million *NERC* FAMOS porphyry **copper** systems
- £2.0 million *NERC* CuBES sediment-hosted **copper** resources
- €5 million *EU* HiTechAlkCarb **REE** in carbonatite systems
- €14 million *EU* CROCODILE secondary supply chain for **cobalt** – including mine wastes
- £4 million *NERC* SMARTEX challenge of deep ocean mining of Mn nodules – **cobalt, nickel, copper**
- £2.5 million *NERC* LiFT alternative sources of **lithium** for technologies – sustainable sourcing and recovery strategies
- £0.5 million *Philanthropy* **Green Research Fellow in geomicrobiology**
- £0.8 million *Industry* LODE 4 – Dedicated lab externally funded – **future positive mining**
- €7.4 million *Horizon Europe* **VECTOR**– Mineral deposits in sediment systems – **future positive mining**
- £672k *NERC Capex* **XRD** facility upgrade - **geonomics**
- $600k *World Bank MUNIS-2* Green economy of Uzbekistan– **future positive mining**
- £1.56 million *DEFRA GCBC Fastrack* **Bio+Mine** - Biodiversity positive mining– **future positive mining**
- £720k *DEFRA GCBC Fastrack* – **DEEPEND -** Undiscovered biodiversity in deep sea **– future positive mining**
- **NEW** £950k **5Ms - Microbial Manufacturing of Metals from Mineral Mining Waste** *Innovate UK* funded project – **future positive mining**
- **NEW** $1.9 million **IvARiCE** – **bioremediation -** Rio Tinto **– future positive mining**
- **NEW** Research Leader in Mineral Sciences – *NHM funded post* - linked to UCL mineral physics – **'geonomics'**

NHM Mining Consultancy activities

- Averages£300-400,000/year – **mining sector**

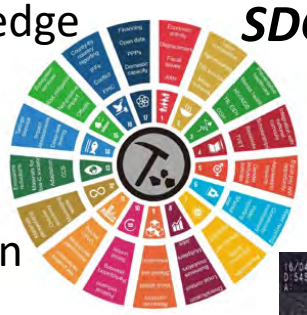
Science Theme *Resourcing the Green Economy*

- **Future positive mining** – integrating discovery and mining with a net positive biodiversity ambition
  - **'Geonomics'** – fundamental mineral sciences applied to materials resourcing
  - **Geodiscovery** – new minerals for the green deal
  - **Geometallurgy** – applied mineral sciences for green discovery & recovery strategies – *zero waste*
  - **Geomicrobiology** – microbiology in mineral processes; biomining, bioremediation
  - **Biodiversity Impacts** – developing metrics
- **Agri-environments - Food systems** - sustainable food production systems and land use



Drivers

- Net zero carbon pledge
- 'Green Deal'
- SDG goals
- Energy transition
- Transport revolution
- Sustainable society



Broadening the public conversation around mining

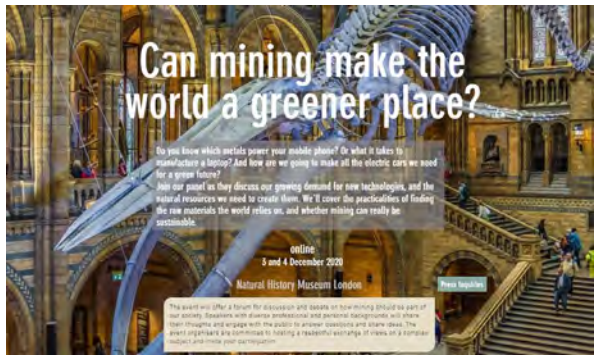
The Guardian
Newspaper of the year

More than 5,000 new species discovered in Pacific deep-sea mining hotspot

UK Parliament

The Observer

Trillions of metallic nodules on the sea floor could help stop global heating, but mining them may damage ocean ecology



GOV.UK

News story

Business Secretary opens latest meeting of the Critical Minerals Expert Committee

Climate Hub
The New York Times

21 JUL 2021

UK Minerals Strategy affirms minerals essential to economy, quality of life and decarbonisation

mpa
essential materials sustainable solutions

THE ROYAL SOCIETY

GEOSCIENTIST
The magazine of the Geological Society of London

Mining our way to net zero

Geoscientists are on the frontline of resource discovery, but also the responsible recovery of these resources and the design of a sustainable post-mining legacy, argues Richard Herrington

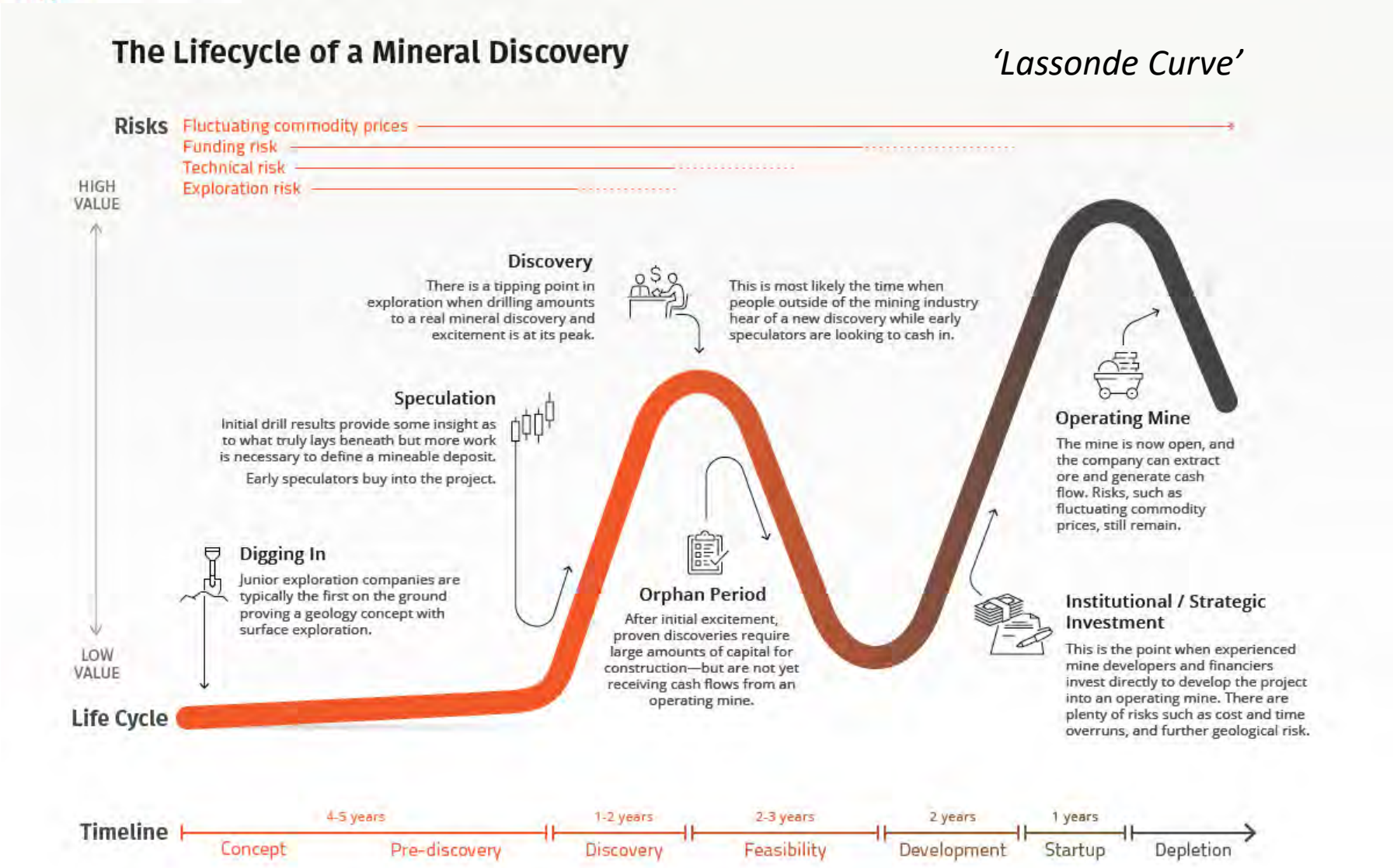
BBC NEWS

Climate change: Will UK mining drive a green revolution?

THE TIMES

Environmental call for return of UK mining

Exploring for the 'right' result?



- Timely, cost-effective successful discovery,
- Company growth, successful mining project,
- Profit delivered, shareholders happy,
- Long-term economic delivery…

