Environmental and Social Benchmarking Analysis of Nautilus Minerals Inc. Solwara 1 Project

EARTH ECONOMICS

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Authors
David Batker & Rowan Schmidt, Earth Economics

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To the extent this study contains any scientific or technical information concerning Nautilus' Solwara 1 project, such information has been reviewed and approved by Michael Johnston, the President and Chief Executive Officer of Nautilus who is a "qualified person" under National Instrument 43-101 of the Canadian Securities Administrators.

The Earth Economics team members who contributed to this report include David Batker (principal economist), Rowan Schmidt (project management), Johnny Mojica (research), Alexander Anbarcioglu (research), Joshua Reyneveld (data center industry information), Brianna Trafton (research), Greg Schundler (GIS analysis), Jessica Hanson (editing), and Angela Fletcher and Paula Wood (cover and layout design).

Purpose of this Document

This study provides a social and environmental review of the Solwara 1 project. It provides a preliminary framework that examines the ecosystem goods and services that may be enhanced, degraded, or consumed by the Solwara 1 project in Papua New Guinea. This study also sets out the first ever natural capital accounting and ecosystem goods and services framework for seabed mining. The Solwara 1 project is compared to modern existing and proposed terrestrial copper mines. Increased recycling and replacement of copper as alternatives to mining and the smelting process are also examined.

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Executive Summary

Image credit: Nautilus

The primary goal of the analysis was to measure the environmental and social impacts of the Solwara 1 project in comparison with three terrestrial mines.

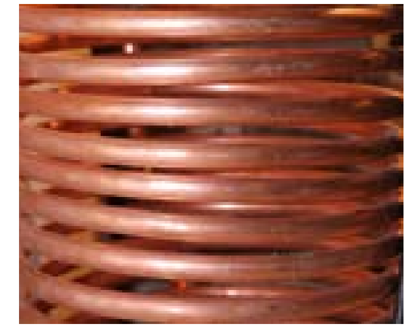
Nautilus Minerals Inc. (Nautilus) is a seafloor resource exploration and development company that intends to commercially explore the seafloor for copper–, gold–, silver– and zinc–rich seafloor massive sulphide deposits and for manganese, nickel, copper and cobalt nodule deposits.

On 11 December 2014, Nautilus formed a joint venture with Eda Kopa (Solwara) Limited, a wholly owned subsidiary of Petromin PNG Holdings Limited, which is the nominee entity of the Independent State of Papua New Guinea for the Solwara 1 Project. Located in the Bismarck Sea of Papua New Guinea (PNG), the Solwara 1 project will be the world's first deep seabed mining project for copper minerals.

Earth Economics was commissioned by Nautilus to conduct an independent environmental and social benchmarking analysis of Nautilus' proposed deep seabed mining project. The primary goal of the analysis was to measure the environmental and social impacts of the Solwara 1 project in comparison with three terrestrial mines. This goal was achieved, as the analysis was sufficiently comprehensive to clearly identify critical social and environmental concerns and potential project benefits.

This analysis utilized a natural capital accounting approach that is internationally recognized based on improvements to the Millennium Ecosystem Assessment (MEA)[1] and The Economics of Ecosystems and Biodiversity (TEEB)[2] methods. The review has provided a comparison of the Solwara 1 project to three terrestrial copper mines, two existing and one proposed.

In this report, the importance and environmental implications of copper mining are discussed and a primer is provided on natural capital accounting and the value flows of environmental goods and services. The report analyses and conclusions are included on the following pages.



▲ Copper coil
Image credit: Pixabay

Report Analyses and Conclusions

Four analyses were completed as follows:

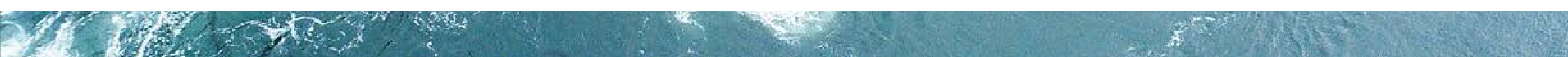
1. Analysis I examined the continued need for copper mining and the potential for recycling or substitution to replace copper mining in the future.
2. Analysis II reviewed 22 natural capital categories of goods and services present in the mining sites at Solwara 1 and the three terrestrial copper mining projects.
3. Analysis III delivered a quantitative analysis of input and effluent physical measures per metric ton of copper produced, again comparing three terrestrial copper mines with Solwara 1.
4. Analysis IV reviewed the potential monetized natural capital accounting impacts of Solwara 1 and the terrestrial mines for 14 of the 22 identified natural capital categories, with results provided in dollar values.

This report also presents a discussion of the Tongling Non-Ferrous Metals Group (TNFM) copper smelter, the smelter that has agreed to purchase the Solwara 1 copper product.

The concentration of copper in terrestrial ore deposits is declining, increasing the financial, social, and environmental costs associated with production.

Copper and the Environment: A Nano–History

1. Over 7 billion people use copper. It is essential to achieving human development goals.
2. Copper is vital for producing numerous forms of electrical power, clean water, and technology.
3. Terrestrial copper mining has significant social and environmental impacts. Risks of terrestrial mining include displacement of communities, water contamination, and damage to downslope communities from waste rock and tailings.
4. The concentration of copper in terrestrial ore deposits is declining. This decline is increasing financial, social, and environmental costs associated with production, on a cost-per-metric ton basis.



Copper recycling is important, but recycling alone cannot fulfill current and projected copper demand.

Analysis I: Copper Recycling and Substitution

1. Copper recycling prices are high, with brisk, robust copper recycling markets. However, there is a limit on idle copper available to be recycled.

2. Copper recycling is likely limited to around 30% of global supply, and the substitution of other materials and technologies for the currently in-use copper stock will not be realized in the near future, thus, demand for copper ore will remain high and copper mining will likely expand globally.

3. Even if recycling a significant portion of the current global built capital stock became feasible, copper ore mining would still be required in order to meet global demand.

The State of Knowledge of the Bismarck Sea Deep Seabed

1. The deep seabed is not generally well understood; however, the Solwara 1 proposed mine site, the North Su volcano, and the South Su conservation site are well studied. The Solwara 1 project environmental impact statement and 35 independently published papers document the area to a degree that would compare very favorably with similar studies for terrestrial mining projects.

2. The Solwara 1 mine site is adjacent to the active North Su undersea volcano, which produces volcanic emissions that far exceed the sediment plume that the Solwara 1 mine is expected to produce.

The final three analyses each provide a comparison of the impacts of the proposed Solwara 1 deep seabed mining project and three terrestrial copper mines: Bingham Canyon (Utah, USA), Prominent Hill (South Australia, Australia), and Intag (a proposed mine in Intag Province, Ecuador). These mines have been chosen for comparison with Solwara 1 for the following reasons:

- The Bingham Canyon Mine is typical of the large scale terrestrial copper porphyry deposits that currently account for most of the world's copper supply;
- The Prominent Hill Mine holds a copper deposit that yields a similar annual amount copper as the projected copper yields for the Solwara 1 Project;

- The proposed Intag Mine is located in an area containing cloud forest that is considered to be a unique and sensitive terrestrial ecosystem with significant species endemism. Similarly, the vent ecosystems of the deep sea are also considered a unique and sensitive ecosystem with notable species endemism.

The results of these analyses are as follows:

▲ Bingham Canyon Mine
Image credit: Spmusick via Wikicommons

Across 22 categories of ecosystem services, deep seabed mining of copper at the Solwara 1 site would involve fewer potential impacts than operations at any of the examined terrestrial mines.

Analysis II: Identification of Copper Mine Impacts for Bingham Canyon, Prominent Hill, Intag and Solwara 1

1. Two terrestrial mines (Prominent Hill and Bingham Canyon) and one proposed terrestrial mine (Intag) were ranked with Solwara 1 across 22 identified environmental and social impact categories. These categories included resource, water, climate, soil, habitat, and cultural values. Rankings were devised using publicly available data such as Global Reporting Initiative, Environmental Impact Assessments, and Annual Report documentation.

2. When ranked across the 22 categories of natural capital accounting, deep seabed mining of the high grade copper material in the 14-hectare Solwara 1 site would involve far fewer impacts than operations at any of the examined terrestrial mines.

3. People will not be displaced by the Solwara 1 deep seabed copper mine.

4. Food production, fresh water supply, disaster risk reduction, pollination, soil formation, erosion, freshwater regulation, recreation, historic, and cultural values will not be impacted by Solwara 1. These natural capital categories are often negatively impacted by terrestrial mines (as in the case of the three comparison mines examined).

5. Raw materials, biological control, climate stability, air quality, waste treatment, habitat and nursery, nutrient cycling, genetic resource values, and science and education values will be impacted by Solwara 1, but less so than for the terrestrial copper mines examined. It is highly likely that the majority of terrestrial mines would have similar impacts as the terrestrial mines examined in this study.

The following table (also found in Analysis II) summarizes the impacts of each mine site. A description and explanation of the values presented in this table is found in Analysis II.

▶ Level of Ecosystem Service Impact by Mine. Level of impact ranges from 0 (lowest) to 3 (highest).

Key
Low impact
Moderate impact
Significant impact
High impact

Ecosystem Service	Level of Impact (0 = lowest, 3 = highest)			
	Solwara 1	Prominent Hill	Bingham Canyon	Intag
Provisioning Services				
Food	0	1	3	3
Medicinal Resources	0	1	1	3
Ornamental Resources	0	0	0	1
Energy & Raw Materials	3	3	3	3
Water Supply	0	1	3	3
Regulating Services				
Biological Control	1	3	2	2
Climate Stability	1	1	2	3
Air Quality	1	0	1	1
Moderation of Extreme Events	0	1	3	3
Pollination	0	1	1	3
Soil Formation	0	3	3	3
Soil Retention	0	3	3	3
Waste Treatment	1	2	3	3
Water Regulation	0	1	3	3
Supporting Services				
Habitat & Nursery	2	2	3	3
Nutrient Cycling	1	2	3	2
Genetic Resources	1	3	3	3
Cultural Services				
Natural Beauty	1	1	3	2
Cultural and Artistic Information	0	1	2	3
Recreation and Tourism	0	0	3	3
Science and Education	1	3	1	2
Spiritual and Historic	0	3	1	3

Analysis III: Quantification of Copper Mine Impacts for Bingham Canyon, Prominent Hill, Intag, and Solwara 1

Producing one metric ton of copper results in far less freshwater use, mineral waste, energy use, area of disturbance and CO_2 emissions in Solwara 1 compared with terrestrial mines.

1 The mining impacts of Solwara 1 were quantified per copper ton produced for freshwater use, mineral waste, energy use, disturbed area and CO_2 emissions, and were then compared with the two operating mines and one proposed mine.

2 Producing one metric ton of copper requires far less freshwater, mineral waste, energy use, area of disturbance and CO_2 emissions in Solwara 1 than in any of the terrestrial mines examined.

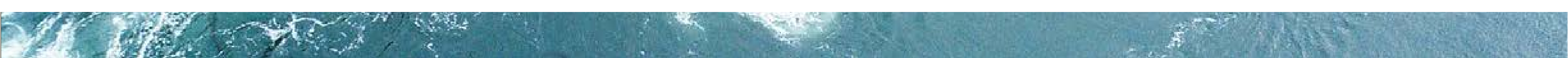
3 The risk of downslope or offsite impacts to human communities is present in all terrestrial mines that dispose of large volumes of waste and tailings materials on the surface. There is no downslope risk to human communities from Solwara 1.

4 All mines present a risk to downstream ecosystems; however, the scale of Solwara 1 is small. The site is also a naturally dynamic area due to the influence of the seafloor volcano, and downstream risks to deep seabed ecosystems are thus greatly reduced relative to the far greater threat of terrestrial copper mines to downstream terrestrial and coastal marine ecosystems.

▼ Mine Comparisons for Inputs Required for 1 Metric Ton of Copper Output

The following table is also found in Analysis III with a fuller explanation and discussion of the values presented.

	Measure	Annual Cu Production	Total Cu Production	Freshwater Use	Energy Use	CO_2 Emissions	Mineral Waste	Area of Disturbance
	Unit	Metric tons	Metric tons	Liters per metric ton of Cu produced	MWh per metric ton of Cu produced	Metric tons of CO_2 per metric ton of Cu produced	Metric tons of tailings & waste rock per metric ton of Cu produced	Square meters per metric ton of Cu produced
COMPARISON MINES	***IMPACT TYPE***							
Solwara 1 (proposed) Total	Mine + Refinery	**77,760**	**127,186**	**0**	**4.0**	**3.6**	**1.9**	**5.4**
Solwara 1 Mine	*Mine*			*0*	*4.0*	*3.6*	*1.9*	*1.1*
Tongling Refinery	*Refinery*			*Data not available*	*Data not available*	*Data not available*	*0*	*4.3*
Prominent Hill Total	Mine + Refinery	**73,362**	**2,046,000**	**83,831**	**15.3**	**5.4**	**36.3**	**7.2**
Bingham Canyon Total	Mine + Refinery + Smelter	**194,000**	**19,000,000**	**21,041**	**24.8**	**7.7**	**11.5**	**5.4**
Intag (proposed) Total	Mine	**484,437**	**9,906,472**	*Data not available*	*Data not available*	*Data not available*	**11.5**	**5.4**



▲ The Prominent Hill Mine
Image credit: Geomartin

Analysis IV: Monetization of Copper Mine Impacts for Bingham Canyon, Prominent Hill, Intag, and Solwara 1

1. The economic value of some ecosystem services impacted by copper mining can be monetized. Not all of the social and environmental impacts can be monetized, therefore the findings of this analysis should be considered an underestimate of the full social and environmental impacts.

2. The monetary damages of the three terrestrial mines and Solwara 1 were estimated across a subset of social and environmental impacts.

3. The magnitude of annual damages was calculated to be USD 1.9 million/year for Prominent Hill; USD 42.9 million/year for Bingham Canyon; USD 8.8 million/year for Intag; and USD 0.025 million/year for Solwara 1.

4. A net present value of impacts for each mine was also calculated, in which Solwara 1 (based on expectations as of the date of this report) would outperform the terrestrial mines. These values do not consider the downstream impacts, which are difficult to quantify, but including these impacts would substantially widen the differential between Solwara 1 and terrestrial mines.

5. Mining in the deep seabed (assuming the creation of sufficient biodiversity conservation sites) has fewer identified, quantified and monetized impacts than terrestrial mining.

▼ Present Value of Ecosystem Service Impacts to Solwara 1 and Comparison Mines

The following table is also found in Analysis III with a fuller explanation and discussion of the values presented.

Mine	Annual Value of Ecosystem Service Impacts	Net Present Value of Ecosystem Service Impacts	Total Copper Production for Lifetime of Mine (metric tons)	Relative Impact on Ecosystem Services per Ton of Copper Produced
Solwara 1 (proposed)	$24,724	$605,871	127,186	1.0
Prominent Hill	$1,919,065	$47,026,675	2,000,000	4.9
Bingham Canyon	$42,864,859	$1,050,403,319	17,000,000	13.0
Intag (proposed)	$8,797,585	$215,584,802	9,906,472	4.6

Copper Concentration, Smelting and Environmental Impacts

1. Though not responsible for the mineralized material at the smelter, Nautilus has chosen one of the world's newest and most efficient smelters, operated by Tongling Non-Ferrous Metals (TNFM) in China to reduce smelting environmental impacts.

2. The TNFM smelter has a closed system, which is more efficient and can better capture pollutants and useful by-products.

Overall Conclusion

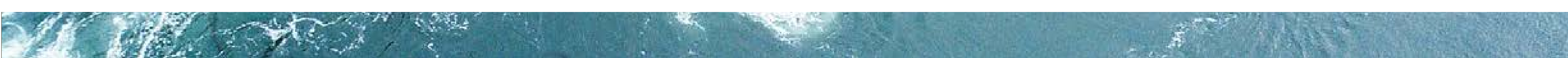
The Nautilus Solwara 1 copper mine has the potential to significantly reduce the social and environmental impacts of copper mining.

The Nautilus Solwara 1 copper mine has the potential to significantly reduce the social and environmental impacts of copper mining.

The deep seabed at the Solwara 1 mine is a remarkably advantageous choice of mining site for a number of reasons. First, no people live at the proposed mine site, and there are no cultural or historical claims to the site. The mine site itself is quite small, covering only 14 hectares of seabed. Natural resources are less impacted by operations at this site as surface or groundwater freshwater resources will be not used or contaminated at Solwara 1. In addition, there is limited overburden covering mineralized material, resulting in very little waste rock material. Finally, the proposed mine operation wastes will be dwarfed in comparison to the impacts of a nearby erupting underwater volcano. Even excluding these by-product credits, the mineralization copper grade alone is approximately 7%,[3] a remarkably high percentage which will lead to numerous efficiencies.