Visual Capitalist 2019

Traditional workflow follows a ‘cradle to grave’ approach

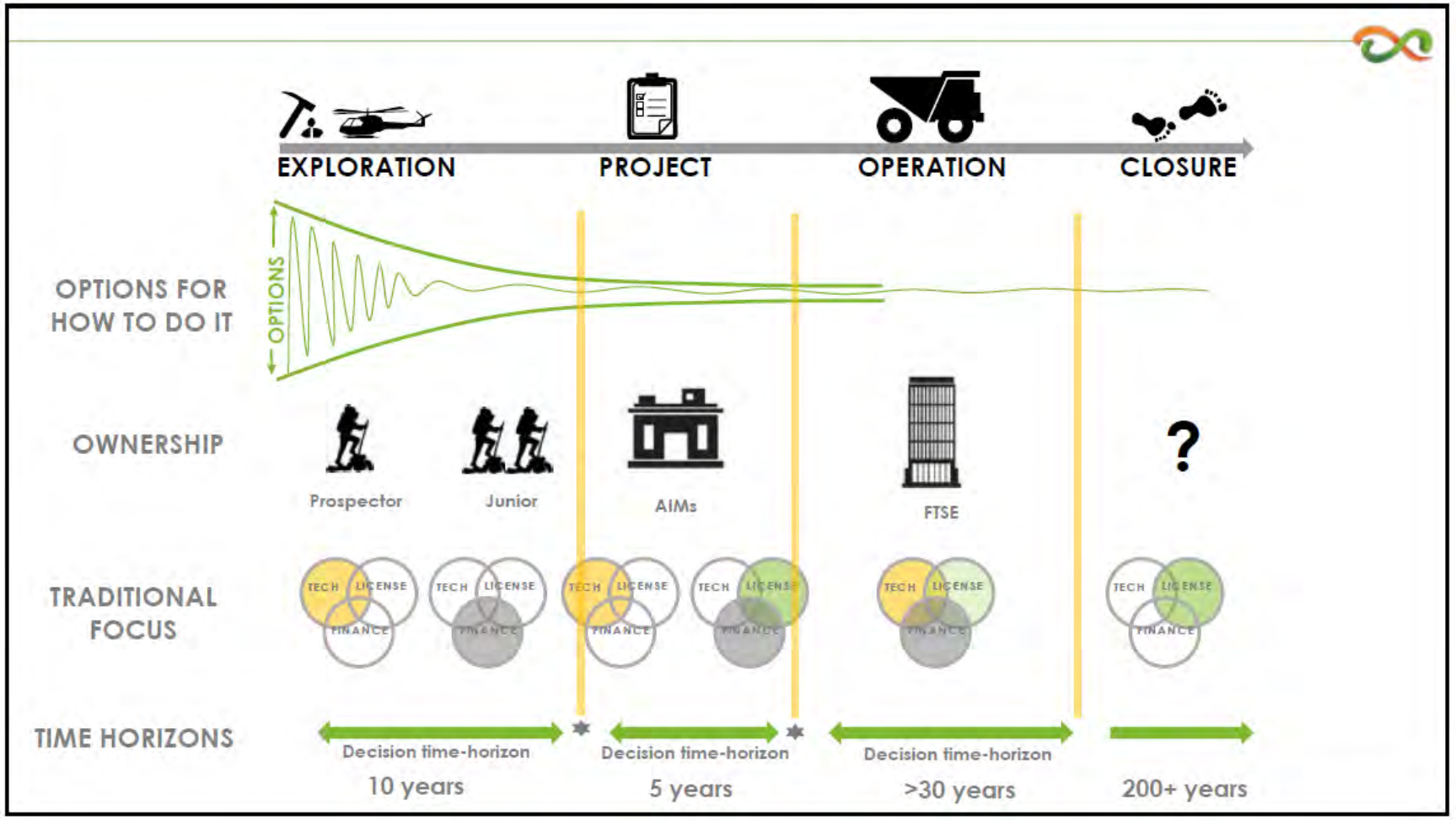


Diagram courtesy of Satarla 2021

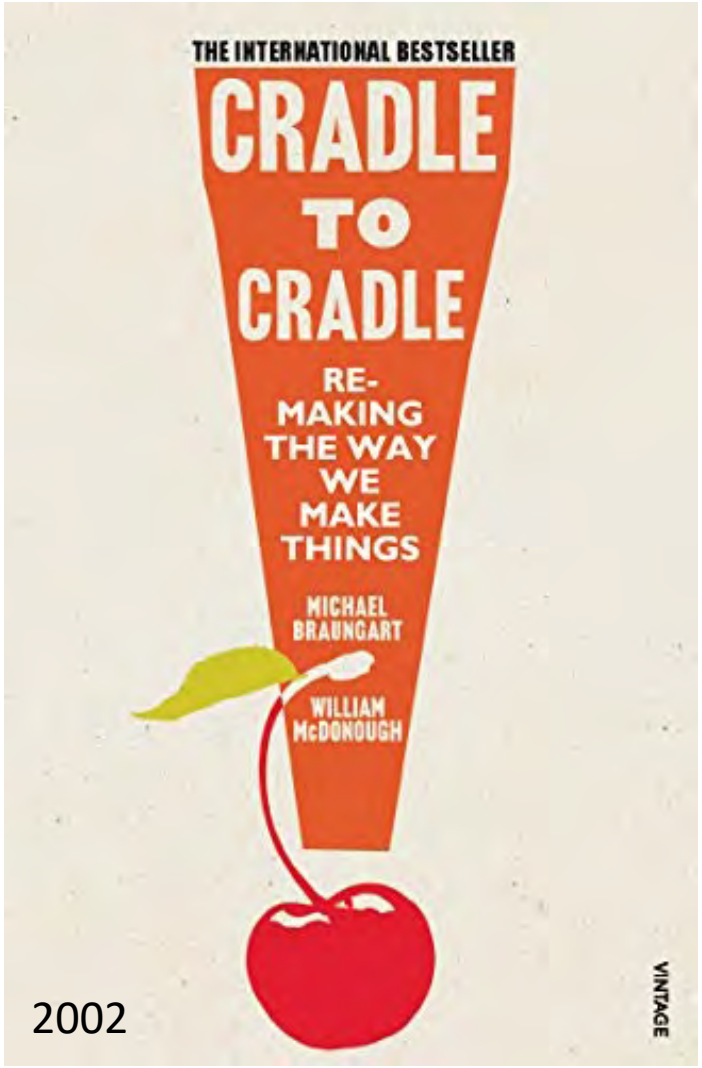
Analysis

- **Mining projects are divided into separate ‘business units’**
- Exploration is the critical first step but is a loss maker (*under pressure to reduce costs*)
- Project stage often focused on increasing stock values to bring to market (*not conducive to fully testing the potential negatives*)
- Operations are what really makes the money (*efficiency and profit key drivers)*
- Closure left to pick up the pieces of any issues generated by the other stages

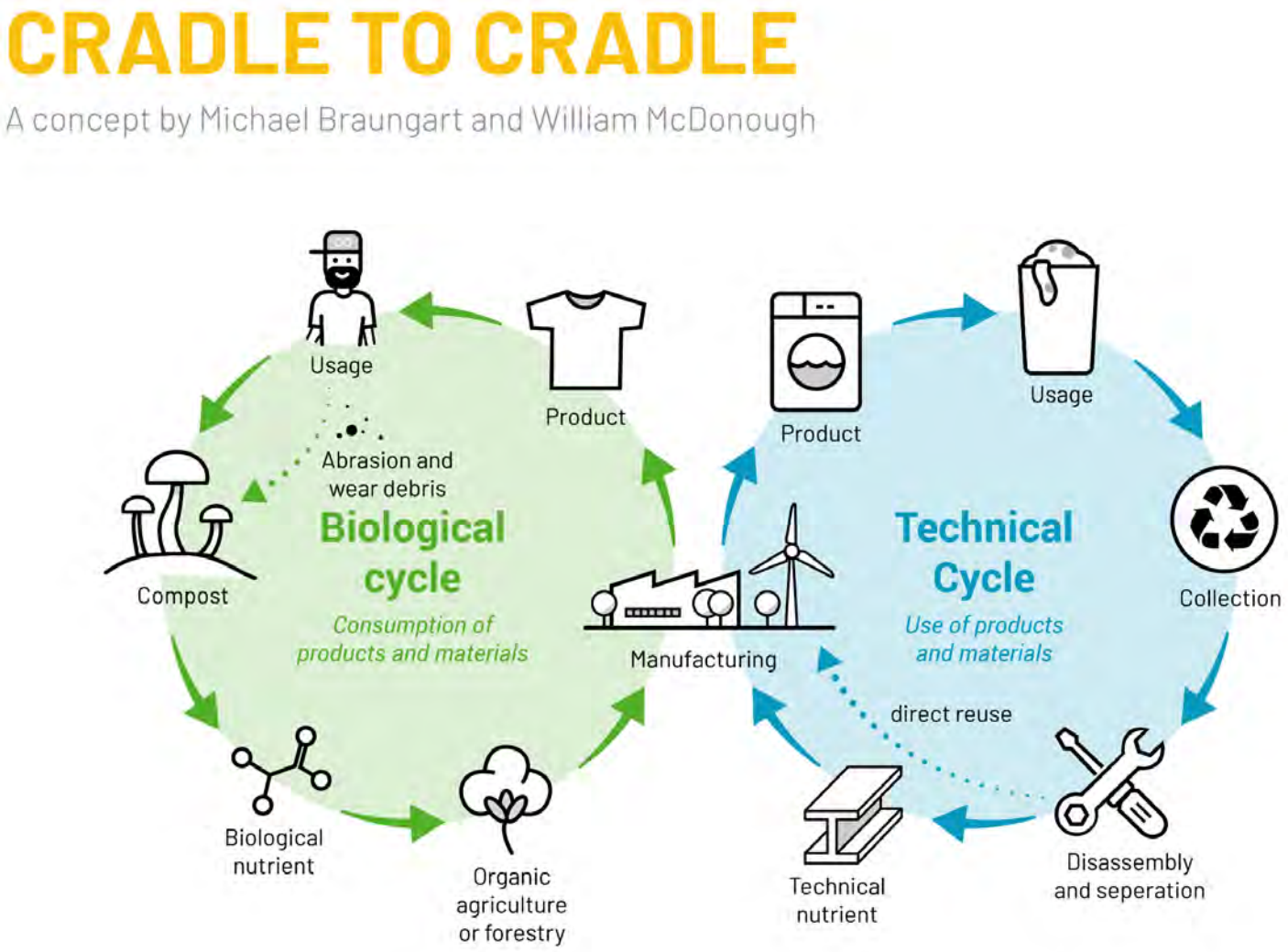
However - economic success alone is not enough

- Elkington 1994 – coined the term **Triple Bottom Line** of economy, society and biosphere (alternatively Profit, People, Planet or Economy, Equity, Ecology) – by its language this focuses on **aligning sustainability and the intentions of a business when it comes to profit**
- McDonough & Braungart 2002 – flipped this into the **Triple Top Line** as they suggested the focus should be to **align sustainability and business profitability from the inception** of a product

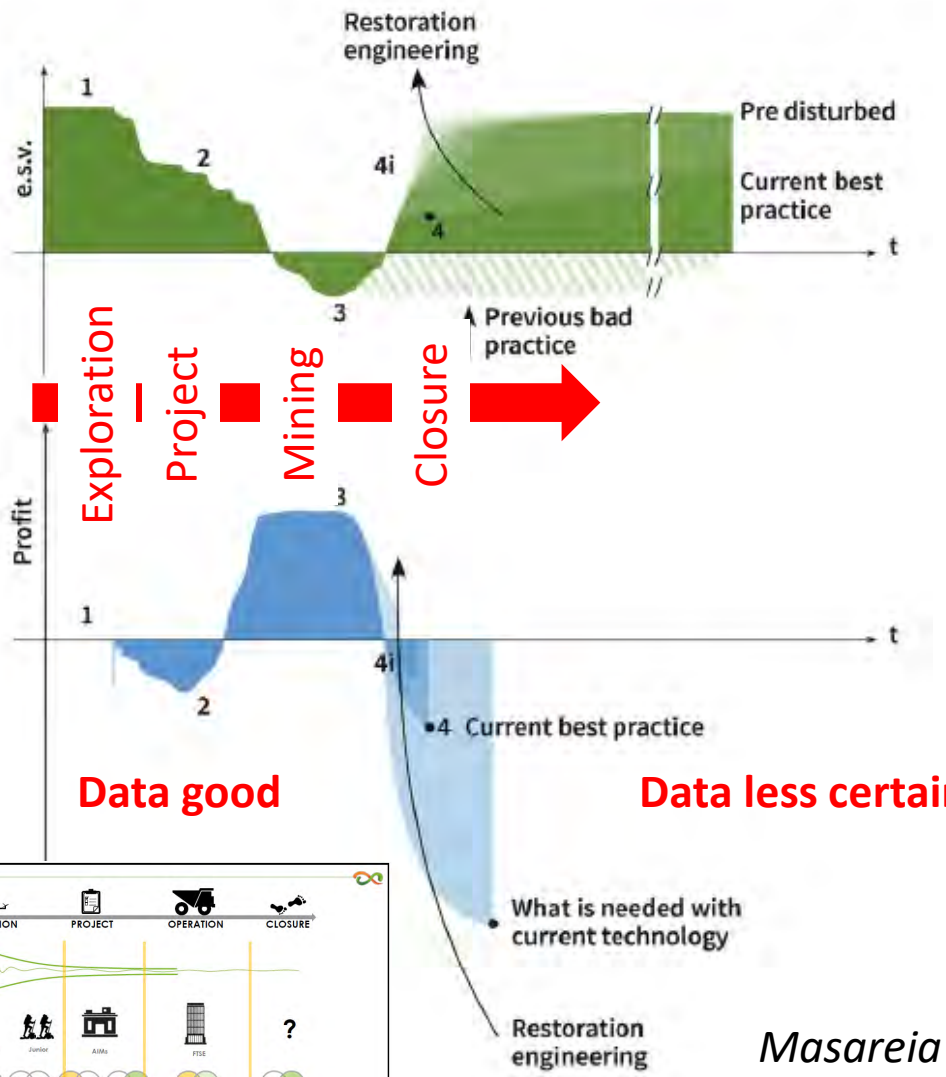
Circular economy concepts

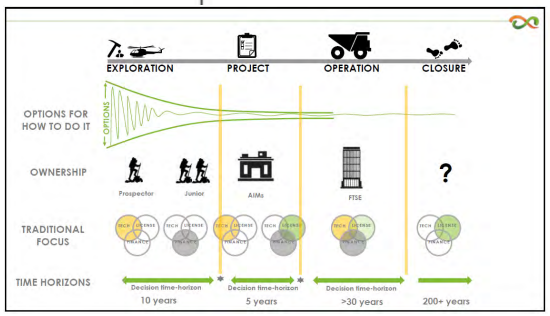


2002



Tracking values through the typical mine life cycle





Masareia et al. 2020

Not only economic values but 'Ecosystem Service Value' should be measured

- ESV and economic returns largely out of kilter through the linear life of a mine
- Intervention should be used to minimise the negative legacy of mine closure whilst rebuilding ESV
- What is really needed is some idea of costs and values right through to the far right of these graphs

Models for current theoretical practices

Coloured regions highlight areas that are fully considered for system design

Current (linear) model

Circular economy

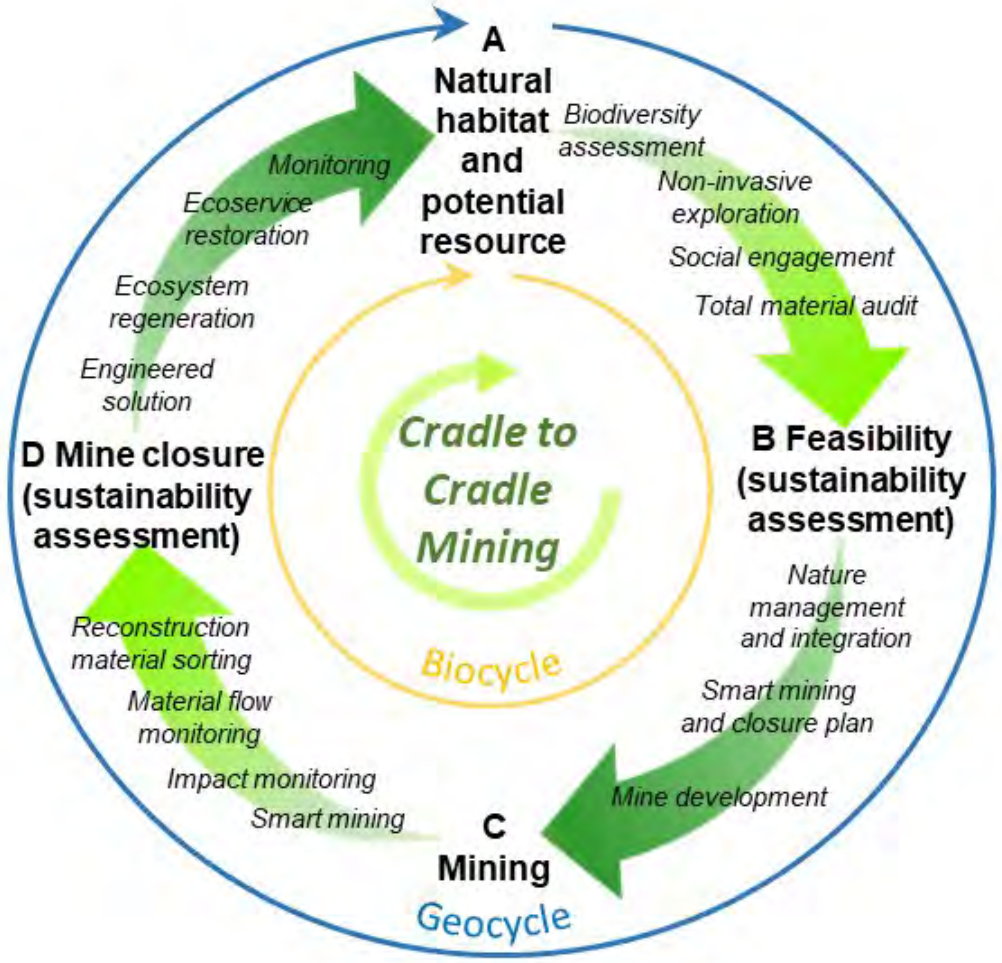
Social enterprise (linear)

Social circular economy

Robinson 2017

Profit **Planet** **People** **People and Planet**

‘Cradle to Cradle Mining’ embracing a ‘social circular economy’



CRADLE

- **Point A** – **define the ‘natural capital’**
  - Develop an exploration programme that puts **social engagement**, **biodiversity assessment** and **whole deposit knowledge** at the core of its activities
- **Point B** – **feasibility and sustainability** assessment with technical, financial, social and environmental aspects incorporating an agreed post-closure plan
  - Maximising recovery of useful components and minimising waste, logging the stocks of ‘future resource’
- **Point C - mining** and ***nature-based*** **progressive rehabilitation**
  - Optimised recovery with monitored stocks and flows, utilising ‘waste’ for secondary use and rehabilitation
- **Point D** – **closure and ecosystem reconstruction** for long term viability and transfer to third party use
  - Site returns to point A with a net positive long-term solution with an ongoing monitoring strategy