The overall conclusion is that Solwara 1 has the potential for far fewer social and environmental impacts than the existing terrestrial mines examined. Based on this analysis, it is highly likely that Solwara 1 would have far less overall impact per ton of copper produced than the currently operating Prominent Hill, Australia, and Bingham Canyon, USA, mines and the proposed Intag, Ecuador, copper mine. Indeed, Solwara 1 may well have far less overall social and environmental impacts than any currently producing copper mine.

Solwara 1 presents an opportunity for PNG to receive mining royalties that will support the national budget for education, health, and other expenditures while achieving significantly fewer social and environmental impacts compared with terrestrial mining. The impacts of terrestrial mining are well demonstrated in the existing PNG mines and elsewhere in the world, and this analysis reveals a



The mineralization copper grade at Solwara 1 is 7%, a remarkably high percentage that will lead to numerous efficiencies.

potential alternative to the heavy impacts of terrestrial mining.

Currently, there are several other Seafloor Massive Sulphide (SMS) deep seabed mining proposals moving forward under the auspices of various companies. As the first company to commercially explore the seafloor for SMS, Nautilus has to date defined the standards for deep seabed mining at the national and international scales. As the first proposed deep seabed mining project, Solwara 1 will set a high sustainability standard as an example for all followers. Solwara 1 is likely to surpass many of the International Finance Corporation (IFC) social and environmental standards for mining practices.

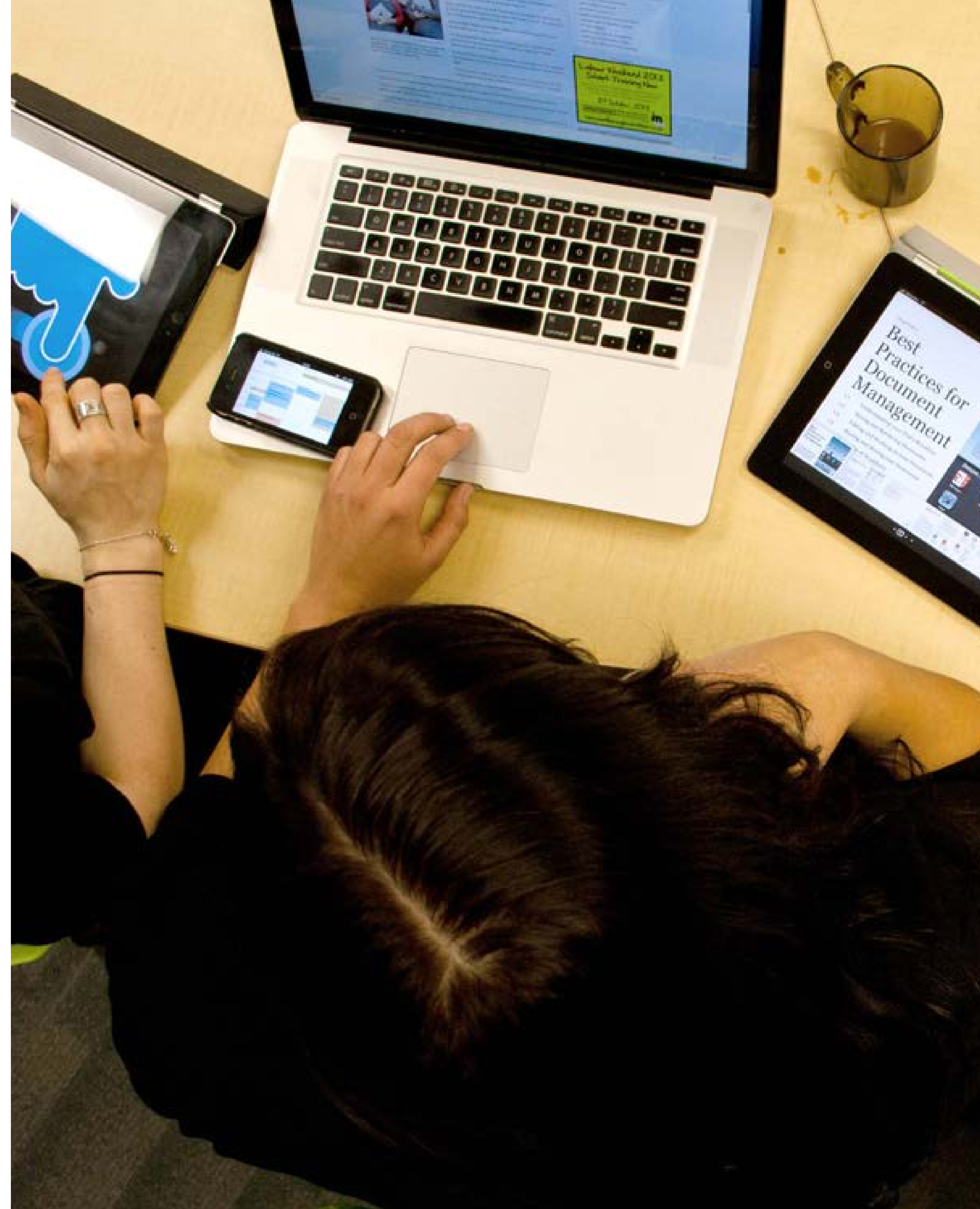
Importantly, Solwara 1 has set a high bar for social and environmental management, study of the seabed, establishment of vent habitat conservation areas, collaboration with the scientific community, transparency, and collaboration with unaffected, but nearby communities for development.

While recognizing Nautilus' efforts to date, the authors also wish to encourage the company to continue to show this high level of responsible leadership in this emerging industry.

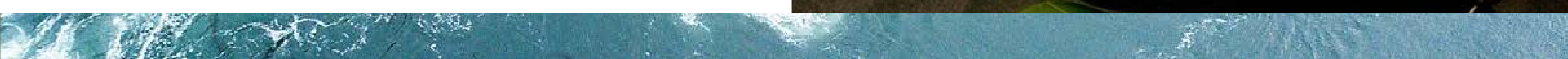
As with any planned project that has yet to enter production, uncertainties remain. Further analysis should be undertaken as Solwara 1 commences operation in order to better understand and record the impacts of deep seabed mining, the post-mining recovery process, and the importance and effectiveness of establishing deep seabed conservation areas.

Copper is an essential element for the 21st century global economy, and it is a critical element in securing a high quality of life for the world's population. With the implementation of appropriate controls and management measures, seabed mining could play a catalytic role in transforming global copper mining into a more sustainable, less damaging, and less risky industry.

Most of the Earth's crust is below the ocean's surface. Opening up this area may reveal higher copper concentrations that have the potential to significantly contribute to global copper supplies and greatly reduce the environmental and social costs of copper mining. Solwara 1 appears to be a well-planned, carefully developed project with a clear opportunity to dramatically reduce the social and environmental impacts of copper mining.

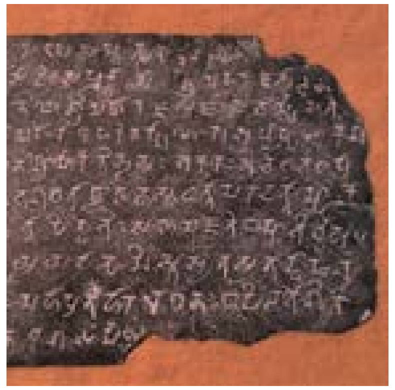


▶ All of our electronic devices use copper
Image credit: Judit Klein via Flickr



Introduction

◀ Drinking Fountain
Image credit: Jeff Turner via Flickr



Copper-plate charter of Budhagupta dated anno 168
Image credit: By Shirazibustan

Economies need nature. Oxygen, water, food, energy, minerals, and materials are just a few of the products of natural capital.

Since early human history, copper has held an important position in human development. Today, its value is no less significant.

Copper continues to have widespread use for humans in applications from telecommunications to electrical power generation. As a result, copper mining has become a widespread industry with significant impacts to both human communities and the environment. To date, copper mining has been restricted exclusively to terrestrial mine sites. In this report, we explore the potential impacts of deep seabed mining through several analyses that compare the impacts of a proposed deep seabed mine site known as the “Solwara 1” project with three terrestrial mine sites located in distinct environments.This study utilizes a natural capital accounting approach to analyze the impacts of each mine site.

Economies need nature. Oxygen, water, food, energy, minerals, and materials are just a few of the products of natural capital. Indeed, all built capital is physically constructed out of natural capital, using energy derived from natural capital. Understanding the qualities, quantities and monetary value of natural systems falls within the realm of social and environmental analysis and natural capital accounting. Modern business, governments and non-profits rely on accounting to provide a clear tally of the value of assets and the streams of benefits or costs to which those assets are tied. Social and natural capital, however, have often been left off the balance sheet, at great cost to the communities and ecosystems with which they are connected. There have been many efforts in recent years to begin valuing natural capital and the environmental benefits (ecosystem goods and services) that flow from it. The United Nations, the World Bank, Global Reporting Initiative, and other organizations have initiated social and natural capital accounting efforts. For example:

- In 2007, the United Nations launched an initiative called “The Economics of Ecosystems and Biodiversity” (TEEB). TEEB laid out a framework and a database that demonstrated values for biodiversity and other services provided by ecosystems, and identified mechanisms for capturing these values in decision making.[4] This study adapts and builds upon the TEEB framework for categorizing and valuing ecosystem services in Analyses II and IV.

- The Global Reporting Initiative (GRI) has initiated voluntary sustainability reporting guidelines for private firms in many sectors of the economy. A number of copper mining companies provide GRI reporting, although a more complete physical reporting is needed. Analysis III in this report use several key GRI categories and examine how Solwara 1 compares to existing copper in a number of environmental impact areas (e.g. freshwater use, CO_2 emissions).

Reconstruction of the copper axe of Ötzi the Iceman, a man who lived around 3,300 BCE
Image credit: Bullenwächter

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- Earth Economics houses the most comprehensive database of natural capital valuation studies in the world, which was used to conduct Analysis IV. The Earth Economics database contains the TEEB database as well as five other ecosystem service databases and thousands of unique studies not yet contained in other databases. Within the field of natural capital accounting, Earth Economics is a globally recognized leader in effectively applying natural capital valuation to decision-making and in advancing the field.

- At the macroeconomic level, the World Bank has initiated a program at the scale of the nation, called the Wealth Accounting and Valuation of Ecosystem Services (WAVES) program, which is developing methods for country-level natural capital accounting. The WAVES program has initiated work in Botswana, Colombia, Costa Rica, Madagascar and the Philippines.[5] This study is conducted at the project level and does not use the WAVES framework; however, it is hoped that information from project-level analyses like the one presented in this report can eventually be used to inform WAVES measures.

The goal of sustainability implies a relationship between human economies and natural systems that leaves natural capital in good health, or restores it to a sufficiently healthy state to support biodiversity and ecosystem services. In the context of copper mining, there is much that could be done to ensure that the mining results in lower impacts to natural capital. This report contributes to the body of knowledge surrounding copper mining and identifies and monetizes specific impacts at four mine sites.

In the next few sections, a brief history of copper and a description of copper’s use in modern society are presented before reaching the first analysis, which examines two alternatives to copper mining: recycling and substitution. Analysis I provides an assessment of whether or not recycling and substitution are viable alternatives to copper mining.

Following this first analysis, this report then turns to the Solwara 1 project area, describing the state of knowledge of this area of deep seabed.

Selection of Comparison Mines

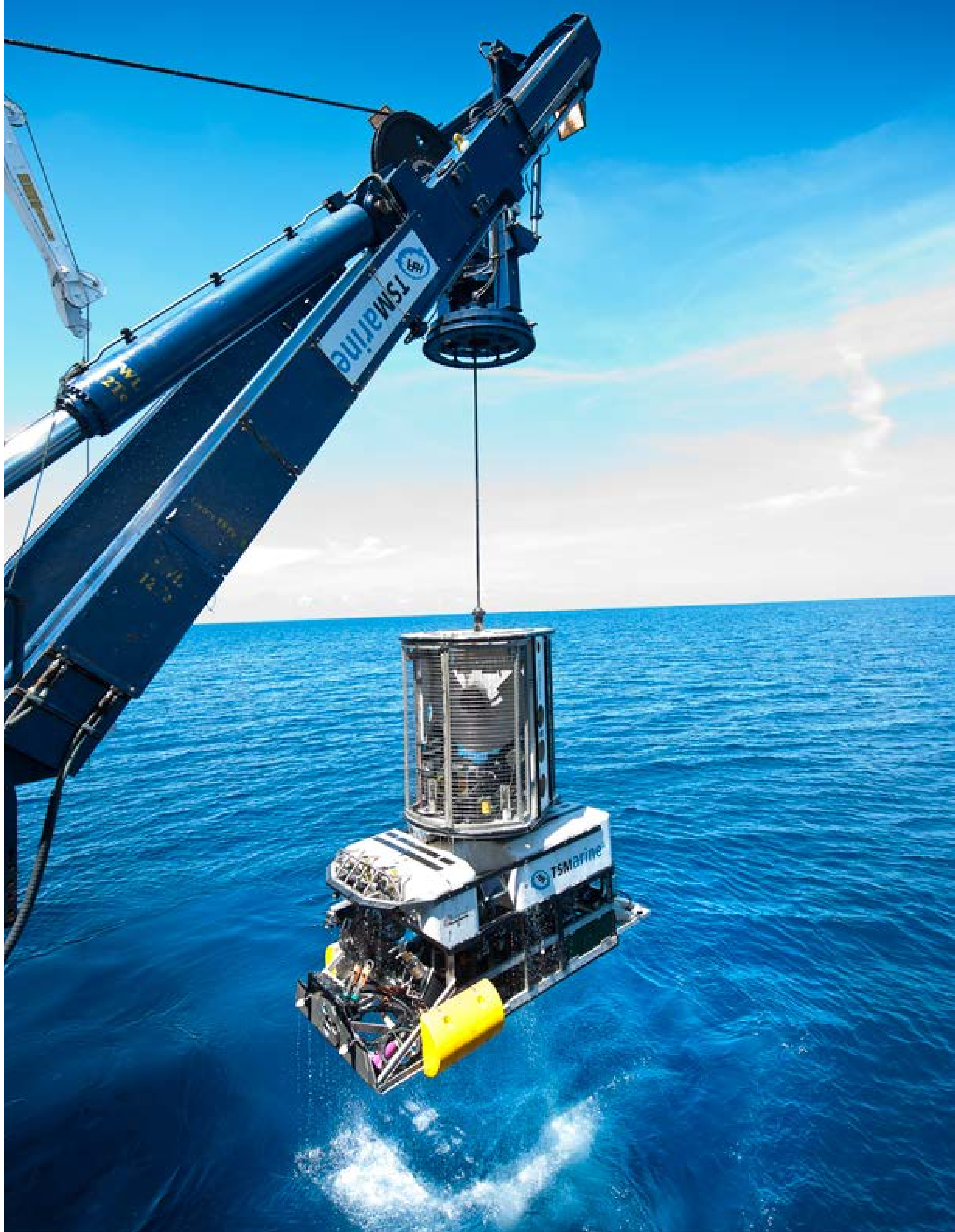
Next, the report provides a background in natural capital accounting before presenting the final three analyses, which each provide a comparison of the impacts of the proposed Solwara 1 deep seabed mining project and three terrestrial copper mines: Bingham Canyon (Utah, USA), Prominent Hill (South Australia, Australia), and Intag (a proposed mine in Intag Province, Ecuador). These mines have been chosen for comparison with Solwara 1 for the following reasons:

- The Bingham Canyon Mine is typical of the large scale terrestrial copper porphyry deposits that currently account for most of the world's copper supply;
- The Prominent Hill Mine holds a copper deposit that yields a similar annual amount copper as the projected copper yields for the Solwara 1 Project;
- The proposed Intag Mine is located in an area containing cloud forest that is considered to be a unique and sensitive terrestrial ecosystem with significant species endemism. Similarly, the vent ecosystems of the deep sea are also considered a unique and sensitive ecosystem with notable species endemism.

Analysis II provides a description of the ecosystem goods and services expected to be impacted by the Solwara 1 project while simultaneously providing a parallel description of the ecosystem goods and services of the three aforementioned terrestrial mines.