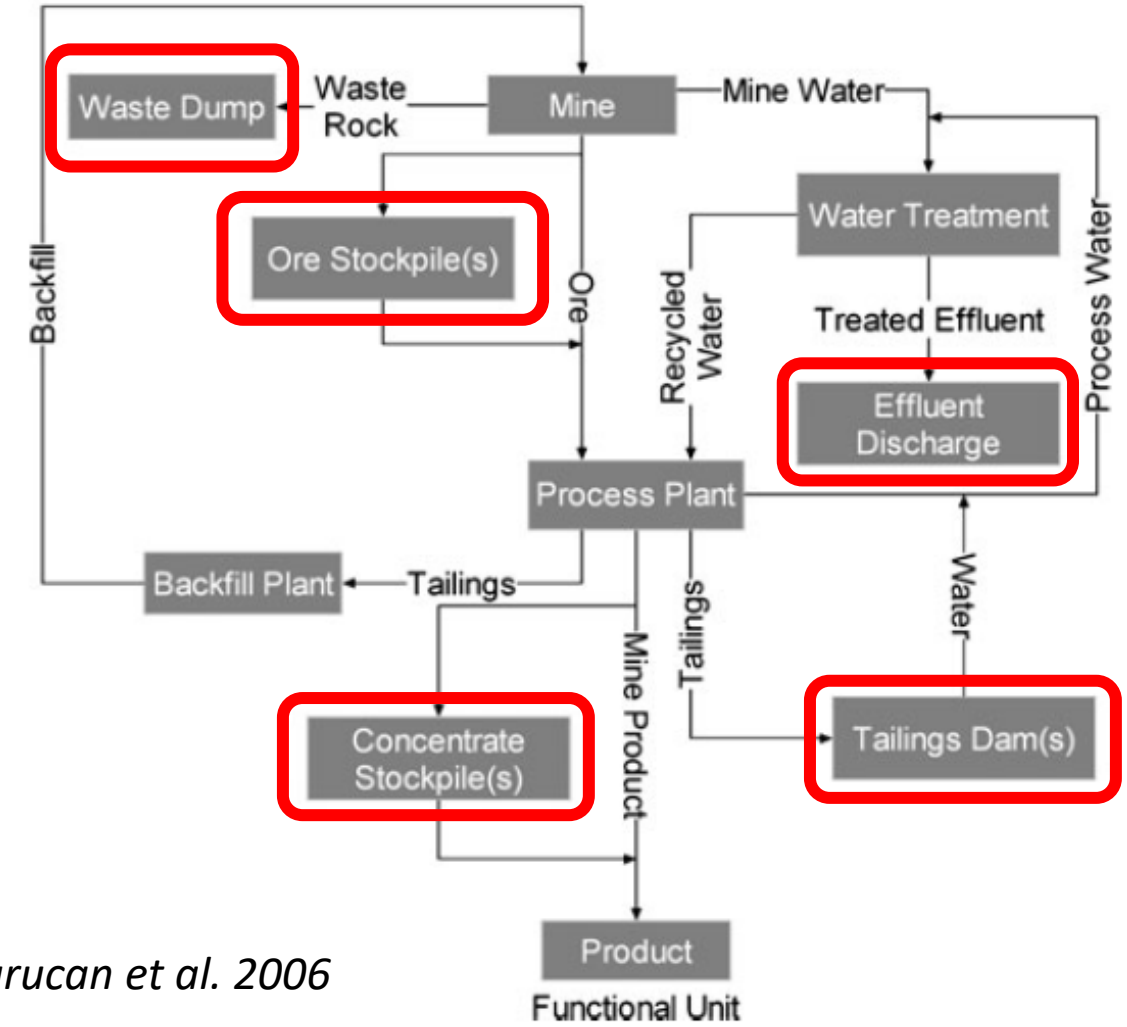
CRADLE

- **Point A** – **‘net positive repurposed site’**

Mine Closure 2022
Proceedings of the 15th International Conference on Mine Closure
4–6 October 2022 | Brisbane, Australia

Herrington & Tibbett 2022

Explorationists therefore need to think of the future mine



Durucan et al. 2006

- The data collected during needs to inform the design of a mine (see diagram left)
- Needs also to also help understand the characteristics and likely behaviour of the various **wastes** and **stockpiles**

Think about the end right from the start……

Table 1 Closure planning phases

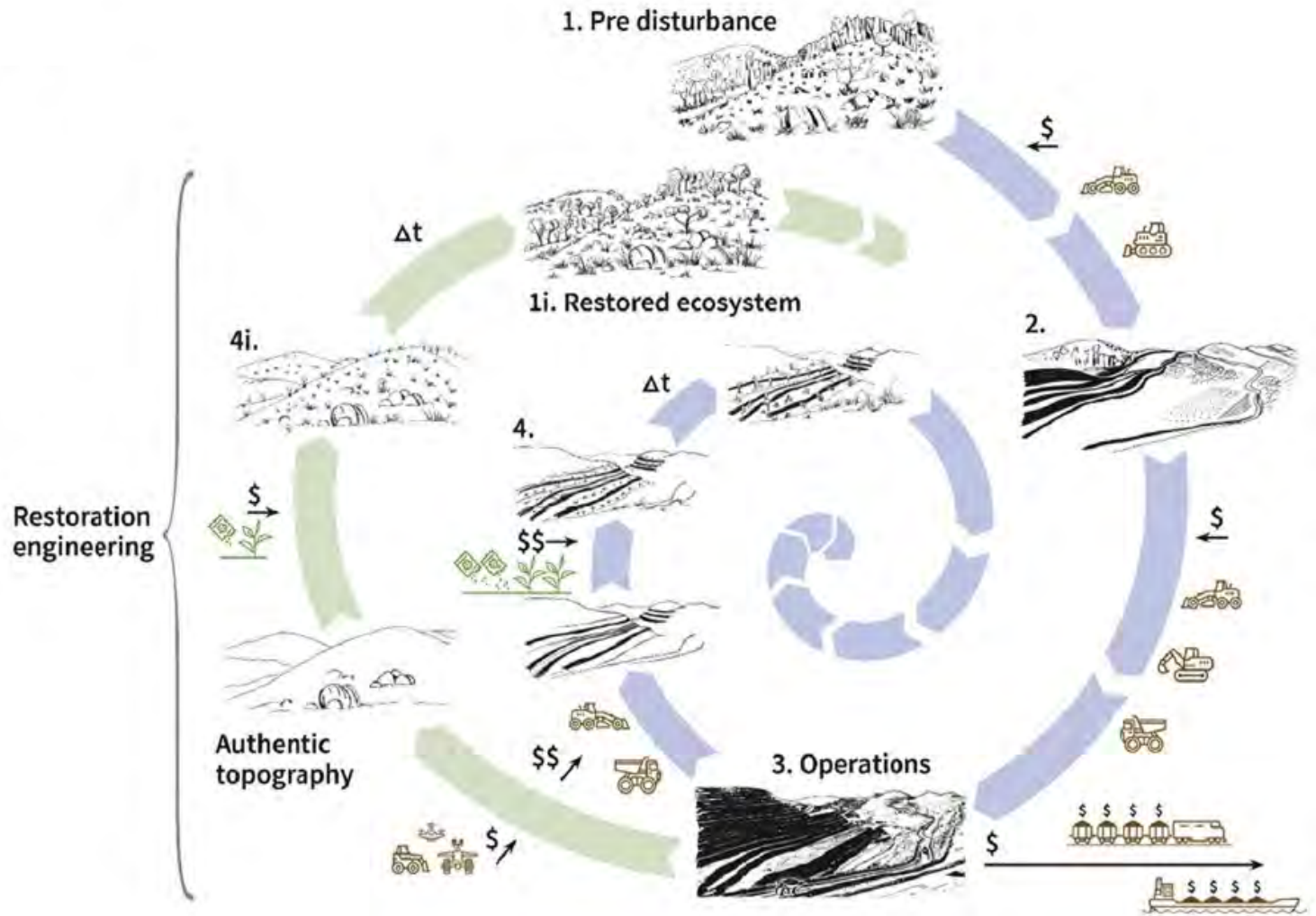
Project Phase	Closure Design	Key Tasks	Documentation
Exploration, concept/scoping study, pre-feasibility study	Low level of certainty	Identify broad sustainability objectives for closure Identify relevant environmental, social, economic and governance issues Conduct targeted stakeholder engagement Conduct a high-level risk assessment Prepare a high-level closure cost estimate and establish a baseline for financial provisioning	Conceptual closure plan including a closure cost estimate to ± 30%
Feasibility study	Moderate level of certainty	Review and revise outcomes of tasks listed above Ensure that closure tasks are fully incorporated into project design and operating plan Conduct wider stakeholder engagement Identify priorities for research and development	Preliminary closure plan that includes a closure cost estimate to ± 10%

Mine Closure 2008 – A.B. Fourie, M. Tibbett, I.M. Weiersbye, P.J. Dye (eds)
© 2008 Australian Centre for Geomechanics, Perth, ISBN 978-0-9804185-6-9
https://papers.acg.uwa.edu.au/p/852_16_Finucane/

Thinking About the End Before You Start — Integrating Mine Closure Planning into Feasibility Studies and Environmental and Social Impact Assessment

S.J. Finucane *URS Australia Pty Ltd, Australia*

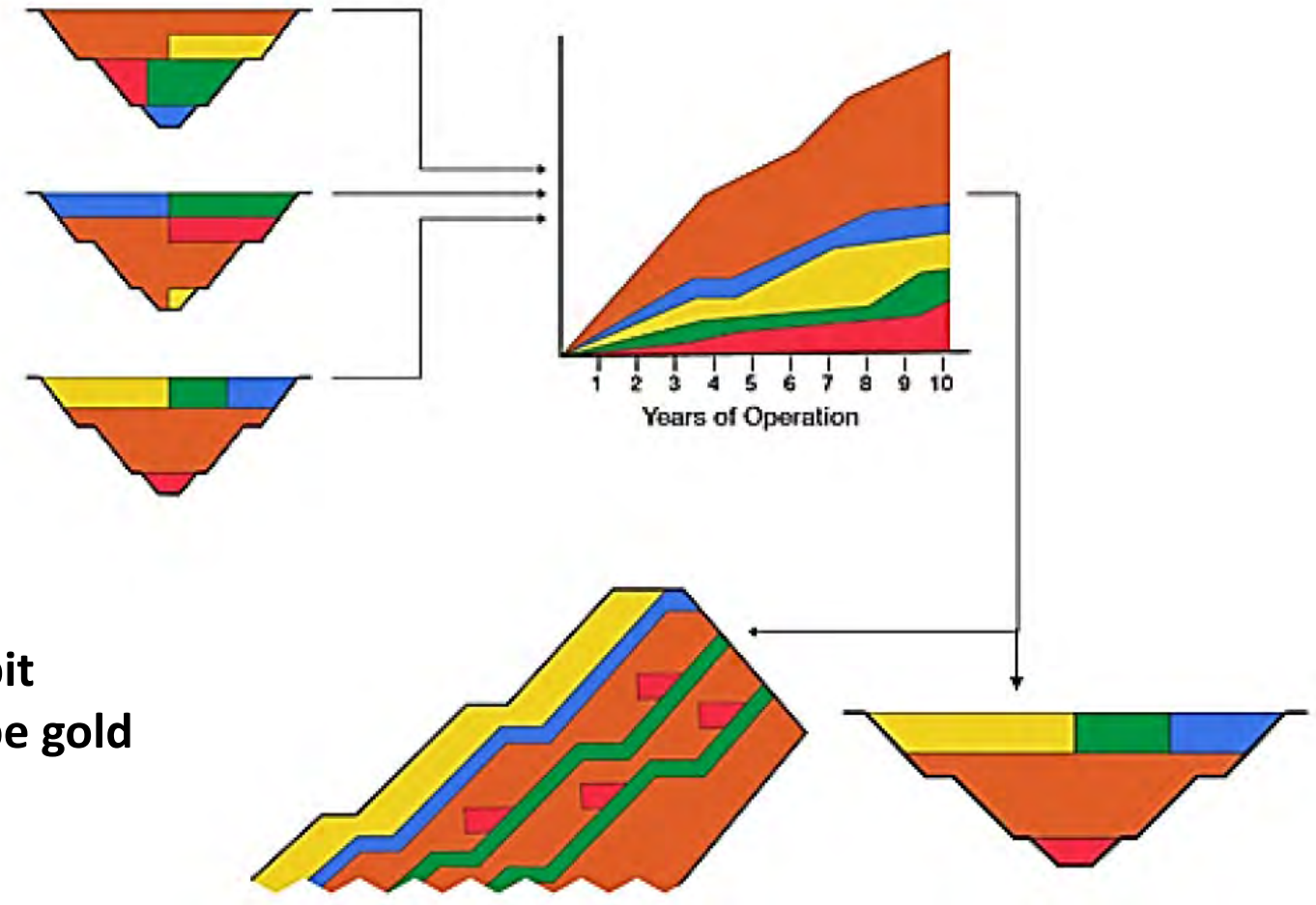
Planned progressive rehabilitation a far better strategy