In Analysis III, Solwara 1 is next compared to these three copper mines in terms of the physical quantities of inputs (water, energy, land) that are required to produce one metric ton of copper. We also quantify the amount of mineral waste and carbon dioxide emitted for every metric ton of copper produced.

Finally, in Analysis IV, the dollar value of annual natural capital ecosystem goods and services lost is estimated for Solwara 1 and the three comparison mines, as is the dollar impact of carbon dioxide emissions. The ecosystem service analysis is based on existing academic ecosystem service valuation studies, and is conducted similarly to a business or house appraisal process.



▶ Remotely operated underwater vehicle
Image credit: Nautilus

Copper and the Environment: A Nano–History

◀ Double paisa of Tipu Sultan, undated, minted at his capital Patan
Image credit: By Rani nurmai

▲ Native Copper
Image credit: Element-collection.com

Copper has been a key resource in human development, and it will likely retain its importance for many years yet to come.

Indeed, copper was the first metal to advance humanity beyond the Stone Age. The social and environmental impacts of copper mining and smelting have been present for at least 7,000 years.[6]

Initially, native copper (comprised of 98% pure copper minerals) was mined, but these rare deposits were quickly exhausted and lower grades of ore were then pursued. Copper ore requires a type of processing called smelting, which extracts the metal from its ore using heat and chemicals, which can lead to further environmental impacts. Ancient copper smelting sites have been found in China, Turkey, Serbia, and Egypt.[7] Arsenic commonly occurs in copper minerals and was combined with copper in early bronze smelting. Ancient smelting sites are still contaminated with high arsenic levels.[8]

140
METRIC TONS
OF ORE MUST BE MINED AND PROCESSED TO EXTRACT A SINGLE METRIC TON OF COPPER AT A TYPICAL MINE

Copper mining and production have expanded extensively since the advent of the Bronze Age. The 20th century was characterized by steep increases in copper production and steep declines in copper ore concentrations. The rising social and environmental impacts of copper mining are closely tied to expanding production and declining ore grades. For example, the Holden Mine in the Pacific Northwest region of the U.S. was a top U.S. copper producing mine during World War II. In operation from 1937 to 1957, Holden Mine removed copper ore with an average concentration of 6%.[9] For every 16.6 metric tons of ore hauled out of the Holden Mine, 1 metric ton of copper was recovered. Unfortunately, terrestrial copper ores of this concentration have largely been mined out and concentrations now yield much lower percentages globally.

Today's largest copper mines, such as the Chuquicamata mine in Chile, have ore grades in the range of 0.7%. This means that, without counting the overburden (the rock and soil above the ore deposit that is removed prior to ore recovery), 140 metric tons of ore must be mined and processed to extract a single metric ton of copper.

As ore concentrations decline, the physical inputs required per ton of copper produced, as well as impacts on the environment, are likely to increase.

Proposed terrestrial mines, such as the site in Intag, Ecuador, have average concentrations beginning at 0.7%, and lower. As ore concentrations decline, the physical inputs required per ton of copper produced, as well as impacts on the environment, are likely to increase.

Figure 1 shows the decline in copper ore grades since 1900, and Figure 2 shows declining world ore grades since 1995 in comparison with the Solwara 1 indicated resource.

Figure 1. ▶
Declining copper ore grades worldwide
Source: Mudd, G.M., 2010. The "Limits to Growth" and 'Finite' Mineral Resources: Re-visiting the Assumptions and Drinking From That Half-Capacity Glass. 4th International Conference on Sustainability Engineering & Science: Transitions to Sustainability.

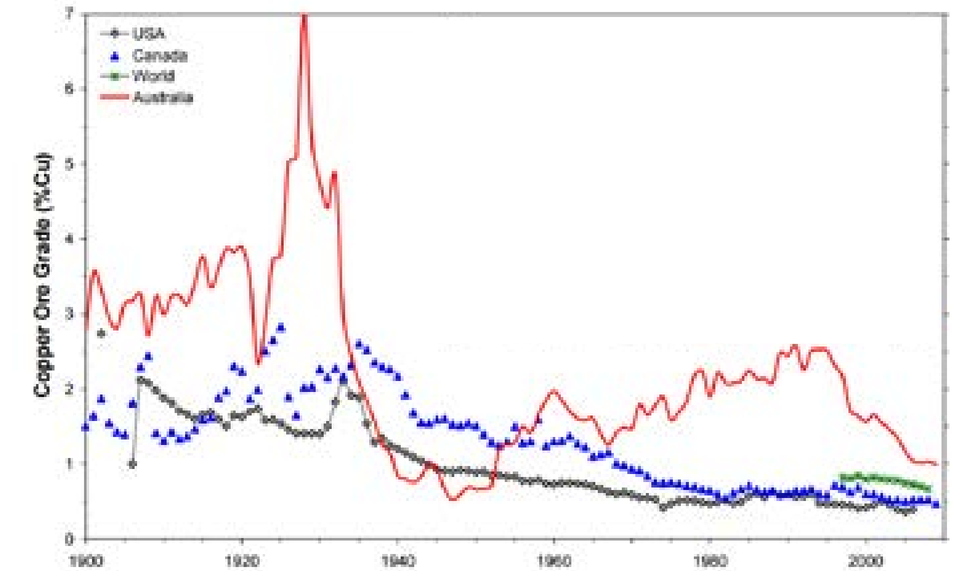
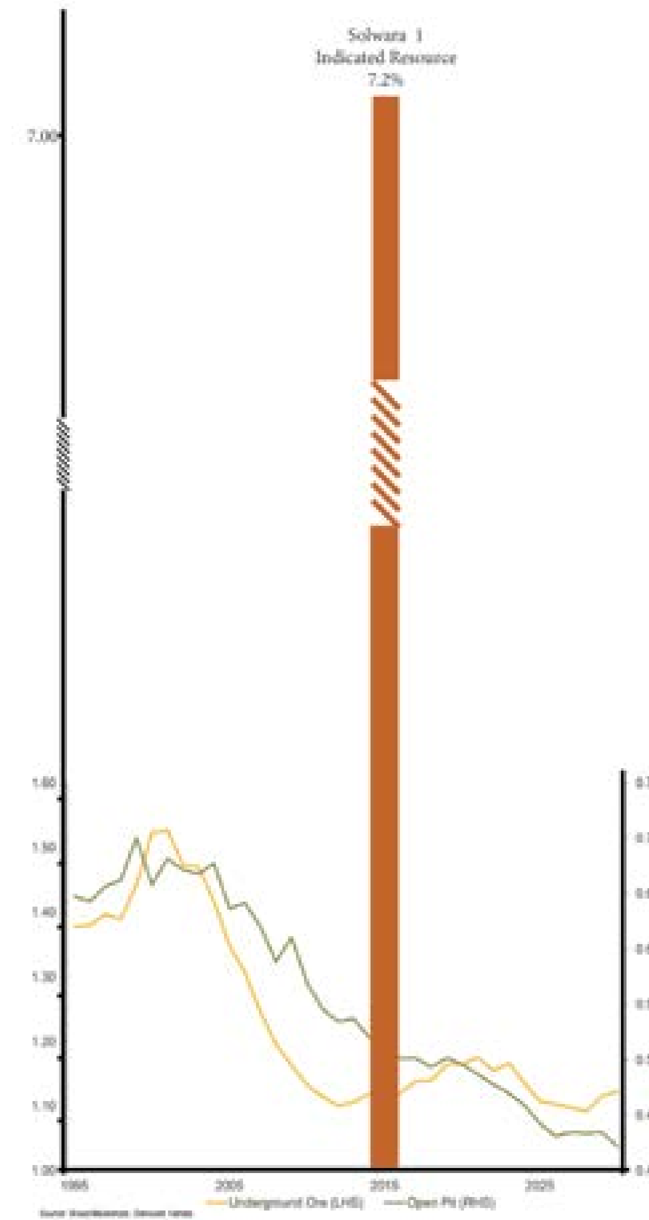


Figure 2. ▶
Declining world ore grades since 1995 in comparison with the Solwara 1 indicated resource
Source:Nautilus



Waste disposal in copper mines also generally has a large surface area impact. The compacted rock is blasted loose and expands in volume by 40% or more. The ore, waste rock and tailings are typically re-deposited upon the earth's surface.

As vast features on the landscape, terrestrial copper mines and their accompanying tailings, dams and leach heaps necessarily impact the biota, surface water and groundwater, and they produce significant air and water pollutants, including emissions of global warming gases. All large open-pit copper mines operate in groundwater strata. Some mines, such as Bingham Canyon in Utah, USA are well over one kilometer deep. Like Bingham Canyon, many copper mines are also located at high elevations as copper is commonly deposited in volcanically active periods. In 2013, the Bingham Canyon mine experienced a catastrophic landslide, though fortunately nobody was hurt.[10]

There is a long history of conflict between mine operators and people living within, around, and downstream of copper mines, tailings, and smelter sites.

With few exceptions, people inhabit or directly use the landscapes where copper mines are established. There is a long history of conflict between mine operators and people living within, around, and downstream of copper mines, tailings, and smelter sites. Appendices D and E provide several examples of copper mine and smelter impacts on local communities.

To date, the 7,000-year history of copper mining has been exclusively terrestrial, but companies are beginning to consider deep seabed mining as a means to achieve copper production goals and potentially reduce impacts. Deep seabed mining eliminates many inherent issues associated with terrestrial mining due to a lack of human inhabitants within the mine site and a lack of long-term liabilities remaining after the mine is closed. Additionally, copper deposits currently discovered at the seabed are not buried beneath large volumes of rock and soil that are considered 'waste' material, and therefore require much less overburden removal than their terrestrial counterparts.

Deep seabed mining needs to be conducted responsibly and sustainably with a firm base in solid science and economics that fully accounts for the social and environmental costs and benefits of such mining operations. Careful accounting of these social and environmental impacts provides critical information in understanding the full costs and benefits of these mining operations.

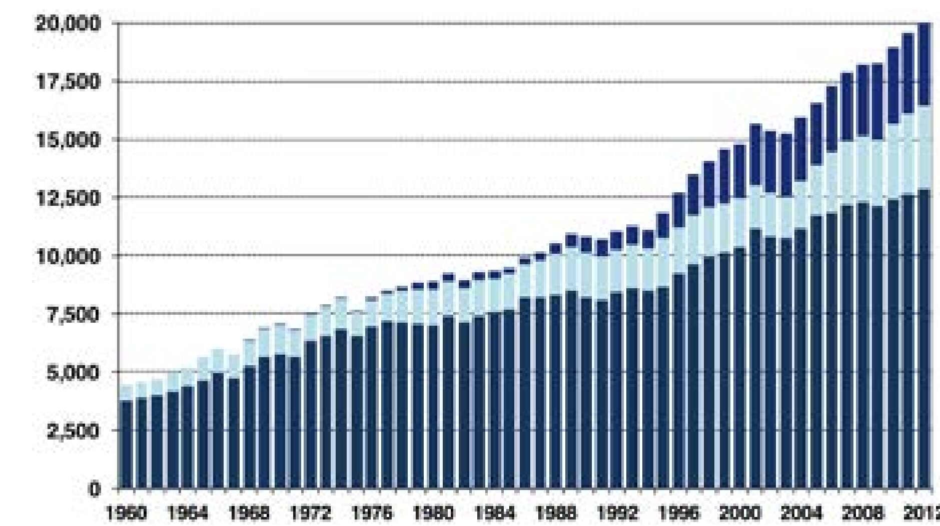
Copper and Modern Economies

Copper is necessary for the expansion of renewable energy resources such as wind, wave, geothermal, and tidal power.

Today, copper, iron and gold are amongst the most widely used metals in modern society.[11] Copper, in particular, is used for a wide range of purposes and is a key element of progress in modern economies. It is currently essential to nearly all equipment powered by electricity. Modern plumbing, which delivers potable water, is heavily dependent upon copper pipes and fittings. Copper is antimicrobial, and therefore highly useful in medical applications.[12] Copper components are found in many items that define the built capital of economic advancement, including refrigerators, cell phones, generators, computers, medical apparatus, plumbing pipes, communications transmission and power tools.

In the production of electrical power, copper is by far the best element for the windings on generators. It is used exclusively in power station generators whether the energy source is coal, gas, oil, hydro, nuclear, wind, wave, geothermal, or solar (steam) power. Over 21 billion-kilowatt hours of electrical power were produced globally in 2012,[13] and these hours were fully dependent upon copper windings. Copper is necessary for the expansion of renewable energy resources such as wind, wave, geothermal, and tidal power. For many uses, there is no known substitute for copper. Copper is ubiquitous in specialized electronics. Instruments utilizing copper are necessary in agriculture, steel production, software development, retail sales, teaching, surveying, and virtually every activity using electricity or technology. Copper is essential to all modern economies and the production of virtually all goods and services.

Figure 3. World Refined Copper Production, 1960-2012. Units in thousand metric tonnes. With the emergence of solvent extraction-electrowinning (SX-EW) technology, refined copper produced from leaching ores has been on the rise, increasing from less than 1% of world refined copper production in the late 1960's to 18% of world output in 2012.
Source: ICSG.



21 BILLION KILOWATT HOURS

OF ELECTRICITY ARE PRODUCED WORLDWIDE EACH YEAR, WHICH ALL DEPEND ON COPPER

Copper Demand and Supply

According to the International Copper Study Group, total refined copper production for 2013 was 21.0 million metric tons, yet world consumption of refined copper stood at 21.2 million metric tons, drawing standing copper stocks down. The first quarter of 2014 saw a 5% rise in copper production, and over 8% rise in consumption, further reducing copper reserves.[14]

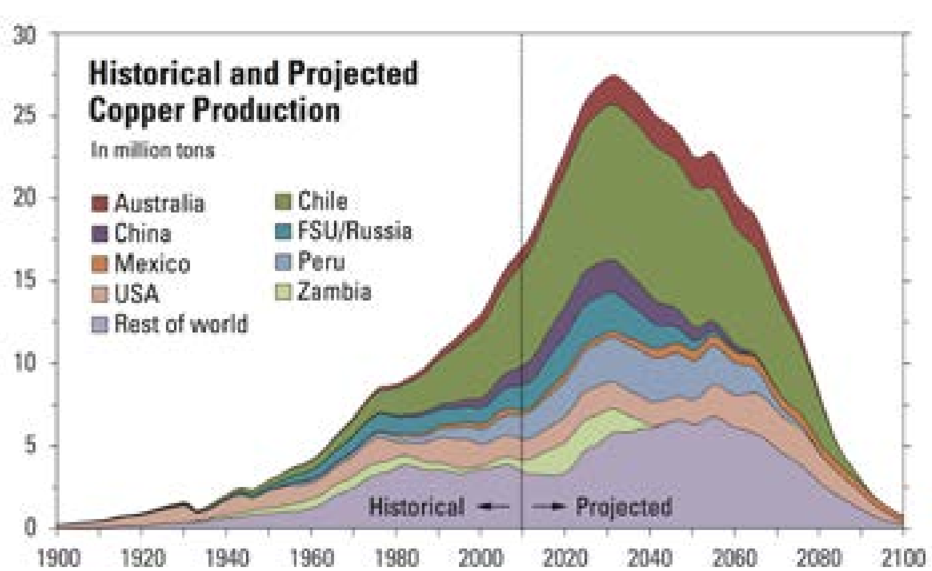
2040

THE YEAR WORLD COPPER PRODUCTION IS PREDICTED TO BEGIN DECLINING

Copper consumption has steadily grown along with the global economy, and it is expected to continue to grow as greater numbers of people have access to electricity, plumbing and modern appliances. The World Bank, for example, has launched lending for rural electrification in the Sub-Saharan Sahel region of Africa with the goal of providing power to an additional 60 million people who are without electricity today.[15] This venture would require untold amounts of copper for implementation, yet this expansion is still dwarfed by the current scale and rate of rural electrification in India and China. China currently utilizes about 40% of the world's copper production. China is also the global leader in copper smelting, producing nearly 6 million metric tons of refined copper in 2013 alone.[16]

Another factor in the increasing demand for copper is that many industrialized nations also have aging power grids. Improvements and capacity expansion of grids in the US, Europe, Japan and Australia continue. To further complicate the picture, a 2014 study published in the journal Science predicted that we may be approaching "peak copper", the time when extraction levels begin to decline due to dwindling accessible reserves (see Figure 4).

Figure 4. Peak Copper
Source: Kerr, R.A., 2014.[17]



Finally, copper is not only used as an industrial commodity. Currently, refined copper ingots are widely used in China as collateral for business loans. There is significant concern that the stock of copper used as collateral is oversubscribed.[18] These collateral and other speculative holdings of copper make understanding demand and supply somewhat more complex than for other commodities.

The Long–Term Liability of Copper Mining

Holden Mine Site: View of Mill Building
Image credit: USFS

Clearly, copper mining is important to human development, yet it does not come without costs. Terrestrial copper mining involves significant and often permanent ecological impact. Invariably, the local biodiversity, surface water and groundwater are impacted. Land covers from forests to wetlands and from deserts to coral reefs are often severely and perhaps irreversibly degraded. Mines move earth on a large scale. Tailings from underground or surface mines are typically measured in the hundreds of millions of metric tons. Terrestrial mining also involves impacts to indigenous peoples, communities, farms, towns, cities and coastal areas.

Active mining operations are not the only threat to local environments and communities. Closed or completed mines can also pose environmental risks and impacts in the form of ongoing rehabilitation requirements. The Holden Mine in Washington State, USA, is one such example. Now owned by Rio Tinto, the mine closed in 1957. In 2012, U.S. Federal Agencies ruled that, even in spite of its lack of on-site production activities, Rio Tinto was responsible for remediation of the mine site. The corporation subsequently embarked on a $200 million remediation project that is slated for completion in 2015.[19] Holden was an underground mine; however, over 100 million metric tons of tailings and acid leach heaps are currently eroding and leaching arsenic and other heavy metals into Lake Chelan and the Columbia River. However, even with a $200 million remediation expense, the wall to hold back erosion and the wastewater treatment system that will remove arsenic and other contaminants are not necessarily a permanent solution. In future decades, the more than 100 million metric tons of waste will likely continue to erode. Fifty-year flood events could wash enormous amounts of waste beyond the retention wall. There is often no permanent or cost-effective solution to the problem of hundreds of millions of metric tons of hazardous mining waste located in an upper watershed.[20]

Terrestrial copper mining involves significant and often permanent ecological impact.

Liability from historic terrestrial mining goes largely unmeasured worldwide, but estimates are substantial by any industry expert's

▲ Bio Bio river dam
Image credit: Roberto Araya Barckhahn

speculation. Aside from liability, other requirements of mining also come with high costs. In recent history, falling in-situ copper ore grades have required increased earth moving and processing that in turn require greater energy inputs for every metric ton of copper produced. Moving hundreds of millions of tons of rock demands energy. In Chile, for example, over 20%, or approximately 3,400 megawatts (MW), of national electrical production is consumed by the copper industry alone. Power and water constraints now limit the expansion of copper mines in Chile. Planned mines such as Intag in Ecuador require the construction of new hydroelectric dams to provide sufficient power for the mine operations.

The social and environmental impacts of open-pit copper mines can be tremendous. Terrestrial mines often have large geographic footprints that expand even after the mine closes as gravity carries mine tailings away from the mine site and eventually to the sea. The Ok Tedi Mine in PNG, for example, has deposited mine material and impacted 620 miles (1000 km) of the Fly River (the longest River in PNG). Hundreds of millions of metric tons of waste rock and mine waste material dumped into the Fly River have increased sediment load to the river by 5-10 times the natural background rate, and increased copper levels in the river system have reached 15 times the natural background rate.[21]

Mining disasters too, are not uncommon. The Marcopper mine in Marinduque, the Philippines, is a prime example of the catastrophic effects that mining disasters can create. In 1996, a retention dam at the mine failed, causing 84 million metric tons of mine tailings, of which 4 million metric tons were rich in sulphuric acid from copper leaching, to be released into the Makulapnit-Boac river system. The spill inundated over two-dozen communities and impacted 12 fishing villages by smothering a stretch of the river, the area's nearby towns, and the coral reef at the river's outlet with mine tailings.[22]

Additional examples of the impacts of copper mines are provided in Appendix E.

The history of terrestrial copper mining, and its large-scale impacts warrants a consideration of alternative options for future copper mining.

One alternative is the careful and responsible mining of copper resources on the seabed.

The history of terrestrial copper mining, including its large-scale impacts, challenges to rehabilitation, and history of significant incidents, warrants a consideration of alternative options for future copper mining. One such alternative is the careful and responsible mining of copper resources on the seabed. Seabed mining, however, should also be assessed for environmental and social impacts. One way to determine whether this alternative should be considered viable in the future is to complete a natural capital assessment of a potential seabed mine and to compare it with the natural capital assessment of a number of existing or proposed terrestrial mines. This report provides that analysis, recognizing that better natural capital accounting in the terrestrial mining industry is also needed in order to fully comprehend the risks and benefits of both terrestrial and marine copper mining. Before comparing the Solwara 1 deep seabed mining project with the three terrestrial mines, the following Analysis I examines the potential for displacement of mining with recycling and substitution.

Conclusions

1. Over 7 billion people use copper. It is essential to achieving human development goals.
2. Copper is vital for producing numerous forms of electrical power, clean water, and technology.
3. Terrestrial copper mining has significant social and environmental impacts. Risks of terrestrial mining include displacement of communities, water contamination, and damage to downslope communities from waste rock and tailings.
4. The concentration of copper in terrestrial ore deposits is declining. This decline is increasing financial, social, and environmental costs associated with production, on a cost-per-metric ton basis.

▼ Offshore windmills
Image credit: Vattenfall via Flickr

Analysis I
Copper Recycling and Substitution

◀ Copper fittings
Image credit: Tony Hisgett.

Can Copper Recycling and Substitution Displace Mining?

▲ Scrap copper, one source of recycled copper
Image credit: www.scrapmetalsydney.com

Recovering and recycling copper helps meet global demand, conserves natural resources, and reduces environmental and social externalities.

At a first look, recycling appears to be a viable option to displace mining.

Copper is virtually 100% recyclable; as an element, it does not decay. Copper does not lose physical, chemical, or performance properties with recycling processes, so recycled copper is no different from copper smelted from ore. Recovering and recycling copper for reuse helps meet global demand, conserves natural resources, and improves sustainability by reducing environmental and social externalities. The process of recycling copper, called secondary production, also uses up to 85% less energy than primary production (mining). Overall, the current level of copper recycling saves an estimated 100 MW of electrical energy and 40 million metric tons of CO_2 worldwide each year.[23]

Currently, recycling provides approximately 30% of the global copper supply. Copper prices are high. The global recycling market is large, brisk and efficient, and there is a strong global awareness that recycling copper provides income. However, it appears that there is no vast stock of copper easily available and simply waiting to be recycled. Copper has a long useful life in most products. In fact, most of the copper mined since 1900 is still in use.[24] With no vast copper resources available for recycling, the potential for fully replacing mining with recycling simply cannot be realized.

Mining today continues to provide the majority of the copper supply. The ever-increasing demand for copper has already reached 24 million tons/year and continues to rise, but this demand is also highly sensitive to economic downturns, particularly in the housing market. Additional copper recycling will be necessary to keep up with the growing demand, but this will not relieve the full demand for copper from mining.[25]
As it is clear that recycling will not supply enough copper to meet growing global demands, the only option left available for displacing mining is substitution. For many applications, copper is a difficult material to replace because it performs so well as a power and heat conductor. Carbon-based conductor replacement materials are on the technological horizon, but they are simply not yet present in quantity.[26]

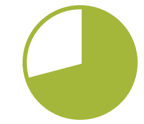
40 MILLION METRIC TONS

OF CO_2 EMISSIONS AVOIDED EACH YEAR BY COPPER RECYCLING

30%

OF THE GLOBAL COPPER SUPPLY

IS PROVIDED BY RECYCLING



Overall, it is clear that continued mining is required to meet growing copper demand and to ensure that more people living in poverty can avail themselves of modern power, drinking water and electronic goods.

Fiber optics cable technology, used in many telecommunications applications, provides an example of a superior substitute for copper in one industry. Fiber optic cable is far faster and more efficient at conducting communications signals than copper, and it has significantly reduced what would have been the demand for copper without fiber optic development. Optic fiber is unquestionably a superior substitution for copper in long-haul communications, and markets have powered this substitution.

Another example of substitution is in aircraft wiring. In this case, aluminum wire is more efficient than copper in the conductivity to weight ratio. However, when weight is not a factor, copper remains the better option. Aluminum has a greater expansion coefficient, which has caused a greater frequency of house fires in aluminum wired houses than in copper wired houses.[27]

Other substitutes such as Pex and aluminum wiring remain more costly, with less overall performance value and therefore less sustainability than copper. Substitution could provide a significant and less costly source of copper; however, supply would still be insufficient.

Overall, it is clear that continued mining is required to meet growing copper demand and to ensure that more people living in poverty can avail themselves of modern power, drinking water and electronic goods.[28] Much of the current copper consumption provides new services such as rural electrification, residential construction, and industrial applications, particularly in China and India.

Conclusion of Analysis I: Copper Recycling and Substitution as Alternatives to Mining

The demand for copper outstrips the available supply. Recycling, substitution, and copper mining are required to meet global demand.

There are two main paths that could potentially reduce the need for additional copper mining. The first option would be to redesign products so that more copper can be pulled from these products when their useful life is complete. The second route would be the substitution of other materials and technologies for a significant portion of the copper stock currently in use. This would require a system for replacing the services of copper and cheaply mining built capital copper stocks without damaging in-use buildings and other facilities.

Though this approach may be viable in the future, it is not yet feasible, and the demand for copper still outstrips the available supply, including recycling and substitution. For a more in-depth discussion of recycling and substitution, please see Appendix C.

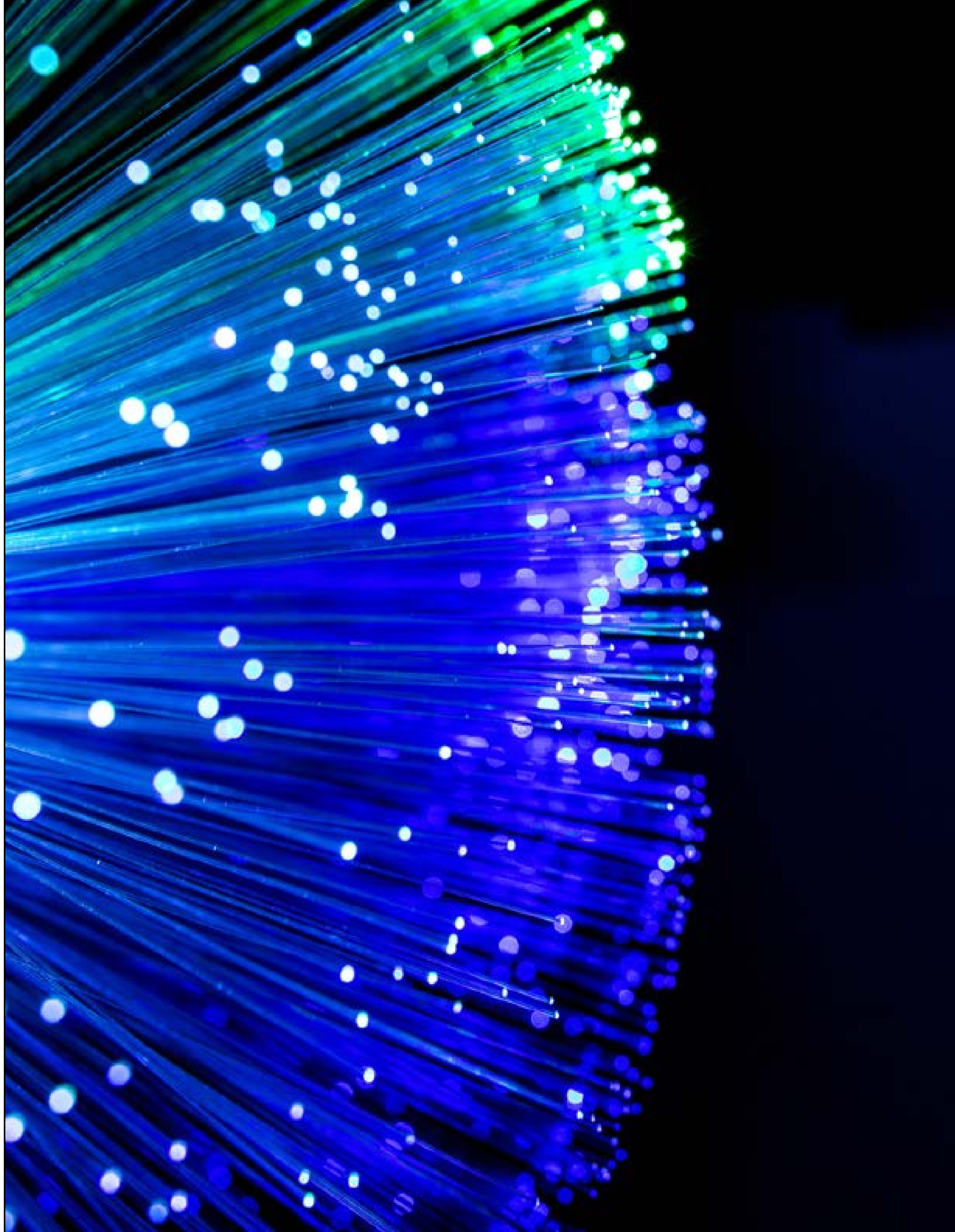
Three important conclusions are:

1. Copper recycling prices are high, with brisk, robust copper recycling markets. However, there is not much idle copper available to be recycled.

2. Copper recycling is likely limited to around 35% of global supply, and the substitution of other materials and technologies for the currently in-use copper stock will not be realized in the near future, thus, demand for copper ore will remain high and copper mining will likely expand globally.

3. Even if recycling a significant portion of the current global built capital stock became feasible, copper ore mining would still be required in order to meet global demand.

As it is clear that neither recycling nor substitution can fully displace mining, the question remains of how best to mine copper with the fewest negative externalities or damaging impacts to communities, biodiversity, water quality, and natural systems. This report aims to contribute to the knowledge of best copper mining practices through a comparison of the Solwara 1 site and the three terrestrial mine sites.



▶ Fiber optic cable
Image credit: Groman123 via Flickr

The State of Knowledge of the Bismarck Sea Deep Seabed

North Su, active subsea volcano
Image credit: Nautilus

The proposed mine site is located in an area with a great deal of volcanic, seismic and hydrothermal activity that causes regular disturbances, estimated to be comparable to the disturbances caused by mining activities.

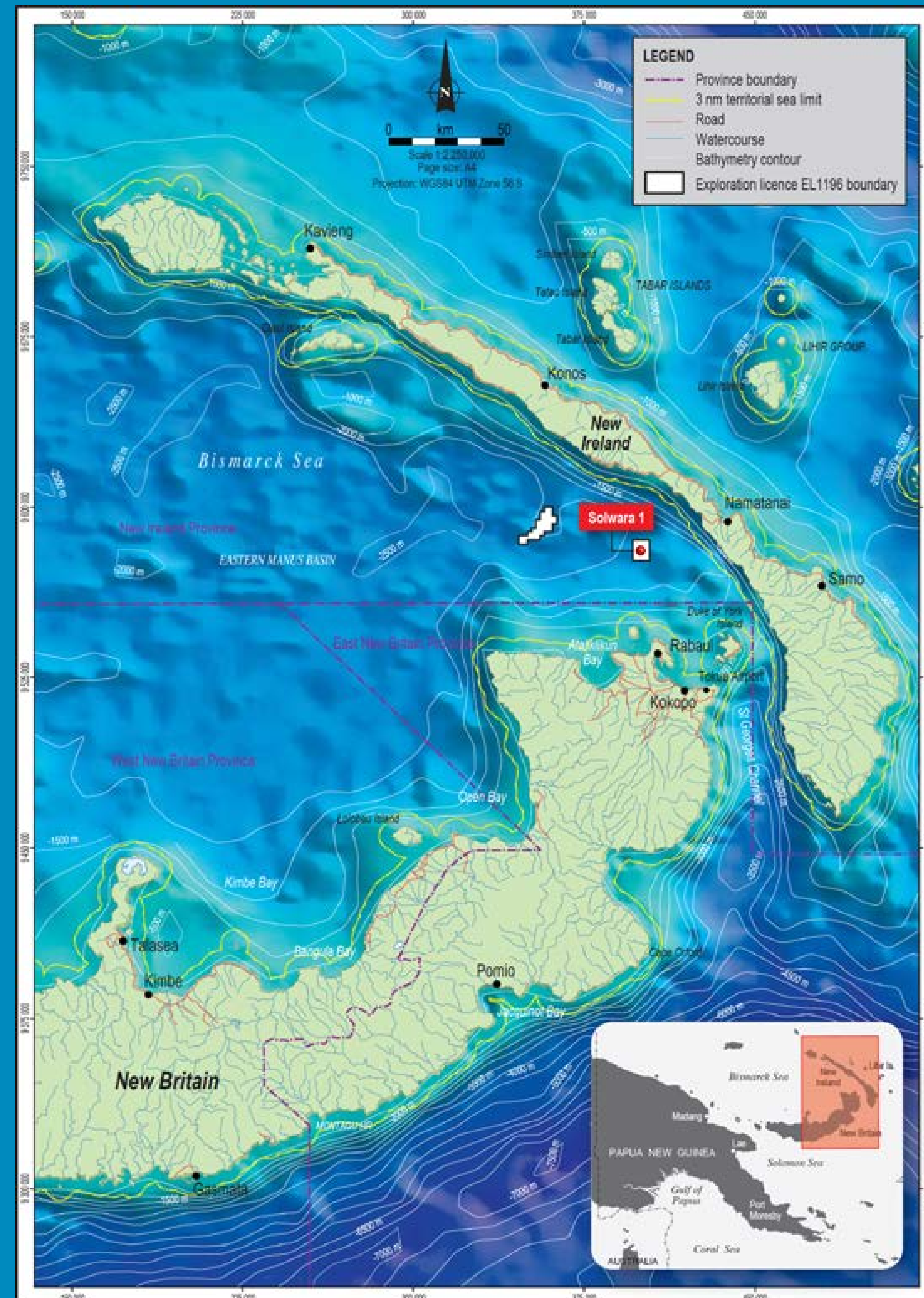
The deep seabed environment, which is the proposed location of the Solwara 1 mine, is a unique area.