Masarei et al. 2020

- Integrating engineering with ecological restoration is the key to delivering a lasting outcome
- Delivery of restoration *ss* in unlikely, however a net-positive reconstruction should be the target
- Move towards more authentic topographic reconstructions favourable
- Geological nature of the materials for the reconstruction fundamental to reconstruction success (or not)

Total deposit knowledge informs waste handling and rehabilitation



Multi-pit Martabe gold mine

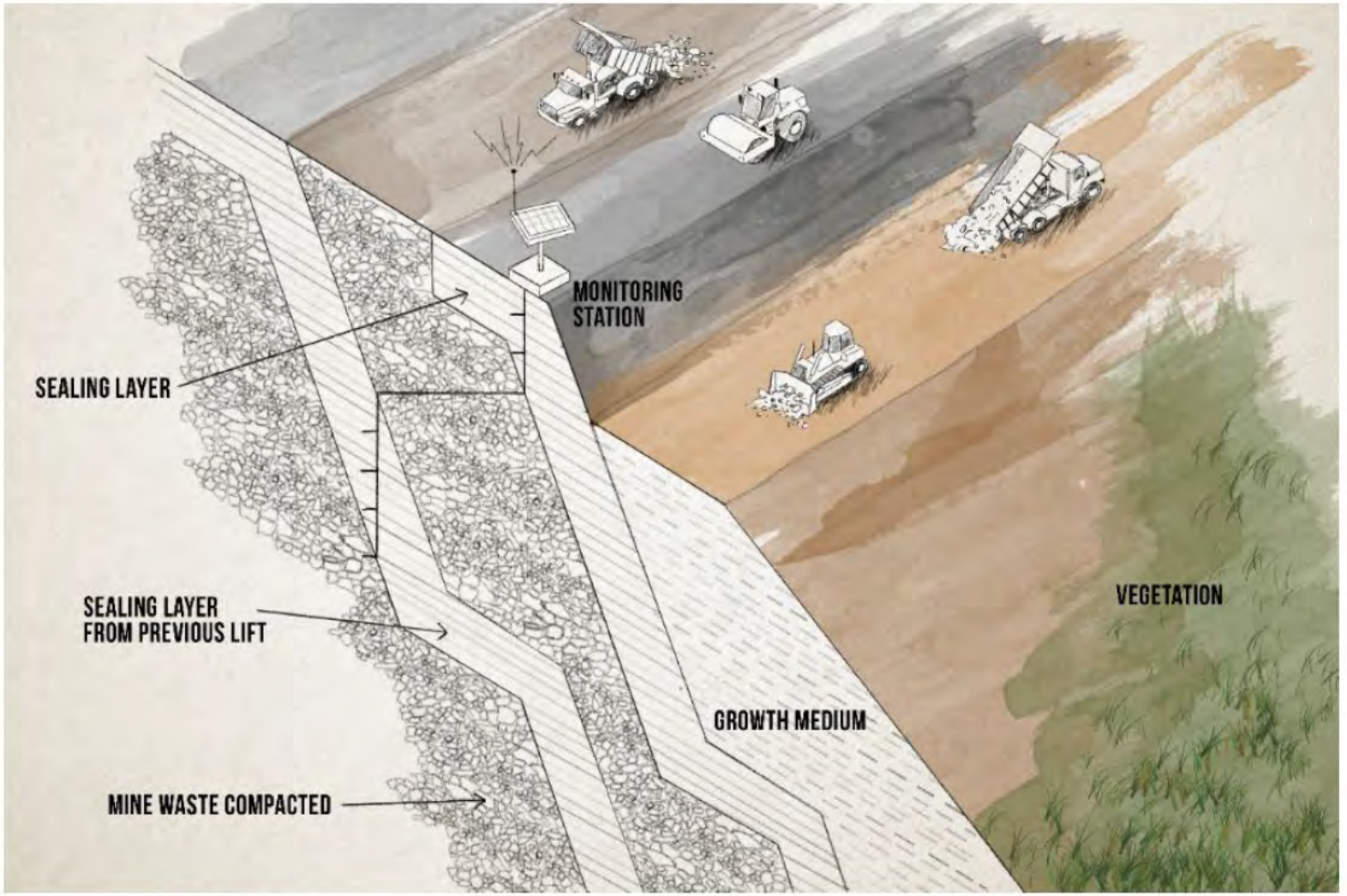
Grohs & Pearce 2019

Paradigm shift

Waste needs to be evaluated in the same way as ore

- Short-term planning included a detailed program of waste grade control
- Long-term planning scheduled the appropriate handling and disposal of waste based on its properties and the progressive closure strategy over the life-of-mine
- In this case (left) pits are optimised in terms of mining and handling of the ***waste*** as well as the ***ore***

Total deposit knowledge informs waste handling and rehabilitation

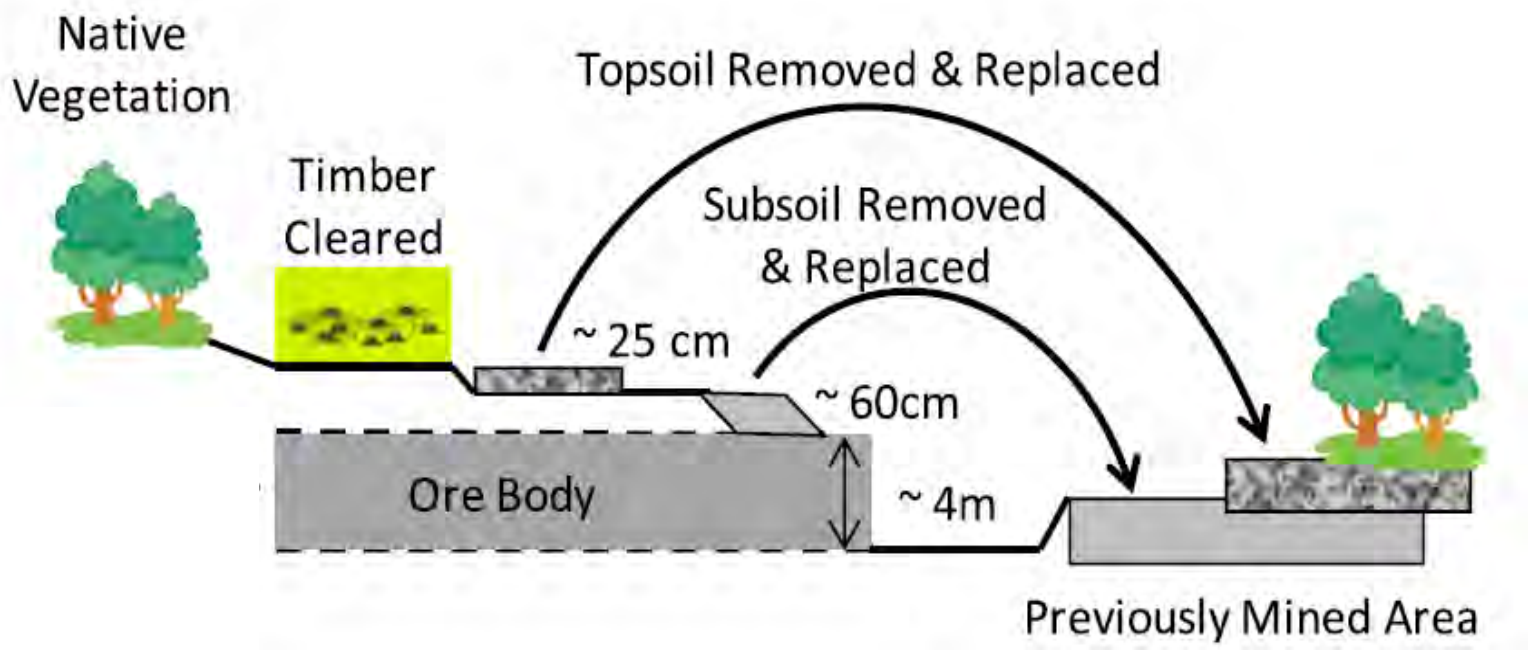


Progressive reconstruction with well-characterised mine materials

- Allows assessment of the chosen strategy during the working life of the mine
- Changes through time can be monitored and interventions adjusted in response

Grohs & Pearce 2019

Engineered solutions integrated with ecosystem reconstruction

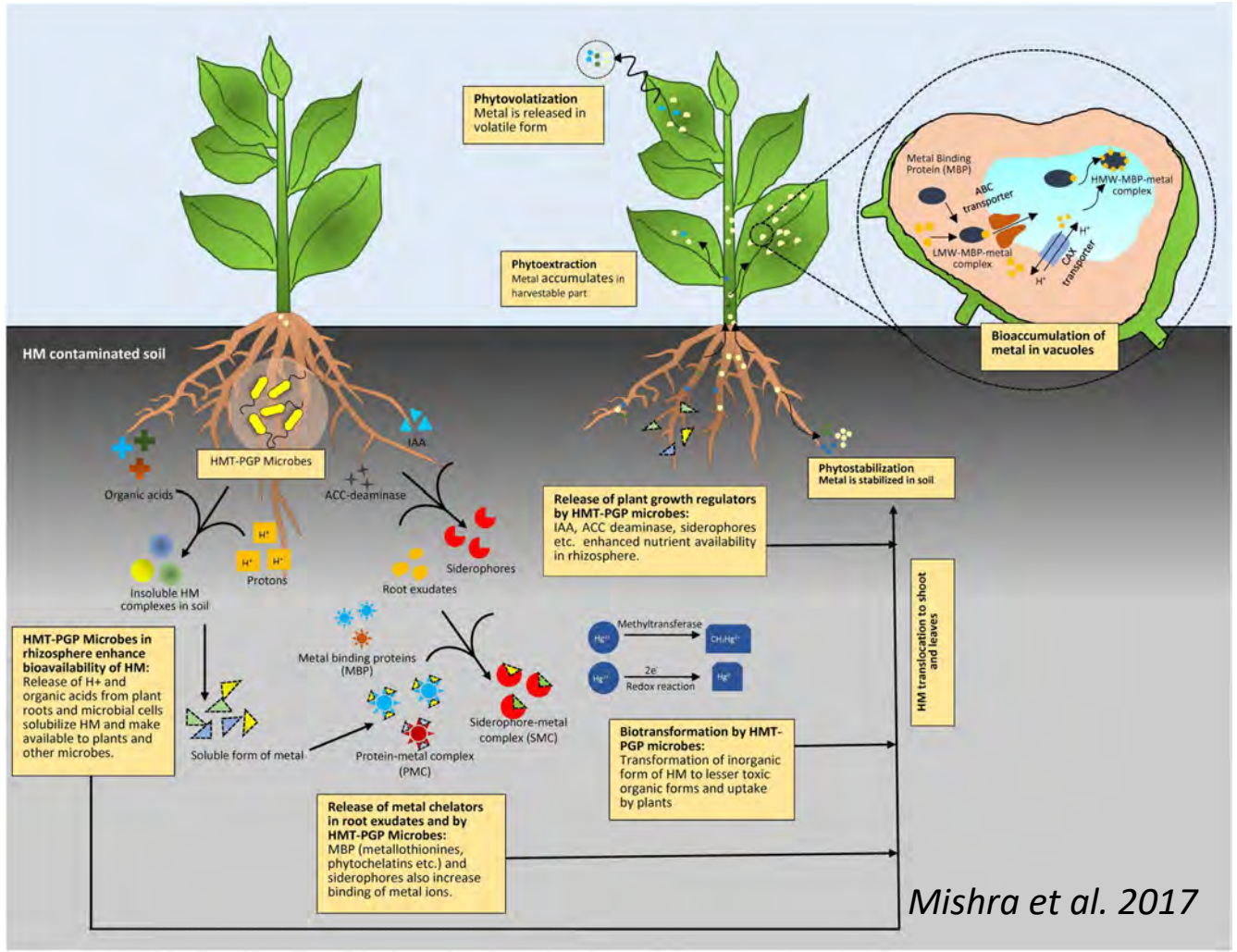


DeJong et al 2014

Solutions incorporate engineering, geology/geochemistry and biology

- Utilising knowledge and materials from pre-mined site
- Soil scientists and restoration ecologists need to collaborate on project design
- Interdisciplinary perspective needs to treat soil as a living ecological system rather than an inert construction material
- Solution needs a methodology to assess have the system is behaving long-term

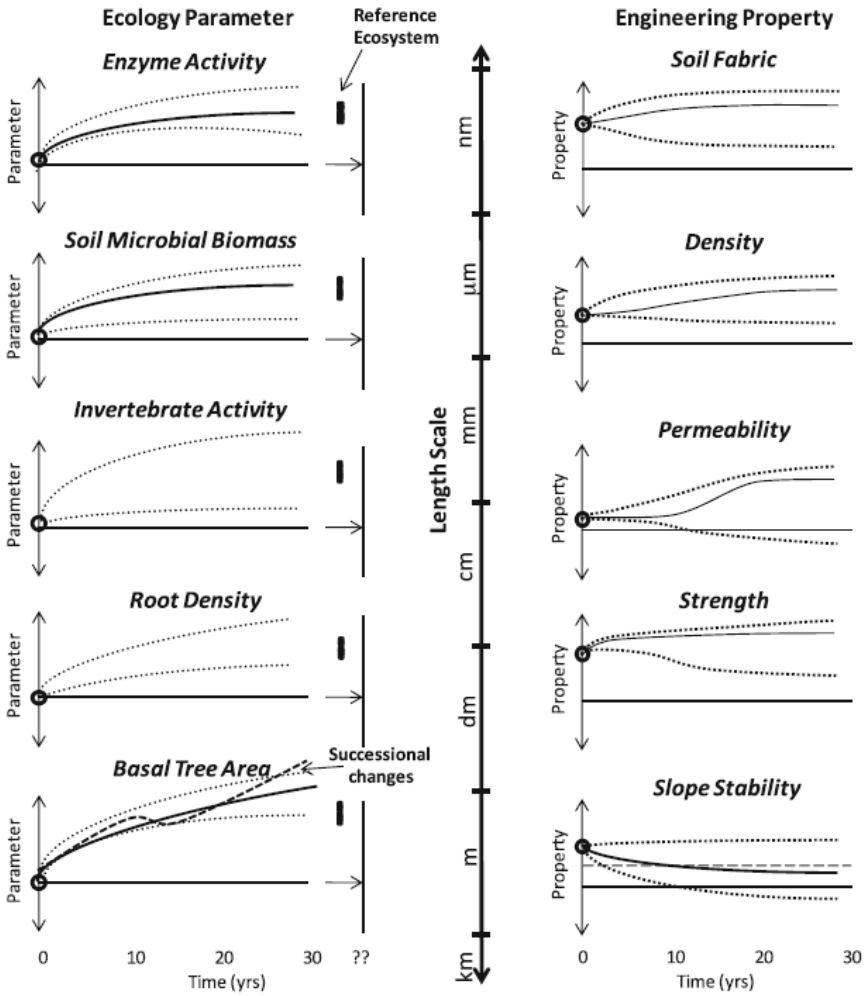
Reconstructed ecosystems must be part of clean up strategies



Mishra et al. 2017

- Plants and their microbiome should be part of the remediation strategy – even for contaminated sites
- **Early audit of the microbiome will give the baseline for the pre-mining ecosystem support system underground**
- Could also yield some useful functional microbes for other purposes too – bioprocessing and bioremediation

Engineered rehabilitation scenarios will evolve through time



- Engineered landscapes are integrated geo-ecological systems
- Soil scientists and restoration ecologists need to collaborate on initial project design and forecast changes
- Geotechnical engineers must be active in long-term management during the facility's service life as the soil system changes
- Interdisciplinary perspective since the soil is a living ecological system, not an inert construction material