The Solwara 1 site is located 30 km off the shore of PNG in the Bismarck Sea near an area known as the “Coral Triangle”. This area occupies approximately 2% of the Earth’s seafloor, yet it contains 76% of the world’s coral population and 37% of the world’s coral fish population.[29] The proposed Solwara 1 mine site is not near the coral reef area, as it is located 30 km offshore at a depth of 1,600m, far below the phototrophic level where sunlight reaches.

The proposed mine site is located in an area that boasts several underwater volcanoes, and thus there is already a great deal of volcanic, seismic and hydrothermal activity in the area that causes regular disturbances that are estimated to be comparable to the disturbances caused by mining activities. The North Su underwater volcano has been erupting for many decades and has a plume much larger than the mine disturbance is predicted to be. The plume also extends higher than the predicted mine impact plume, and there is no evidence to date of the volcanic plume extending into the epipelagic (upper) part of the ocean, even though it occurs higher in the water column than the Solwara 1 mine plume will occur.

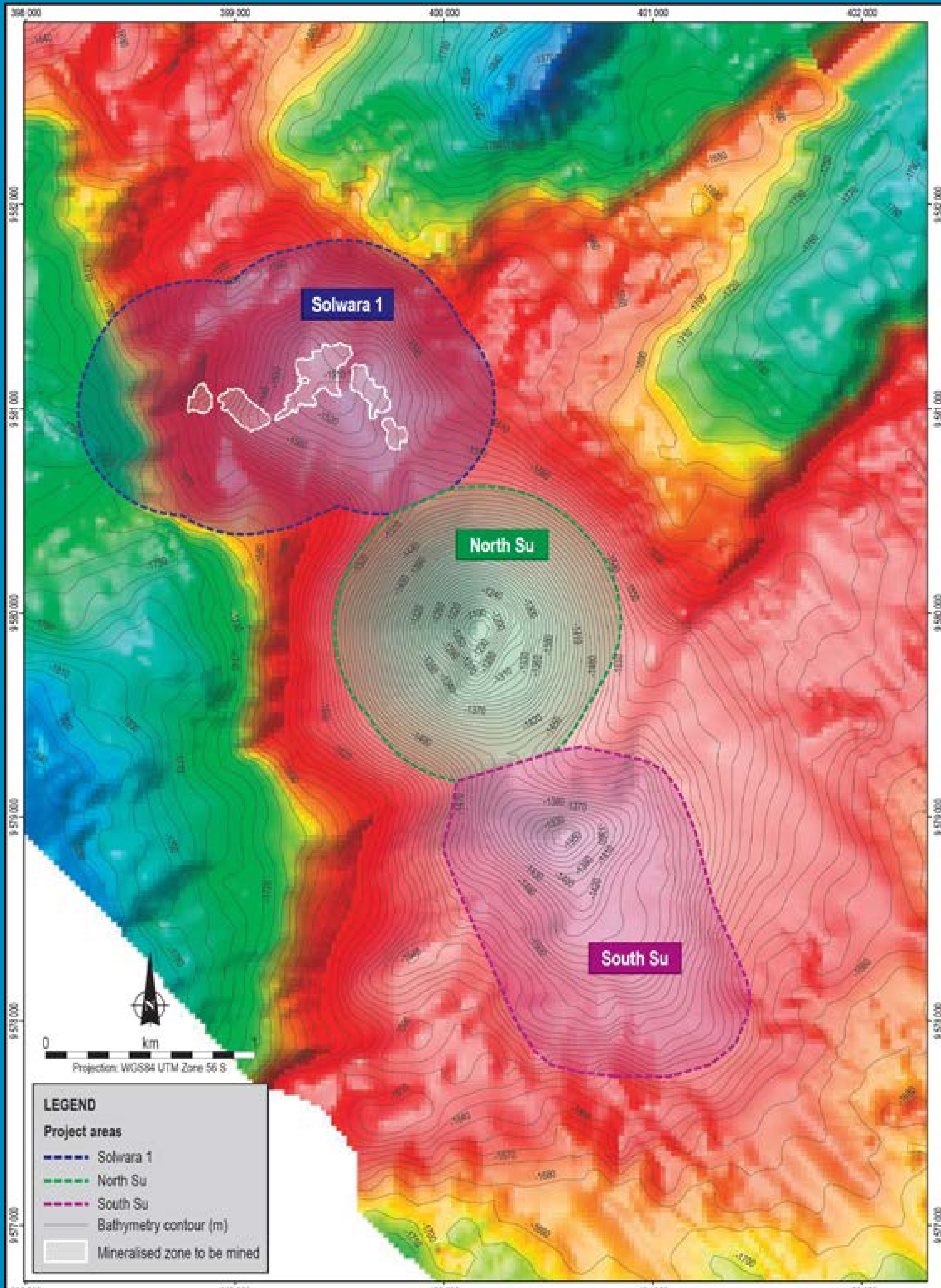
Vent fauna is naturally more abundant at sites such as Solwara 1 that are actively venting, than at other deep seafloor areas where venting does not occur. However, species density and diversity at both Solwara 1 and the South Su reference site is low for all habitat zones when compared with other vent systems worldwide.[30] A full list of the species at Solwara 1 can be found in the publicly available Nautilus Environmental Impact Statement. High levels of genetic diversity amongst microorganisms have also been found at the Solwara site, with few “dominant” species.[31] Typical ranges for any given species are generally below one meter. Species only feet away from each other might have little to no relation or shared genetic material.[32] This may be due to limited data, not limited microbial migrations as the current provides mobility.[33]

Vent systems in the Solwara 1 mine area exhibit dramatic disturbance, with vents naturally turning on and off with variations in volcanic activity. When vents turn off, the associated vent fauna dies off almost immediately, and newly formed vents are colonized by larval recruits.[34] Areas of inactive venting where hard substrates occur are also influenced by the venting activity, potentially utilizing active vents as an upstream food source, although it is more difficult to discern



▶ Location of the Solwara 1 site

Image credit: Nautilus



The area surrounding Solwara 1 is among the best-studied deep seabed areas in the world, having been studied and surveyed by research teams since 1993.

the relationship between active and inactive hard substrates.[35] As Nautilus indicates, this natural phenomenon may indicate that the mine site could recover relatively quickly following disturbance, if adequate hard substrates and larval recruits are available. Research in the East Pacific Rise seems to support this expectation.[36]

The 1,600 m depth of the Solwara 1 site, the high level of background sulphur content, and the significant natural shocks that already occur in the terrain surrounding the mine site[37] suggest that it is unlikely that the Solwara 1 project could significantly and permanently alter this deep seabed ecosystem. However, Nautilus has also adopted a precautionary principle-based approach to environmental management and has identified a reserve area, South Su, for preservation as a source for larval recruitment following mining.[38] The suitability of this site as a reserve for Solwara 1 was determined with a series of scientific investigations carried out by independently contracted genetics specialists.[39]

30+

INDEPENDENTLY PUBLISHED ACADEMIC ARTICLES RELATED TO SOLWARA 1

Finally, the Solwara 1 site is small, a mine site area of 11 hectares, with a total maximum predicted disturbance of 14 hectares, and well-studied. By all indications, this location appears to be preferable for deep sea mining. The mining and rehabilitation process will enable Nautilus and research institutions to gather more data from the deep seabed of both undisturbed and disturbed environments, and to monitor the recovery of the area and species after mining is completed.

Deep seabed environments are generally not well-studied due to the constraints of time, expense, and logistics. However, the area surrounding Solwara 1 is among the best-studied deep seabed areas, having been studied and surveyed by a number of deep seabed research teams since 1993. The Woods Hole Oceanographic Institute provides a study of the general state of knowledge concerning life associated with deep seafloor massive sulfide deposits. The study shows the dearth of knowledge about these ecosystems compared to the relative abundance of knowledge about the Solwara 1 site.[40] There are over 30 independently published research articles relating to Solwara 1, in addition to the internal studies completed by Nautilus. These articles are publicly available and independently peer reviewed. A summary of these studies is provided in Table 1 below.

◀ Topography of the Solwara 1 site; Image credit: Nautilus

▼ **Table 1. (following pages)** Summary of Independently Published Articles on Solwara 1

No.	Report Title	Full Citation
1	A biological survey method applied to Seafloor Massive Sulphides with contiguously distributed hydrothermal vent fauna	Collins P.C., Kennedy R., Van Dover C.L. (2012) A biological survey method applied to seafloor massive sulphides (SMS) with contagiously distributed hydrothermal-vent fauna, Marine Ecology Progress Series, vol. 452, pp. 89-107.
2	Application of biological studies to deep-sea governance and management of deep-sea resources	Van Dover, C. L., Arnaud-Haond, S., Clark M., Smith, S., Thaler, A. D., Van den Hove, S. (2011) Application of biological studies to deep-sea governance and management of deep-sea resources. Biological Sampling in the Deep Sea, Wiley-Blackwell Publishing, 488pp.
3	Biogeography ecology and vulnerability of chemosynthetic ecosystems in the deep sea	Baker, M. C., Ramirez-Llodra, E. Z., Tyler, P. A., German, C. R., Boetius, A., Cordes, E., E., Dubilier, N., Fisher, C., R., Levin, L., A., Metaxas, A., Rowden, A. A., Santos, R. S., Shank, T. M., Van Dover, C. L., Young, C. M., Waren, A. (2010). Biogeography, Ecology and Vulnerability of Chemosynthetic Ecosystems in the Deep Sea, Life in the World's Oceans: Diversity, Distribution, and Abundance, McIntyre, A, D. (Ed), Chapter 9, pp. 161-182, Blackwell Publishing Limited.
4	Bone-eating marine worms- habitat specialists or generalists?	Vrijenhoek, R. C., Collins, P, and Van Dover, C. L. (2008). Bone-eating worms: habitat specialists or generalists? Proceedings of the Royal Society, doi:10.1098/3sbp.2008.0350.
5	Characterisation of 9 polymorphic microsatellite loci in Chorocaris sp. (Crustacea, Caridea, Alvinocarididae) from deep-sea hydrothermal vents	Zelnio, K. Z., Thaler, A D., Jones, R. E., Saleu, W., Schultz, T. F., Van Dover, C. L., Carlsson, J. (2010). Characterisation of nine polymorphic microsatellite loci in Chorocaris sp. (Crustacea, Caridea, Alvinocarididae) from deep-sea hydrothermal vents, Conservation Genetic Resources, vol 2, no. 1, pp. 223-226.
6	Characterization of 10 polymorphic microsatellite loci in Munidopsis lauensis, a squat-lobster from the southwestern Pacific	Boyle, E. A., Thaler, A. D., Jacobson, A., Plouviez, S., Van Dover, C. L. (2013). Characterization of 10 polymorphic microsatellite loci in Munidopsis lauensis, a squat-lobster from the southwestern Pacific, Conservation Genetic Resources, vol. 4, no. 4, doi 10.1007/s12686-013-9872-1.
7	Characterization of 12 polymorphic microsatellite loci in Ifremeria	Thaler, A. D., Zelnio, K. A., Jones, R. E., Carlsson, J., Van Dover, C. L., Schultz, T. F. (2010). Characterization of 12 polymorphic microsatellite loci in Ifremeria nautilei, a chemoautotrophic gastropod from deep-sea hydrothermal vents. Conservation Genetic Resources, vol. 2, pp. 101-103.
8	Characterization of 18 polymorphic microsatellite loci from the deep-sea hydrothermal vent mussel Bathymodiolus manusensis	Schultz., T., F., Hsing, P., Eng, A., Zelnio, K., A., Thaler, A. D., Carlsson, J., Van Dover, C. L. (2010). Characterization of 18 polymorphic microsatellite loci from Bathymodiolus manusensis (Bivalvia, Mytilidae) from deep-sea hydrothermal vents, Conservation Genetic Resources, vol. 3, no. 1, pp. 25-27.
9	Characterization of host-symbiont relationships in hydrothermal vent gastropods of hte genus Alviniconcha from the Southwest Pacific	Suzuki, Y, Kojima, S, Sasaki, T, Suzuki, M, Utsumi, T, Watanabe, H, Urakawa, H, Tsuchida, S, Nunoura, T, Hirayama, H, Takai, K, Nealson, K. H, Horikoshi, K. (2006). Host-symbiont relationships in hydrothermal vent gastropods of the genus Alviniconcha from the southwest Pacific, Applied and Environmental Microbiology, vol. 72, no. 2, pp. 1388-1393.
10	Macrobenthos community structure and trophic relationships within active and inactive Pacific hydrothermal sediments	Levin, L. A., Mendoza, G. F., Konotchick, T, and Lee, R. (2009). Macrobenthos community structure and trophic relationships within active and inactive Pacific hydrothermal sediments, Journal of Deep Sea Research II, doi: 10.1016/j.dsr2.2009.05.010.
11	Comparative population genetics of two hydrothermal-vent-endemic species, Chorocaris spp. and Olgasolaris tollmanni from southwest Pacific back arc basins	Thaler, A., Plouviez, S., Zelnio, K. A., Jacobson, A., Jollivet, D., Carlsson, J., Schultz, T., Van Dover, C. L. (2012). Comparative population genetics of two hydrothermal-vent-endemic species, Chorocaris spp. and Olgasolaris tollmanni from southwest Pacific back arc basins, Poster from 13th International Deep-Sea Biology Symposium.