DeJong et al 2014

Geoengineering for a future-proofed intervention

Traditional ‘bench and platform’ style reclamation

Martin Duque et al. 2020

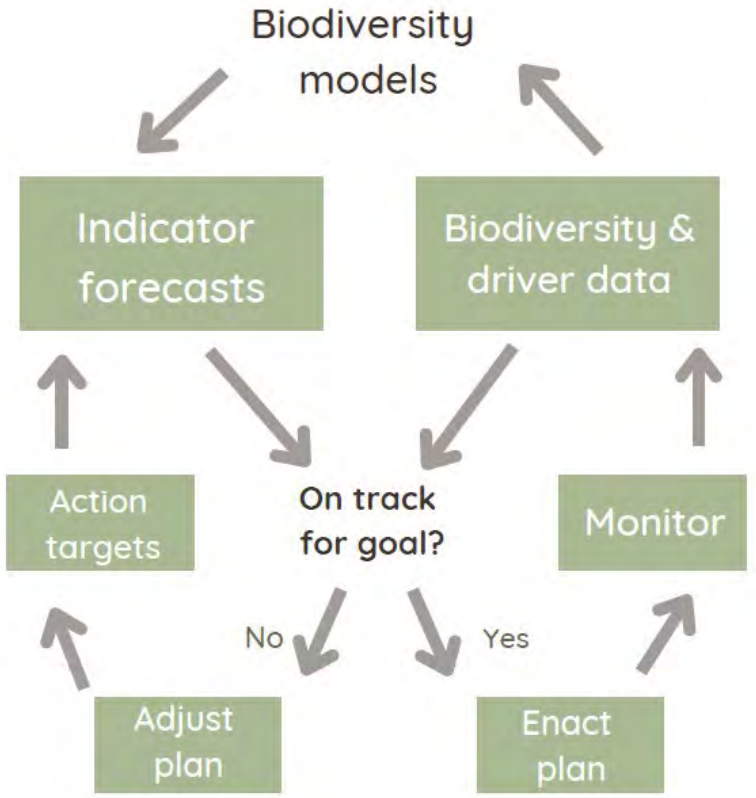
Hard engineered solution

Progressive geomorphic restoration

Geomorphic outcome

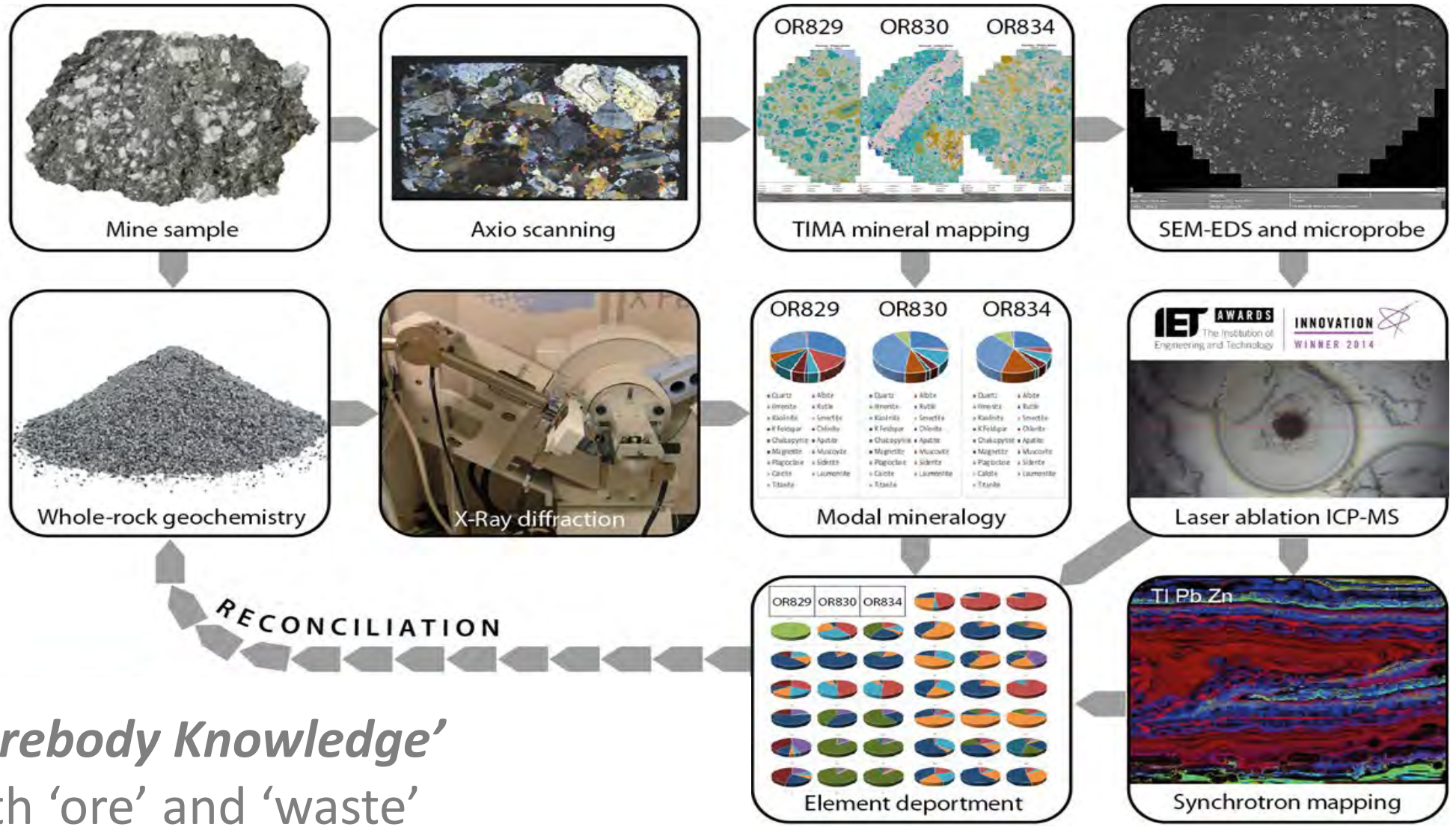
Biodiversity metrics – modelling performance of any intervention

- **Agreed biodiversity metrics are an essential but missing parameter for measuring project impacts**
  - Climate change is measured in carbon and against a 1.5 degree target - no common currency or single metric for biodiversity
  - One helpful distinction is between **metrics that convey extinction risk** and those that convey the **state and functionality of ecosystems**
- **Governments and businesses need metrics that are scientifically robust, easy to interpret, and applicable at multiple scales**
- The **Natural History Museum's Biodiversity Intactness Index (BII)** conveys the percentage of the original number of species that remain, and their abundance, in any given area
  - Unlike most indicators - including the vast majority currently being considered under the UNCBD's Global Biodiversity Framework, the **BII** can be used to project performance into the future rather than document past change
  - The Dasgupta Review used BII to examine the economics of biodiversity
  - Being based on models, it can act as a 'sat nav' for nature



NHM Andy Purvis 2022

Exploration workflow - geology



'Total Orebody Knowledge'

For both 'ore' and 'waste'

NHM Lode Lab Workflow

Exploration workflow – biology (+ metagenomics)

Sample collection

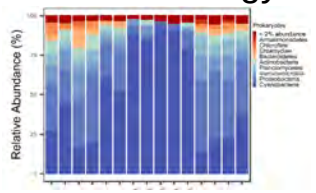
DNA extraction

PCR amplification of marker genes

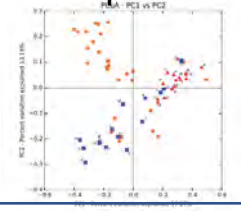
Genomes of soil microbiology

Illumina high throughput sequencing technology

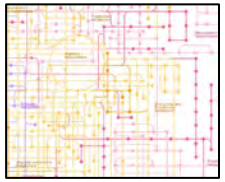
Taxonomic profiling of microbiology



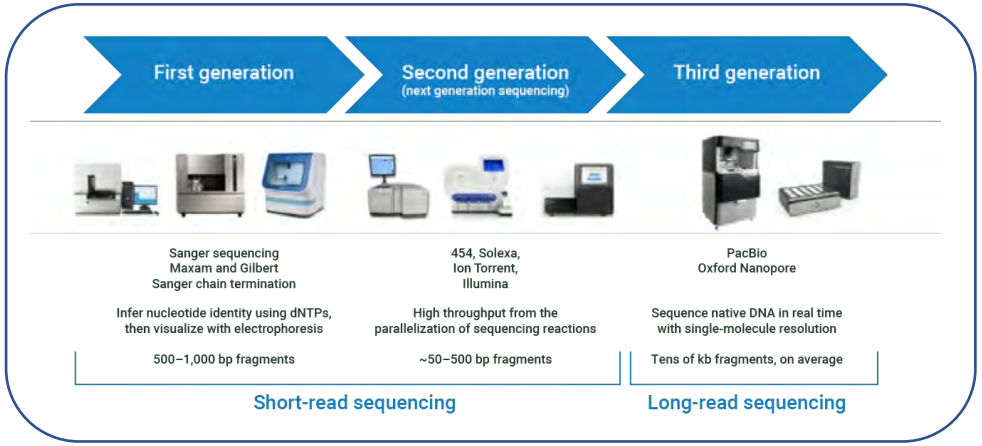
Microbial community comparison



Mapping of metabolic pathways

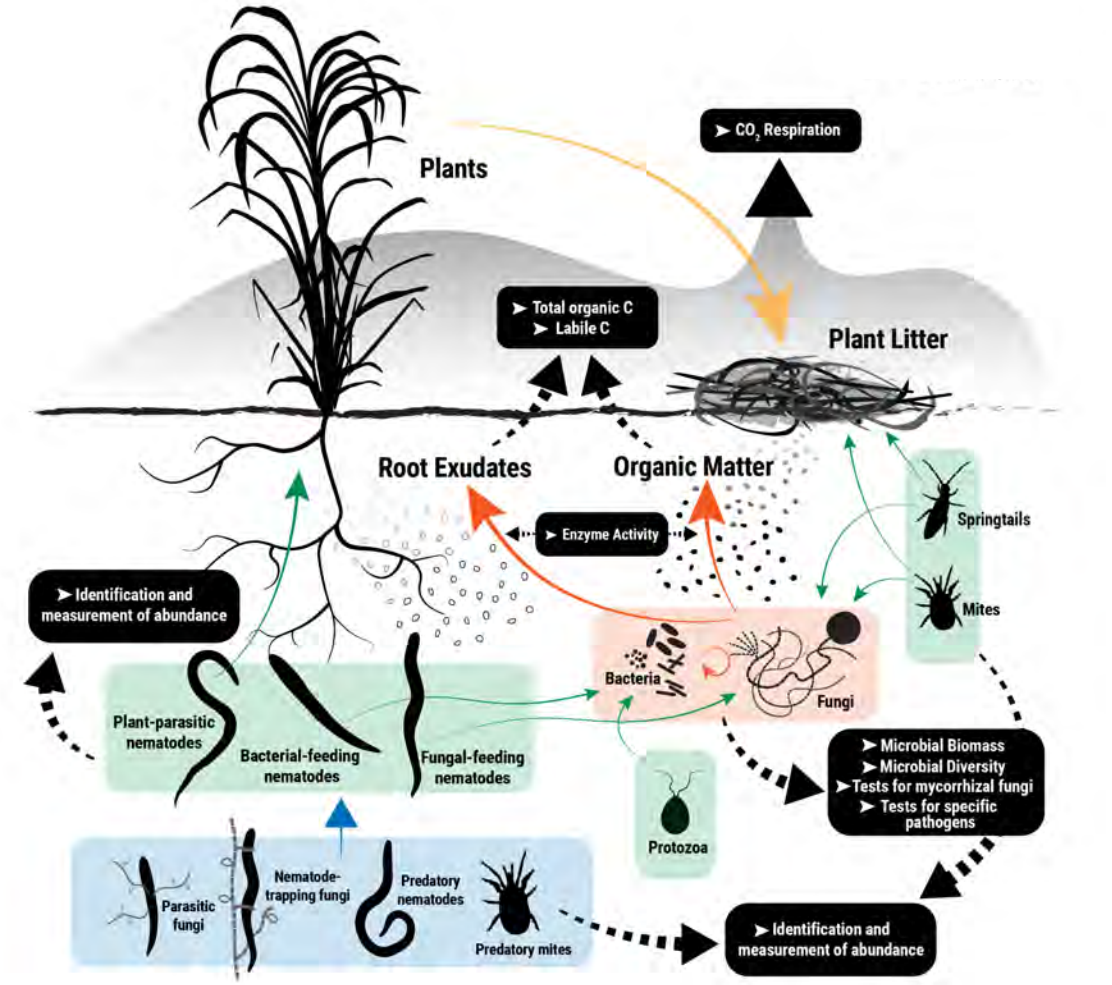


Functional gene comparison



NHM Genomics Workflow

Rehabilitating recognises that the *geo* meets the *bio*



Brackin et al., 2016

- Need to appreciate that biodiversity built from the soil and water systems upwards
- The soil and water ecosystem is essential for higher plants and invertebrates
- **Key point: assessing biodiversity needs to address aspects of both a) extinction risk and b) functionality of ecosystems**
- **Ecosystem functionality critical for understanding rehabilitation strategy and long-term future use of site (e.g. agriculture etc.)**

History has delivered some mine closure horrors

- Closure with no agreed plan can be problematic in a number of ways
- São Domingos mine, Portugal closed suddenly in 1966 to avoid incoming mine closure legislation
- Has left an environmental disaster **and** local unemployment


São Domingos copper mine, Portugal


Iron-rich acid mine drainage

Contributing to many of the social views of mining

POLITICO

Portugal to scrap lithium mining project

Locals spent years fighting to halt the project, a cornerstone of Lisbon's raw materials policy.