No.	Report Title	Full Citation
12	Designating networks of chemosynthetic ecosystem reserves in the deep sea	Van Dover, C. L., Smith, C. R., Ardron, J., Dunn, D., Gjerde, K., Levin, S., Smith, S. (2011). Designating networks of chemosynthetic ecosystem reserves in the deep sea, Marine Policy, vol. 36, pp. 378-381.
13	Distribution and Sources of Trace Metals in Volcaniclastic Sediments of the SuSu Knolls Hydrothermal Field, Manus Basin, Papua New Guinea	Hrischeva, E. H., and S. D. Scott. (2007). Distribution and Sources of Trace Metals in Volcaniclastic Sediments of the SuSu Knolls Hydrothermal Field, Eastern Manus Basin, Papua New Guinea. American Geophysical Union Fall Meeting Abstracts, vol. 1, p. 0750.
14	Host-Symbiont Relationships in Hydrothermal Vent Gastropods of the Genus Alviniconcha from the Southwest Pacific	Suzuki, Y., Kojima, S., Sasaki, T., Suzuki, M., Utsumi, T., Watanabe, H., Urakawa, H., Tsuchida, S., Nunoura, T., Hirayama, H., Takai, K., Nealson, K. H., and Horikoshi, K. (2006). Host-Symbiont Relationships in Hydrothermal Vent Gastropods of the Genus Alviniconcha from the Southwest Pacific, Applied and Environmental Microbiology, vol. 72., no. 2, pp. 1388-1393.
15	Evidence for a chemoautotrophically based food web at inactive hydrothermal vents	Erikson, K. L., Macko, S. A. and Van Dover, C. L. (2009) Evidence for a chemoautotrophically based food web at inactive hydrothermal vents (Manus Basin), Deep Sea Research II, vol. 56, pp. 1577-1585.
16	Evolution of the Metallothionein gene family in bathymodiolin mussels	Hsing, P., Carlsson, J., Jones, R., Sobel, A., THaler, A., Van Dover, C. L., Schultz., T. (2014). Evolution of the Metallothionein gene family in bathymodiolin mussels, Poster for VentBase Workshop, Wellington, 2014.
17	Facilitating fine-scale population genetic studies at Manus Basin hydrothermal fields	Carlsson, J., Jones, R., Schultz., T., Sobel, A., Thaler, A., Zelnio, K., Van Dover, C. L. (2014). Facilitating fine-scale population genetic studies at Manus Basin hydrothermal vent fields, Post for VentBase Workshop, Wellington, 2014.
18	Food Web Structure at Manus Basin Hydrothermal Vents	Honig, D. L., Hsing, P., Jones, R., Schultz, T., Sobel, A., Thaler, A., Van Dover, C. L. (2008). American Geophysical Union Fall Meeting Abstracts, no. 12.
19	Comparative Population Structure of Two Deep-Sea Hydrothermal-Vent-Associated Decapods (Chorocaris sp. 2 and Munidopsis lauensis) from Southwestern Pacific Back-Arc Basins	Thaler, A. D., Plouviez, S., Saleu, W, Alei, F, Jacobson, A., Boyle, E. A, Schultz, T. F., Carlson, J., Van Dover, C. L. (2014). Comparative Population Structure of Two Deep-Sea Hydrothermal-Vent-Associated Decapods (Chorocaris sp. 2 and Munidopsis lauensis) from Southwestern Pacific Back-Arc Basins, PLOS ONE, vol. 9, no. 7, e101345.
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21	Genetic differentiation of populations of a hydrothermal vent-endemic gastropod, Ifremeria nautilei, between the North Fiji Basin and the Manus Basin revealed by nucleotide sequences of mitochondrial DNA	Kojima, S., Segawa, R., Fujiwara, Y., Hashimoto, J., Ohta, S. (2000). Genetic differentiation of populations of a hydrothermal vent-endemic gastropod, Ifremeria nautilei, between the North Fiji Basin and the Manus Basin revealed by nucleotide sequences of mitochondrial DNA, Zoological Science, vol. 17, pp. 1167-1174.
22	The SuSu Knolls hydrothermal field, Eastern Manus Basin, Papua New Guinea: An active submarine high sulfidation copper-gold system	Yeats, C. J., Parr, J. M., Binns, R. A., Gemmell, J. B., Scott, S. D. (2014). The SuSu Knolls hydrothermal field, Eastern Manus Basin, Papua New Guinea: An active submarine high sulfidation copper-gold system, Economic Geology, vol. 109, pp. 2207-2226.
23	Habitats of the Su Su Knolls hydrothermal site	Beaudoin, Y. and Smith, S. (2010). Habitats of the SuSu Knolls hydrothermal site. In Harris, P. T. And Baker, E. K. (eds). (2010). Seafloor Geomorphology as Benthic Habitat: GeoHAB Atlas of Seafloor Geomorphic Features and Benthic Habitats, Elsevier.
24	Hydrothermal Input into Volcaniclastic Sediments of the SuSu Knolls Hydrothermal Field	Hrischeva, E. H., Scott, S. D. (2005). Hydrothermal input into volcaniclastic sediments of the SuSu Knolls hydrothermal field, Eastern Manus Basin, Bismarck Sea, Papua New Guinea, American Geophysical Union Spring Meeting Abstracts, no. V52A-06.

No.	Report Title	Full Citation
25	Metalliferous sediments associated with presently forming volcanogenic massive sulfides	Hrischeva, E., Scott, S. D., Weston, R. (2007). Metalliferous sediments associated with presently forming volcanogenic massive sulphides: the SuSu Knolls hydrothermal field, Eastern Manus Basin, Papua New Guinea, Economic Geology, vol. 102, pp. 55-73.
26	Mining seafloor massive sulphides and biodiversity – what is at risk	Van Dover, C. L. (2010). Mining seafloor massive sulphides and biodiversity: what is at risk?, ICES Journal of Marine Science; doi:10.1093/icejms/fsq086.
27	Molecular phylogenetic analysis of a known and a new hydrothermal vent octopod: their relationship with the genus Benthoctopus (Cephalapoda: Octopodidae)	Strugnell, J., Voight, J. R., Collins, P. C., Allcock, A. L. (2009). Molecular phylogenetic analysis of a known and a new hydrothermal vent octopod: their relationship with the genus Benthoctopus (Cephalapoda: Octopodidae), Zootaxa, vol. 2096, pp. 442-459.
28	Molecular taxonomy and naming of five cryptic species of Alviniconcha snails (Gastropoda: Abyssochrysidae) from hydrothermal vents	Johnson, S. B., Waren, A., Tunnicliffe, V., Van Dover, C. L., Wheat, C. G., Schultz, T. F., Vrijenhoek, R. C. (2015). Molecular taxonomy and naming of five cryptic species of Alviniconcha snails (Gastropoda: Abyssochrysidae) from hydrothermal vents, Systematics and Biodiversity, vol. 13, no. 3, pp. 278-295.
29	Population Genetics of Species Associated with Deep-Sea Hydrothermal Vents in the Western Pacific	Thaler, A. D. (2012). Population Genetics of Species Associated with Deep-sea Hydrothermal Vents in the Western Pacific, Doctoral dissertation, Duke University.
30	The spatial scale of genetic subdivision in populations of Ifremeria nautilei, a hydrothermal-vent gastropod from the southwest Pacific	Thaler, A. D., Zelnio, K., Saleu, W., Schultz, T. F., Carlsson, J., Cunningham, C., Vrijenhoek, R. C., Van Dover, C. L. (2011). The spatial scale of genetic subdivision in populations of Ifremeria nautilei, a hydrothermal-vent gastropod from the southwest Pacific, BCM Evolutionary Biology, vol. 11, no. 372.
31	Two species of caridean shrimps (Decapoda: Hippolytidae and Nematocarcinidae) newly recorded from the Manus Basin, southwestern Pacific	Komai, T., Collins, P. (2009). Two species of caridean shrimps (Decapoda: Hippolytidae and Nematocarcinidae) newly recorded from the Manus Basin, southwestern Pacific, Crustacean Research, no. 38, pp. 28-41.
32	Ecological restoration in the deep sea: Desiderata	Van Dover, C. L., Aronson, J., Pendleton, L., Smith, S., Arnaud-Haond, S., Moreno-Mateos, D., Barberi, E., Billett, D., Bowers, K., Danovaro, R., Edwards, A., Kellert, S., Morato, T., Pollard, E., Rogers, A., Warner, R. (2014). Ecological restoration in the deep sea: Desiderata, Marine Policy, vol. 44, pp. 98-106.
33	A primer for use of genetic tools in environmental impact assessment: selecting and testing the suitability of set-aside sites for deep-sea seafloor massive sulphide mining.	Collins, P., Tunnicliffe, V., Carlsson, J., Gardner, J., Lowe, J., McCrone, A., Metaxas, A., Sinniger, F., Swaddling, A., Boschen, R. (in press). A primer for use of genetic tools in environmental impact assessment: selecting and testing the suitability of set-aside sites for deep-sea seafloor massive sulphide mining, (no publication details yet).
34	Tighten regulations on deep-sea mining	Van Dover, C. L. (2011). Tighten regulations on deep-sea mining, Nature, vol. 470, pp. 31-33.
35	Genetic diversity and connectivity of deep-sea hydrothermal vent metapopulations	Vrijenhoek, R. C. (2010). Genetic diversity and connectivity of deep-sea hydrothermal vent metapopulations, Molecular Ecology, vol. 19, pp. 4391-4411.

► Snails on a deep sea vent
Image credit: Nautilus

Ecosystem Goods and Services: A Primer

Healthy watershed
Image credit: inhfblog.org

What Is Natural Capital?

In the following section, a foundational explanation of natural capital is provided in order to form the basis of the final three analyses of this report.

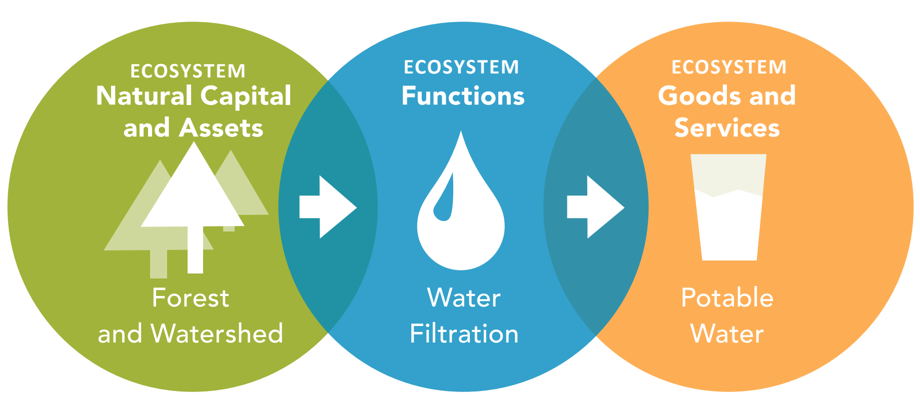
Economies depend upon four key types of capital: built, natural, financial, and human. Built capital consists of cars, houses, machinery, software, and the "tangible systems that humans design, build and use for productive purposes."[41] All built capital is created from natural capital, which is composed of energy and materials from nature. Natural capital consists of the "minerals, energy, plants, animals, ecosystems, (climatic processes, nutrient cycles and other natural structures and systems) found on Earth that provide a flow of natural goods and services."[42] Financial capital consists of the stocks, bonds, equity, collateral, currency, precious metals, paper and electronic currency that people accept as holding exchange value. Human capital consists of people, their education, health, skills, labor, knowledge, and talents.[43]

Ecosystem goods and services are the benefits that people derive from nature.

Like any form of capital, natural capital provides a flow of goods and services. These ecosystem goods and services are the benefits that people derive from nature. In other words, the infrastructure and assets (e.g., forests and watersheds) of any given ecosystem perform natural functions (such as intercepting rainfall and filtering water) that provide goods and services that humans need to survive (e.g., a clean water supply and reduction of peak flood flows downstream).

Most of these goods and services are largely taken for granted. Breathable air, drinkable water, nourishing food, flood risk reduction, waste treatment, and stable atmospheric conditions are all prime examples of underappreciated ecosystem goods and services.

Figure 5.
The Link between Natural Capital and Functions and the Provision of Ecosystem Goods and Services



Natural capital performs a wide range of functions that are critical to human health and well-being. Without natural capital, we would not have the benefit of its service. Figure 3 illustrates the relationship between natural capital and the production of ecosystem services.

The Importance of Valuing Ecosystem Services and Accounting for Natural Capital

The benefits of ecosystem goods and services are similar to the benefits typically valued in the economy, such as the services and outputs of skilled workers, buildings and infrastructure.

Understanding and accounting for the value of natural capital assets and the ecosystem services they provide can reveal the economic benefits of investment in natural capital. Throughout economic history, new means of measuring economic contributing factors has been necessary. In 1930, all nations lacked measures of Gross Domestic Product (GDP), unemployment, inflation, consumer spending, and money supply. Benefit-Cost Analysis and rate of return calculations were initiated after the 1930s to examine and compare government investments in built capital assets such as roads, power plants, factories, and dams. Private companies have relied on increasingly sophisticated approaches to calculating the expected rate of return on investments (ROI). As these examples demonstrate, decision-makers, both private and public, were investment blind without the basic economic measures and tools which are now widely accepted and expected in guiding the vast scale of investment in today's economy. It is high time that valuation of natural capital assets and ecosystem services because a part of investment planning.

The benefits of ecosystem goods and services are similar to the economic benefits typically valued in the economy, such as the services and outputs of skilled workers, buildings and infrastructure. Many ecosystem goods such as fish, fruit and water are already valued and sold in markets. Some ecosystem services, however, are not amenable to markets and have not been traditionally valued, even though they provide vast economic value. Flood protection and climate stability are prime examples of ecosystem services that provide vast value and yet go largely unvalued within traditional accounting. To illustrate, when the flood protection services of a watershed are lost, economic damages from floods can include job losses, infrastructure repairs, reconstruction and restoration costs, property damages and deaths. Conversely, when investments are made to protect and support these services, local economies are more stable and less prone to the sudden need for burdensome expenditures on disaster mitigation. In addition to the economic value associated with these avoided costs, natural capital such as healthy watersheds provides a myriad of other services, including water supply, carbon sequestration, water filtration, biodiversity and more. All ecosystem services provide additive economic value locally, regionally and globally.

Today, there are now economic methods available to quantify and value natural capital and many non-market ecosystem services. When valued in dollars, these services can be incorporated into a number of economic tools, including benefit-cost analysis, accounting, environmental impact statements, asset management plans, and rate of return on investment calculations. Their inclusion ultimately strengthens decision-making. When natural capital assets and ecosystem services are not considered in economic analysis, they are effectively valued at zero. This omission can lead to poor decisions, inefficient capital investments, higher incurred costs, and losses due to unexpected events.

When natural capital assets and ecosystem services are not considered in economic analysis, they are effectively valued at zero.

Ecosystem goods and services flow from natural capital and provide direct economic benefits to people from a range of terrestrial and marine ecosystems. As such, ecosystem services and natural capital accounting are inherently related to people. However, due to the remote nature of deep seabed mining, far fewer ecosystem goods and services, and ultimately people, are impacted. For example, there is no surface or groundwater freshwater contamination at the mine site in Solwara 1 (discussed further in Analysis II). This is remarkable, if not unprecedented, in the history of copper mining, and it removes a major environmental impact from the mining process. The mine site itself is unaffected by surface and groundwater contamination, but damage to surface and groundwater can still take place later on in the process as the ore is concentrated and refined at the smelting site.

Protecting Assets, Saving Lives, and Reducing Taxpayer costs: Accounting for Natural Capital in US Federal Benefit–Cost Analysis

Correctly calculating return on investment is critical for success in private industry and government, and a full calculation will include natural capital. The US Federal Emergency Management Agency's (FEMA) recently instated use of ecosystem service values provides a clear example of the benefits of including natural capital in consideration.

In post-disaster recovery, FEMA uses benefit-cost analysis to determine where to invest its resources for the greatest benefits relative to taxpayer cost. FEMA has developed its own BCA Toolkit, a software package that is used to measure the cost effectiveness of disaster recovery projects (such as helping home or business owners to rebuild) and determine eligibility for funding through the agency's hazard mitigation program.

However, the previous FEMA BCA Toolkit did not value floodplain lands (subject to structure buyout) for their flood risk reduction value, habitat, and other benefits. By moving structures out of the floodplain, rather than rebuilding them, the effective area of the floodplain is expanded and provides additional flood risk reduction to other properties up and downstream by storing and/or better conveying floodwaters. These lands also protect water quality, reduce sedimentation, provide recreation and secure other economic benefits.

In 2012, Earth Economics provided FEMA with 17 ecosystem service values for inclusion in the updated FEMA BCA Tool. An expert panel reviewed the values, as well as FEMA staff and management. The values were tested on past flood applications and were found to improve decision-making, reduce repetitive damage, protect human life, and lower disaster expenditures.

By valuing flood protection benefits of restored floodplains, for example, FEMA has the economic tools to better spend mitigation funds with clearer knowledge of when to remove, rather than rebuild, structures in areas that experience frequent flood or hurricane damage.

These values were approved for use beginning in 2013. Realizing the potential savings to taxpayers, homeowners, and businesses, FEMA also adopted these values for the FEMA mitigation portion of $59 billion dollars of mitigation and recovery funds allocated to Hurricane Sandy.

A Framework for Assessing Natural Capital and Ecosystem Services

The landmark Millennium Ecosystem Assessment provides a framework that classifies ecosystem services into four broad categories.

In 2001, an international coalition of over 1,360 scientists and experts from the United Nations Environmental Program, the World Bank, and the World Resources Institute initiated an assessment of the effects of ecosystem change on human wellbeing. A key goal of the assessment was to develop a better understanding of the interactions between ecological and social systems, and in turn develop a knowledge base of concepts and methods that would improve our ability to "...assess options that can enhance the contribution of ecosystems to human well-being." As a result of this study, the landmark Millennium Ecosystem Assessment (MEA) was produced, providing a framework that classifies ecosystem services into four broad categories according to how they benefit humans.