BY AITOR HERNÁNDEZ-MORALES AND SOFIA DIOGO MATEUS

April 27, 2021 | 10:11 pm

Serbia

Rio Tinto plans for Serbia lithium mine suspended after protests

Local authorities put $2.4bn project on hold after scale of opposition shakes country's government

Associated Press in Belgrade

Thu 16 Dec 2021 18.34 GMT

Le Télégramme

Publié le 23 octobre 2015

Manif anti-mines. L'avis en jeu

Mine closure successes

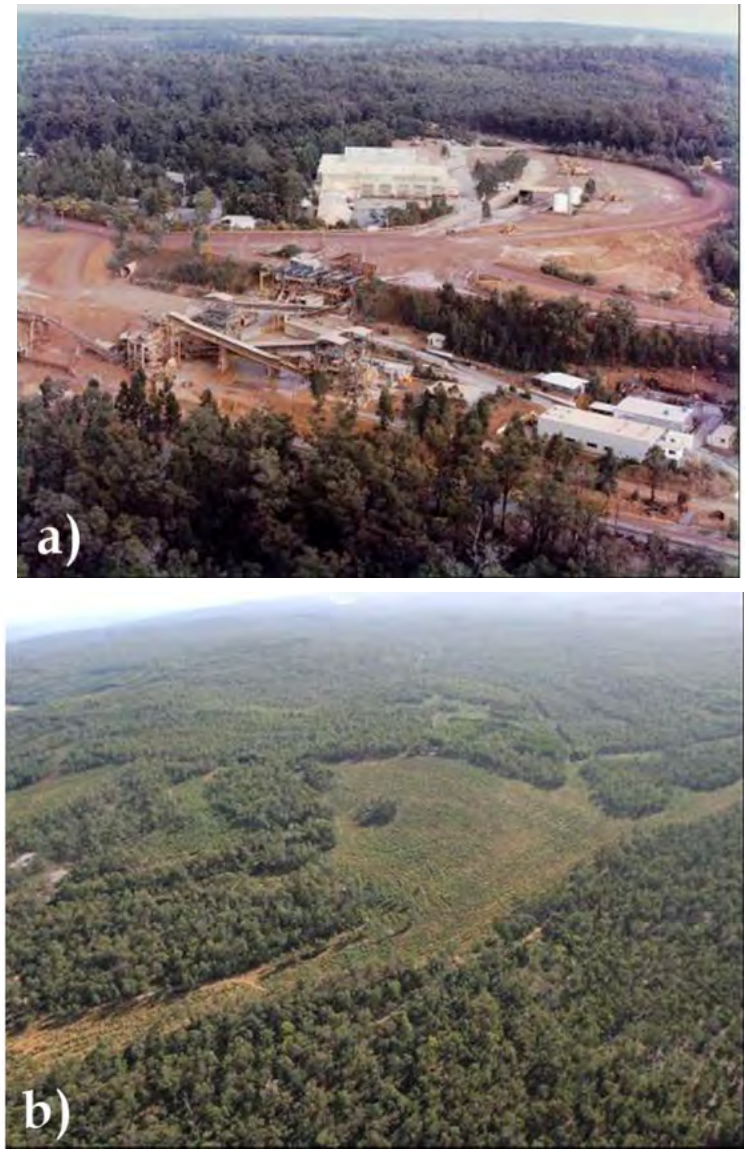
Consensual informed rehabilitation can work effectively

- **Eden Project in Cornwall, England**
- Integrated approach turned a open pit clay mine closed in 1990s into a profitable new sustainable business
  - Now the largest indoor rain forest in the world with over 1,000 plant species
  - Cornwall's first undercover ice rink
  - A popular wedding, entertainment and conference venue
- Opened in 2001, it cost £140 million to create, used local mineral waste and compost to make soil for the biomes
- 20 million visitors in the first 20 years and has generated an estimated £2.5 billion for the local economy in that time, 7% value of the local economy
- Employs 350 people
- Now up to 2 million visitors annually
- Project undertaken by an innovative 3rd party with local support

Other successes?

Flambeau Cu-sulfide mine Wisconsin

a) Pre-mining
b) Mining operations
c) Post-mining



Jarrahdale bauxite mine

a) Mining operations
b) Post-mining

However: **These look like good outcomes visually, but other key questions are:**

How can we also judge the success of these projects in social or biodiversity terms?

Different corporate approaches yield different results

THE TIMES

Cornish Lithium raises £6 million in new Crowdfunding Raise

Investors crowd in to fund Cornish Lithium

Fundraising 'sells out in 15 minutes'

Emily Gosden

Tuesday June 22 202
The Times

CornwallLive

Residents fear a return to mining will devastate an area of Cornwall

An opposition group believes the work will lead to radical changes to where they live

9 AUG 2021

A spokesperson for Great Wheal Vor Community and Environment Group (GWVCEG) said earlier this year: "There is widespread concern over the lack of transparency in the approach made by Cornish Tin which has left landowners feeling pressured into signing access agreements without understanding their rights and other residents uninformed about the drilling activities."

Embedding the local community should yield better results

- Some examples of success are where broader community groups are empowered to benefit rather than specific localised stakeholders

Community Power Cornwall

SHETLAND COMMUNITY BENEFIT FUND

Sustaining & developing Shetland communities

Some take home thoughts

- Mining is only a temporary intervention to recover subsurface resources of value, in a finite timescale, from a site where minerals are only one part of the ‘natural capital’
- The site of the mine will need to be returned fit for third party use after mining ceases and rehabilitation is completed
- Any mining therefore needs to be net positive for people and the planet whilst yielding value to the miner
- Social licence needs to begin from the start, stakeholders need to be embedded from the first exploration efforts so there is a shared, common purpose with shared vision of the outcome
- Exploration needs to collect enough social, geological and ecosystem data to be able monitor stocks, flows and residues, plan the mining and rehabilitation and evaluate the nature, behaviour and impacts of any wastes
- Design of the post mining landscape needs to begin at the exploration stage (at least in outline form) so there can be a shared vision of the post mining landscape for all stakeholders
- The linear model for mining needs to become a virtuous circle (‘cradle to cradle’) with net positivity (and effectively zero waste) created at each decision point of the circle

Mining through the lens of the ‘Three Horizons’ foresight tool

Global Sustainability

Accepted manuscript

Mineral revolution for the Wellbeing Economy

Published online by Cambridge University Press: **12 August 2022**

Richard Gloaguen, Saleem H. Ali, Richard Herrington, Leila Ajjabou, Elizabeth Downey and Iain S. Stewart

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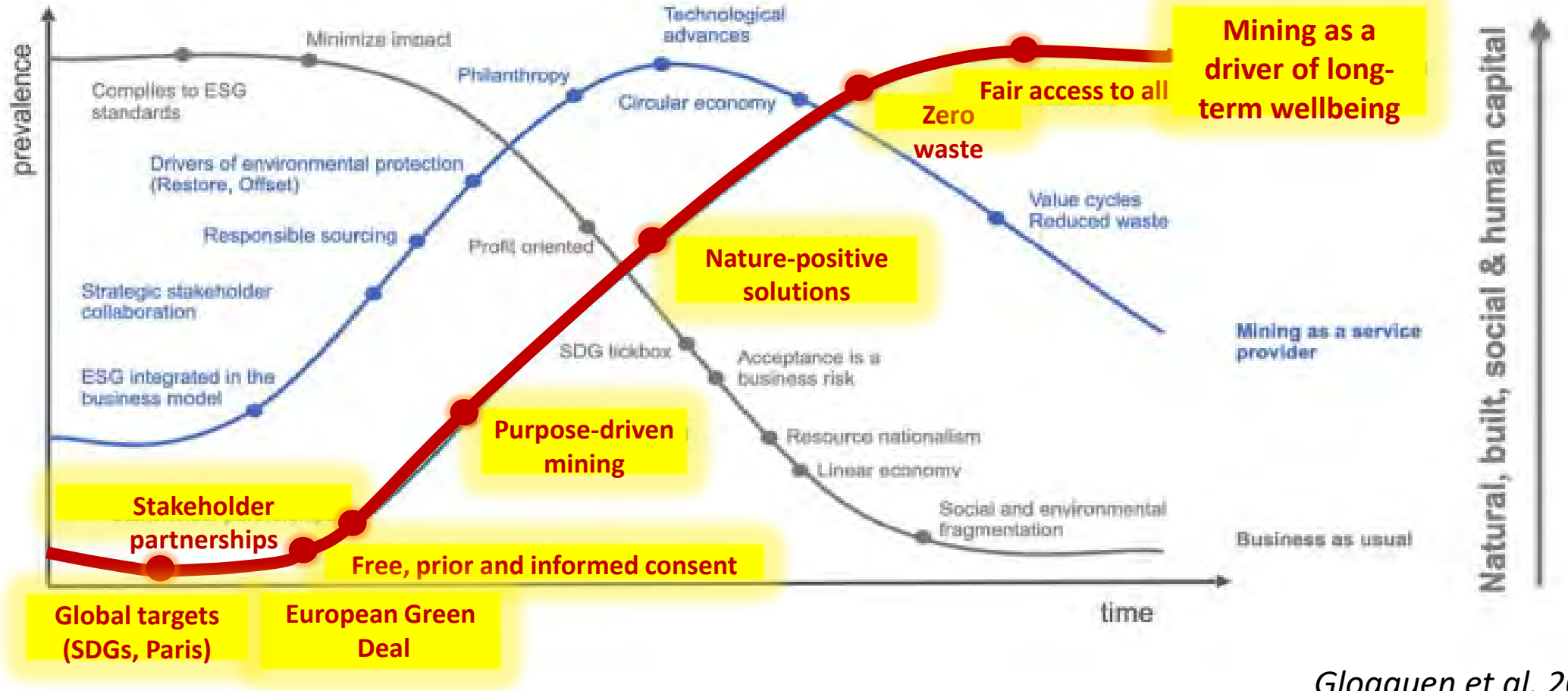

Gloaguen et al. 2022

Natural History Museum

Questions?

r.herrington@nhm.ac.uk