These four broad categories are now commonly used descriptions in the field of ecological economics. Although the deep seabed has not yet been well studied in relation to each of the major MEA framework categories, this study presents a ground-breaking seabed analysis. The four overarching categories are discussed below, followed by descriptions of these ecosystem services as they appear at the Solwara 1 deep seabed site.

Provisioning goods and services provide physical materials and energy for society that vary according to the ecosystems in which they are found. Forests provide lumber, while agricultural lands grow food and rivers provide drinking water.

Deep seabed provisioning goods include oil and gas reserves, and potentially minerals such as copper, gold, manganese, other metals and rare earth minerals. There are vast areas of the deep seabed that contain a significant abundance of resources and low-density distributions of life. Species-rich high-density faunal communities are also found near vents in the deep sea (though by terrestrial or coastal marine standards, species diversity is still very limited in these areas). Squid and other harvested species migrate from moderate depths to feed close to the surface. Life at the seabed may also hold pharmaceutical or medicinal goods and other benefits to humanity as well as species as yet undiscovered.

Regulating services are benefits obtained from the natural control of ecosystem processes. Intact ecosystems provide regulation of climate, water quality, delivery timing, and soil erosion or accumulation, and they also keep disease organisms in check.

Degraded systems propagate disease organisms to the detriment of human health. The difference between regulating and supporting services is generally that regulating services, such as the storm protection of wetlands, can be measured and valued. Regulating services are generally terrestrial or continental shelf-based services such as freshwater quality, storm and flood buffering (by wetlands, forests, or coral reefs), erosion control, pollination and such. Climate stability can be grouped in either regulating services or supporting services, but TEEB includes climate stability in regulating services. The deep seabed is the largest, most resilient and long-term location for carbon sequestration and storage. Most global oil reserves were formed in oxygen deprived seabed environments. Overall, there are very few regulating services at the deep seabed, and unlike terrestrial systems, the regulating services of the deep sea are likely to be highly resilient to mining activities, particularly on the scale of the Solwara 1 Project, due to the massive comparative size of the ecosystem. Carbon sequestration in the deep sea, for example, is unaffected by ore mining.

Supporting services include primary productivity (natural plant growth) and nutrient cycling (nitrogen, phosphorus, and carbon cycles). These services are the basis of the vast majority of food webs and life on the planet.

Deep seabed supporting services include globally significant buffering capacity for nutrient and carbon cycles. Deep seabed environments span an enormous area of the earth's solid surface. Primary productivity is very low in most of the oceanic abyssal plain, but can be high in vent areas. Habitat and biodiversity are often included in the supporting services category and are significant and unique at the seabed. In addition, the large stock of cold water in the deep sea is a valuable vast global temperature sink. Deep currents are critical in global climate and weather patterns.

Cultural services are functions that allow humans to interact meaningfully with nature. These services include providing spiritually significant species and natural areas, natural places for recreation, and scientific research and educational opportunities.

There is clearly great scientific research value for further study of these relatively little known deep seabed ecological communities. There have been discussions in the literature about cultural values attached to the deep sea, but these values are small in comparison to terrestrial cultural values. For example, there are over 150 separate recreational activity values in the academic literature associated with natural capital at the earth's surface. These include walking, biking, hiking, boating, swimming, fishing, hunting and such. None of these involve the deep seabed. Religious, historic, and cultural sites are prevalent on land and largely absent in the deep sea. The Solwara 1 site is almost unique as a mining site in the lack of impact to cultural value. Even the most remote terrestrial copper mines impact cultural values; copper mining in the Atacama Desert has destroyed important burial sites, for example. Solwara 1 would have the potential to impact critical cultural values if the project impacted coastal or terrestrial ecosystems, however.

Table 2 provides an overview of the broad categories of natural capital goods and services (ecosystem services) with brief explanations of the associated benefits to people. It should be noted that these categories also have many sub-categories. For example, moderation of extreme events includes flood risk reduction, buffering of tropical storms for wind and water damage, tidal, storm surge and tsunami impact dampening and more.

The first step in a natural capital accounting process is to identify natural capital and the ecosystem goods and services present and potentially impacted by the project. The second step, as data allows, is to quantify this impact. The third step is, where possible, to monetize the impact. The following sections present these steps in regards to the Solwara 1 Project and three comparison mine sites.

Table 2. [following page] ▶
Ecosystem Goods and Services.
Adapted from: de Groot et al., 2002 [44] and TEEB, 2009.

Ecosystem Service	Economic Benefit to People
Provisioning Services	
Food	Producing crops, fish, game, and fruits
Medicinal Resources	Providing traditional medicines, pharmaceuticals, and assay organisms
Ornamental Resources	Providing resources for clothing, jewelry, handicraft, worship, and decoration
Energy & Raw Materials	Providing fuel, fiber, fertilizer, minerals, and energy
Water Supply	Provisioning of surface and ground water for drinking water, irrigation and industrial use
Supporting Services	
Habitat & Nursery	Maintaining genetic and biological diversity, the basis for most other ecosystem functions; promoting growth of commercially harvested species
Nutrient Cycling	Promotes global nitrogen, phosphorus, carbon, water and other nutrient cycles.
Genetic Resources	Improving crop and livestock resistance to pathogens and pests
Cultural Services	
Natural Beauty	Enjoying and appreciating the presence, scenery, sounds, and smells of nature
Cultural and Artistic Information	Using nature as motifs in art, film, folklore, books, cultural symbols, architecture, and media
Recreation and Tourism	Experiencing the natural world and enjoying outdoor activities
Science and Education	Using natural systems for education and scientific research
Spiritual and Historic	Using nature for religious and spiritual purposes

Ecosystem Service	Economic Benefit to People
Regulating Services	
Biological Control	Providing pest and disease control
Climate Stability	Supporting a stable climate at global and local levels through carbon sequestration and other processes
Air Quality	Providing clean, breathable air
Moderation of Extreme Events	Preventing and mitigating natural hazards such as floods, hurricanes, fires, and droughts
Pollination	Pollination of wild and domestic plant species
Soil Formation	Creating soils for agricultural and ecosystems integrity; maintenance of soil fertility
Soil Retention	Retaining arable land, slope stability, and coastal integrity
Waste Treatment	Improving soil, water, and air quality by decomposing human and animal waste and removing pollutants
Water Regulation	Providing natural irrigation, drainage, ground water recharge, river flows, and navigation

Analysis II: Identification of Copper Mine Impacts for Bingham Canyon, Prominent Hill, Intag, and Solwara 1

◀ Chimney sampling
Image credit: Nautilus

Analysis II provides a description of the ecosystem goods and services expected to be impacted by the Solwara 1 project, compared with impacts at Bingham Canyon, Prominent Hill, and the proposed Intag mine.

Analysis II provides a description of the ecosystem goods and services expected to be impacted by the Solwara 1 project while providing a parallel description of the ecosystem goods and services of the currently operating Bingham Canyon and Prominent Hill mines and the proposed Intag mine. The section first presents a brief description of each mine, then the specific ecosystem services are identified and evaluated in regards to each of the sites. A comprehensive comparison of the impacts for each ecosystem good or service is provided.

Proposed Solwara 1 Copper Mine, Bismarck Sea, Papua New Guinea

7% CONCENTRATION

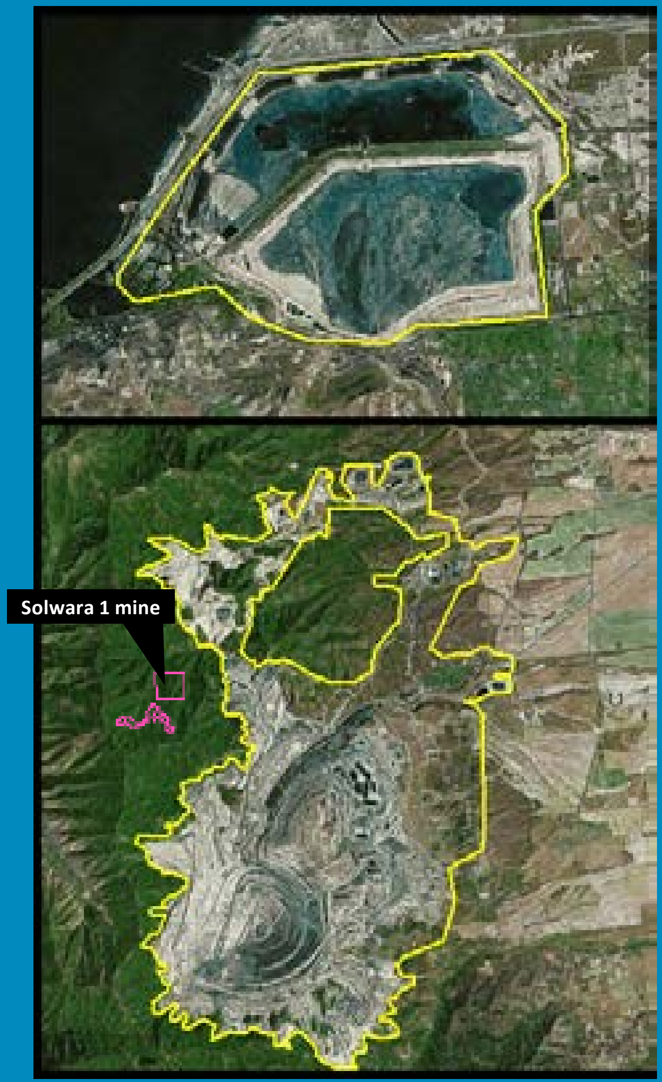
OF COPPER IN THE MINERALIZED MATERIAL AT SOLWARA 1 IS CONSIDERED REMARKABLY HIGH BY TERRESTRIAL MINING STANDARDS

The Solwara 1 deposit and the seafloor production system that Nautilus proposes to deploy at the Solwara 1 site are well described in the Nautilus documents. The mineralized material has a remarkably high concentration of copper (average over 7%[45]) as well as accompanying valuable elements such as gold and silver. Copper is present almost exclusively as chalcopyrite, with pyrite also present. The total area of mining is projected to be no greater than 11 ha (0.11km2).

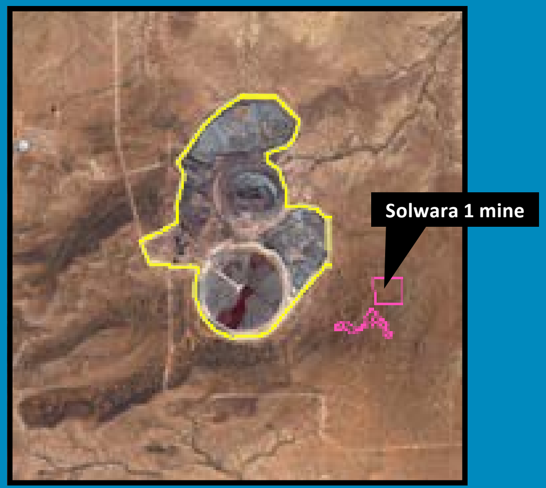
For the purposes of this study, it is assumed that the proposed Solwara 1 mine will produce approximately 1,957,000 metric tons of mineralized material over three years[46] at an average grade of approximately 7% copper.[47] Nautilus has not completed a preliminary economic assessment, pre-feasibility study, feasibility study or any other similar economic analysis of the proposed development of the Solwara 1 project.[48]

Solwara 1 may also have an added 3 ha (0.03km2) area of impact due to disposal of sediment overburden, as well as a larger area which will be impacted to a lesser extent by sedimentation from the mine-derived plume. For the calculation of natural capital impacts, this report uses a total projected maximum mine site and sediment disposal area of 14 ha (0.14km2).[49] This area does not include the zone that will be impacted by the mine-associated sediment plume. Although this zone will be subject to increased sedimentation during the mining period, it is also already subject to naturally high sedimentation as a result of the activity of the nearby North Su volcano.

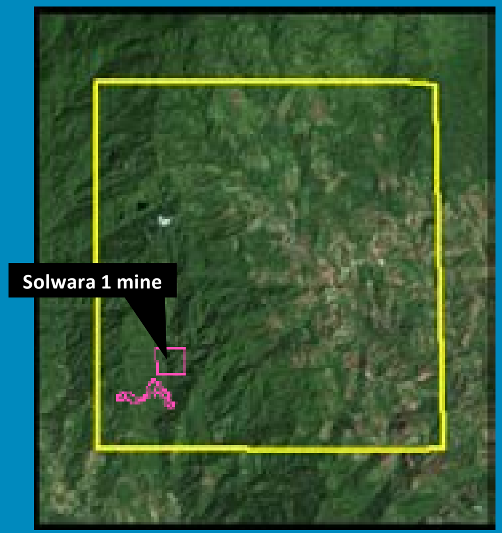
Figure 6.
GIS maps of relative sizes of mine sites



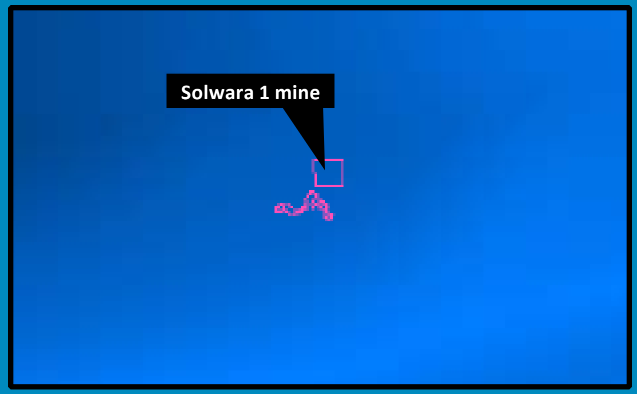
Bingham Canyon: Tailings Pond (above) and Mine (below)



Prominent Hill Mine

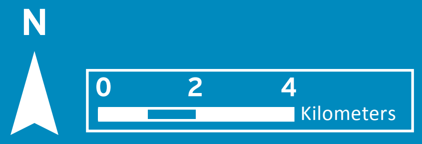


Proposed Intag Mine*



Solwara 1 Mine Site, with Tongling Refinery area* (square)

JFK Airport, New York City
(for size comparison)



*This shape is not indicative of the overall footprint, as the design is not publically available

The proposed mining operations will impact dense forests in a region of Ecuador that spans two of the world's 34 most biologically important regions

Proposed Intag Copper Mine, Intag Province, Ecuador

Intag is a proposed open-pit copper mine on the western slope of the Andes within the Intag region in Ecuador. The Intag mining proposal aims to exploit sulphide deposits with a concentration of 0.7% copper,[50] (although notably, this grade is 10 times lower than the grade of the Solwara 1 deposit), a percentage that is considered feasible by current terrestrial mining standards. A report carried out by the Japanese International Co-operation Agency (JICA) estimates that Intag might have as much as 1.3 billion metric tons of low-grade copper ore.

The proposed mining operations will impact dense forests in a region of Ecuador that spans two of the world's 34 most biologically important regions, the Tropical Andes biological hotspot and the Tumbes-Chocó-Magdalena biological hotspot.[51] Additionally, the potential mine will be located high in the Andes Mountains where steep slopes and high annual rainfall averages abound. The downstream area and parts of the proposed mine area already have established farming communities and adjoin the headwaters of the Esmeraldas River.

Over the last decade, the communities of Intag have worked to develop and implement a prosperous approach to the region's economy which does not include mining. This proposal has resulted in very significant opposition to the mine. A lengthier project description of the Intag copper mining proposal and a regional ecosystem service analysis is available in a 2011 Earth Economics report on the Intag copper mine proposal.[52]

19 MILLION TONS OF COPPER

HAVE BEEN PRODUCED BY BINGHAM CANYON SINCE 1905

Bingham Canyon Mine, Utah, USA

The Bingham Canyon mine is an open-pit copper mining operation located in Utah, USA, that is owned by Rio Tinto Group and managed by Kennecott Utah Copper Corporation. At approximately 1 km deep and 4 km wide, the mine is one of the deepest open-pit mines in the world.[53] Since the mine's opening in 1905, the mine has produced over 19 million tons of copper, 715 tons of gold, 5,900 tons of silver, and 386,000 tons of molybdenum.[54] In 2013 alone, the mine produced approximately 194,000 tons of copper, accounting for 25% of all U.S. copper production,[55] and it employed approximately 2,800 people.[56] Although Bingham Canyon has proved to be one of the most valuable mines in the world, it has also generated significant negative impacts for the surrounding landscape and communities. As an example, at least 28 reportable spills were recorded between 1998 and 2011. These spills resulted in millions of gallons of process water (reportedly containing arsenic), copper tailings, and sulphuric acid being released into the environment.[57] It is estimated that a 72-square-mile plume of groundwater is now likely contaminated due to multiple spills over the years.[58] The release of a number of toxic substances including selenium, copper, arsenic, zinc, lead and cadmium may have also resulted in significant impacts to fish, bird and wildlife habitats.[59]

1.1%

THE CONCENTRATION OF COPPER IN ORE AT PROMINENT HILL, CONSIDERED ABOVE AVERAGE BY CURRENT TERRESTRIAL MINING STANDARDS

Prominent Hill Mine, South Australia, Australia

Prominent Hill mine is a copper mine located approximately 650 km north-northwest of Adelaide in the state of South Australia, Australia. Employing approximately 1,400 staff and contractors, the mine consists of the "Malu" open pit mine and the "Ankata" underground mine. Production at Prominent Hill began in 2009, and by 2013, the mine produced approximately 73,362 metric tons of copper and 3.6 metric tons of gold. As of 2014, it was estimated that the overall mineral resource base at Prominent Hill amounted to 178 million tons of ore containing 1.1% copper, or roughly 1.9 million tons of copper.[60] Prominent Hill is located within the Woomera Prohibited Area, a restricted-access weapons-testing site in a desert region, with relatively few adjacent landholders and downstream users compared to the other terrestrial mines.

Table 3 provides a listing of land cover or seabed classifications found at the four mine sites as well as a listing of the potentially associated categories of natural capital goods and services. A white box indicates that a good or service is not present in the land cover or seabed natural capital classification. For example, there is no food harvesting at the Solwara 1 site, and the high levels of heavy metals present in the seafloor organisms is likely to prevent them from ever becoming a viable food source.[61] Pollination and fresh water provisioning are not present and have no possibility of being present at the Solwara 1 site. A orange box indicates the presence or possible presence of a good or service, and an "X" in the orange box indicates that market transactions or peer reviewed academic journal valuation studies exist which can be used to help establish dollar values for the natural capital goods and services present.

Table 3. Ecosystem Services Present and Monetized for Solwara 1 and Comparison Mines

Key	
	Ecosystem Service Not Present
	Ecosystem Service Present but No Valuation
x	Ecosystem Service Present with Valuation Studies

Ecosystem Service	Solwara 1	Prominent Hill	Bingham Canyon	Intag
Provisioning Services				
Food			x	x
Medicinal Resources				
Ornamental Resources				
Energy & Raw Materials			x	x
Water Supply				x
Regulating Services				
Biological Control	x			x
Climate Stability		x		x
Air Quality			x	
Moderation of Extreme Events			x	
Pollination				x
Soil Formation				x
Soil Retention			x	x
Waste Treatment			x	x
Water Regulation			x	x
Supporting Services				
Habitat & Nursery	x	x	x	x
Nutrient Cycling				x
Genetic Resources	x			x
Cultural Services				
Natural Beauty			x	
Cultural and Artistic Information				
Recreation and Tourism			x	x
Science and Education				
Spiritual and Historic				

Table 3 clearly shows fewer potential impacts for Solwara 1 than for the other mine sites. In the deep seabed environment, up to 11 ecosystem services are produced, while the other terrestrial environments each contain at least 19 ecosystem services. While the deep sea environment may also contribute to the regulating services associated with water regulation and moderation of extreme events, these services are unlikely to be significant for a footprint the size of the Solwara 1 Project. There are limited historic market transactions or valuation studies of the ecosystem services of deep sea environments in the academic or grey literature, so the value of these impacts is difficult to quantify. However, significant ecosystem services that are typically strongly impacted by mining, such as freshwater supply and quality or soil formation and erosion control, are not present at the proposed Solwara 1 mine site.

Table 4 below shows the estimated level of impact on each ecosystem service across Solwara 1 and the three comparison mines. The level of impact estimates for Solwara 1 was based on a 2008 Environmental Impact Statement.[62] The Prominent Hill mine level of impact estimates were based on documents published by Prominent Hill mine owner OZ Minerals.[63] The level of impact estimates for the Bingham Canyon mine were based on sources from mine owner Rio Tinto[64] and the EPA.[65] The level of impact estimates for the proposed Intag mine are based on a Japan International Cooperation Agency mine assessment[66] and an Earth Economics analysis of the Intag Region and mining proposal.[67]

2
ECOSYSTEM SERVICE VALUATION STUDIES
HAVE BEEN PUBLISHED ON THE DEEP SEA BED TO DATE

Though there is a dearth of information about the value of ecosystem goods and services provided at the seabed, the issue of valuing goods and services can be bounded within a framework and methodology that takes a highly conservative approach by using the highest terrestrial dollar values where no deep seabed estimates exist. For example, waste treatment is present at the Solwara 1 site. It is, however, unquestionably less valuable than a wetland in processing wastes for an adjacent community because it is remote from any human habitation and the physical throughput is far lower. Valuing the loss of waste treatment at Solwara 1 as if it were equal in value to a terrestrial wetland would clearly overestimate the damage of waste treatment loss at Solwara 1.

Table 4.
Level of Ecosystem Service Impact by Mine

Key
Low impact
Moderate impact
Significant impact
High impact

Ecosystem Service	Level of Impact (0 = lowest, 3 = highest)			
	Solwara 1	Prominent Hill	Bingham Canyon	Intag
Provisioning Services				
Food	0	1	3	3
Medicinal Resources	0	1	1	3
Ornamental Resources	0	0	0	1
Energy & Raw Materials	3	3	3	3
Water Supply	0	1	3	3
Regulating Services				
Biological Control	1	3	2	2
Climate Stability	1	1	2	3
Air Quality	1	0	1	1
Moderation of Extreme Events	0	1	3	3
Pollination	0	1	1	3
Soil Formation	0	3	3	3
Soil Retention	0	3	3	3
Waste Treatment	1	2	3	3
Water Regulation	0	1	3	3
Supporting Services				
Habitat & Nursery	2	2	3	3
Nutrient Cycling	1	2	3	2
Genetic Resources	1	3	3	3
Cultural Services				
Natural Beauty	1	1	3	2
Cultural and Artistic Information	0	1	2	3
Recreation and Tourism	0	0	3	3
Science and Education	1	3	1	2
Spiritual and Historic	0	3	1	3

The deep sea is one of the least studied land cover/seascapes types in terms of ecosystem services. The first article discussing the ecosystem functions and services of the deep sea was published by Thurber et al on July 14, 2014, in Biogeosciences.[68] This article provided a structure for examining ecosystem functions and services provided by deep marine environments where built capital structures or uses are either non-existent, present or abundant. A table from that article has been modified below simply to show presence or potential presence and marked to show overlap with the Solwara 1 site.

Table 5.
Built and Natural Capital Goods and Services Present in Deep Sea Ecosystem Types
Source: Derived from Thurber et al., 2014, Table 1.

	Key
	Ecosystem Service Not Present
	Ecosystem Service Present but No Valuation
X	Ecosystem Service Present with Valuation Studies

Built and Natural Capital Goods/ Services Present	Deep Sea Ecosystem Types								
	Abyssal Plains	Biogenic Habitats	Canyons	Deep Pelagic	Margins	Mid-ocean Ridges	Sea-mounts	Trenches	Vents and Seeps
Alternative energy									X
Bio prospecting (Genetic & Medicinal Resources)									X
Carbon capture and disposal									
Communication cables									
Fisheries									
Metal-rich sediments									
Methane harvesting									
Military									
Oil and gas extraction									
Phosphate mining									
Polymetallic crusts									X
Polymetallic nodules									
Rare Earth elements									
Seafloor massive sulphides									X
Waste disposal									

Four boxes (those with an "X") in Table 5 show that the site, within the Thurber et al. classification, could provide metals, alternative energy and bio prospecting values. These categories are fully contained within the Earth Economics modified TEEB framework provided above, which includes additional natural capital benefits such as scientific knowledge.

Discussion of Impacts of Solwara 1 and Three Comparison Mines

The following discussion identifies each natural capital accounting category and compares Solwara 1 with the Intag, Prominent Hill, and Bingham Canyon mines. Each ecosystem service is summarized, its presence or lack thereof is described for each mine site and, finally, a more in-depth discussion of the ramifications of impacts to each service is presented.

The level of impact estimates for the Prominent Hill mine were based on documents published by Prominent Hill mine owner OZ Minerals.[69] The level of impact estimates for the Bingham Canyon mine were based on sources from Rio Tinto (mine owner)[70] and the EPA.[71] The level of impact estimates for the proposed Intag mine are based on a Japan International Cooperation Agency mine assessment[72] and an Earth Economics analysis of the Intag Region and mining proposal.[73]

Provisioning Services

▲ Rice varieties
Image credit: IRRI Images

Food

This service is the provisioning of food for human consumption.

Intag: The Intag mine will eliminate agricultural production inside the mine site and may threaten food production downstream, meriting a high impact classification.

Prominent Hill: There is no threat within the mine site, but mine waste may threaten downstream food production in the future. This is, however, a reduced risk due to the desert ecosystem and land access constraints.

Bingham Canyon: There is no threat within the mine site, but mine waste and groundwater contamination present a high and growing threat to downstream food production.

Solwara 1: The mine should have no impact on food provisioning. The Nautilus Environmental Impact Statement[74] examined the purse seine and long-line fisheries as well as subsistence fisheries. Tuna migrations do not appear to move through the site's area, and tuna does not forage in the deep ocean. The exclusion zone around the mine site, which prohibits fishing activity, is limited to 500 m in any direction of the production support vessel. This is a very small area that is unlikely to impact fishing activities.

Discussion: Threats to food provisioning generally result in social conflict. Most food is terrestrially produced, although in developing island economies, much protein is sourced from the oceans. Marine systems provide critically important foods from wild marine ecosystems. The Bismarck Sea has important coastal and pelagic fish species; however, the Solwara 1 site is distant from the coast and 1,600 m below the surface where no commercial, recreational or subsistence species exist. The mine is therefore not expected to impact human food production. Regarding the other terrestrial sites, mines in deserts have less impact on food provisioning than mines in areas with good soils and rainfall, though local people relying on desert foods may be severely impacted.

▲ Medicinal plant
Image credit: Köhler Images

Medicinal Resources

This service is the production of medicines and pharmaceuticals useful to people.

Intag: Medicinal resources utilized by local people were identified as impacted at the Intag site.

Prominent Hill: The impact to medicinal resources is low. Some indigenous desert medicinal plants are present, but within a wide geographic range.

Bingham Canyon: The impact to medicinal resources is low. Some indigenous desert medicinal plants are present, but within a wide geographic range.

Solwara 1: Medicinal resources are not discussed in the environmental impact assessment and are not known to be present at this site. There is currently no collection of medicinal resources at the site, although sampling could enable the discovery of medicinal resources. Solwara 1 nevertheless is given a 0 rating as medicinal resources have yet to be discovered.

Discussion: Tropical areas such as the Intag region boast a greater diversity of species and genetics with far more proteins and other organic molecules present than any of the other sites. As a result, there is an increased potential for the loss of medicinal resources due to mining activity at this location. Of slightly less concern, both Prominent Hill and Bingham Canyon do impact known indigenous medicinal resources; however, the landscape housing these known resources is also vast. Finally, regarding Solwara 1, there is little information and few existing investigations concerning medicinal resources from deep seabed environments. However, Nautilus is planning to include a scientific laboratory on the production vessel that could facilitate the discovery of medicinal resources in the deep seabed, if they are indeed present.

Abalone necklace, Miwok
Image credit: By Daderot via Wikimedia Commons

Ornamental Resources

This service creates aesthetics for clothing, jewelry, handicraft, worship and decoration.

Intag: Ornamental resources, such as orchids, are present and utilized by local people.

Prominent Hill: No threat to ornamental resources has been identified.

Bingham Canyon: No threat to ornamental resources has been identified.

Solwara 1: Ornamental resources are not known to be present.

Discussion: Of the comparison sites, only Intag has identified ornamental resources. Prominent Hill and Bingham Canyon did not contain any identified ornamental resources. If any ornamental resources do exist in the Solwara 1 site, they would be virtually impossible for a local community to collect as the site is 1 mile below the ocean.

Fiber extraction
Image credit: Ecuador Living

Energy and Raw Materials

This service is the provision of fuel, fiber, minerals and energy.

Intag: Copper minerals are present at a 0.7 % grade. Energy resources are not present. Mine operation will require the construction of a dam to provide sufficient electrical power for large-scale earth moving equipment such as draglines, but the impact of this dam was not examined.

Prominent Hill: Copper minerals are present, ore grade is approximately at 1.1%, and solar power could potentially be utilized.

Bingham Canyon: Copper minerals are present, ore grade is less than 1%, but no significant energy resources are present.

Solwara 1: Copper minerals are present at a 7% grade.[75] Geothermal energy is also present at the mine site and could potentially be utilized, but only at an extremely high cost.

Discussion: The material at Solwara 1 has by far the highest concentration of copper of all comparison sites. Prominent Hill and Bingham Canyon have already mined out their highest-concentration ore, as have most terrestrial mines.

Intag River Valley
Image credit: Ecuador Living

Water Supply/Quality

This service is the provision of water quantity (a good) and water quality (a service).

Intag: The mine site is located in an elevated position in a large, populated catchment. Population density rises with proximity to the coastal plain. The mine will have significant potential impacts on water supply and water quantity in surface and groundwater resources. This catchment provides fresh water for human consumption, agricultural production, and manufacturing.

Prominent Hill: This site poses low impacts to surface water and groundwater quality, and there are possible impacts to aquatic fauna and riparian vegetation.[63]

Bingham Canyon: The impact is high, including impacts on water supply and water quality within the Salt Lake City watershed. The mine has contaminated surface and groundwater supplies with acid, metals and sulphates (the contaminated groundwater plume is currently 70 square miles) that threaten water community supplies.[76]

Solwara 1 is expected to have no impact on terrestrial freshwater supply or water quality (surface waters or aquifers). In this respect, the project may be completely unique in the history of copper mining

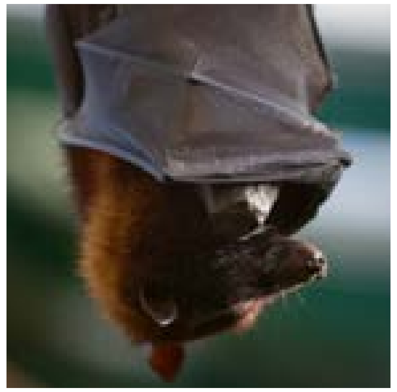
Solwara 1: The mine is expected to have no impact on terrestrial freshwater supply or water quality (surface waters or aquifers). In this respect, the project may be completely unique in the history of copper mining. The TNFM smelting facility will also use wastewater, not freshwater, to process the Solwara 1 mineralized material.[77]

Discussion: Impacts to freshwater supplies from mining are one of the greatest sources of environmental damage and social conflict. All three terrestrial mines have significant impacts. Intag, due to its location on a steep sloped, high rainfall area with a large downstream population, has the potential for severe water supply and water quality impacts.

Deep seabed mining, on the other hand, cannot damage freshwater supplies or quality at the mine site, and Nautilus has stated that it is committed to monitoring saltwater quality. The mine plan has been amended to remove the requirement to stockpile mineralized material at a terrestrial location in PNG, and, as a result, the mine should not affect PNG fresh water quality or supplies.

There are currently no water quality standards for copper mining in marine systems, and this is a gap in existing management approaches that will need to be addressed. Solwara 1 is located near an erupting underwater volcano and vent system with a high background level of what would be considered contaminants in a terrestrial freshwater system or non-volcanic coastal marine system. Nautilus has also examined impacts to fresh water from the concentration and smelting processes, even though this goes beyond their custody of the mineralized material. This topic is discussed further in the smelting section of this report.

Regulating Services



▲ Bat
Image credit: Longhorndave

Biological Control

This service affords pest and disease control.

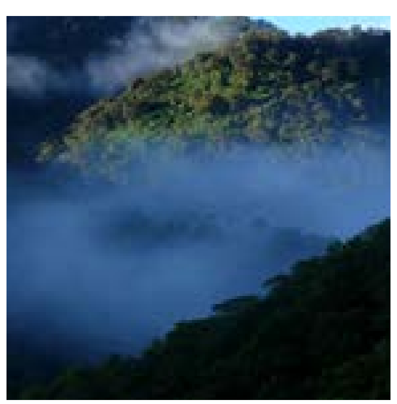
Intag: The disturbance associated with the mine may result in the loss of biological control values identified as present in five land cover types at the Intag site.

Prominent Hill: The disturbance associated with the mine may result in the loss of biological control, but few people reside around the mine.

Bingham Canyon: The disturbance associated with the mine may result in the loss of biological control values. The mine is close to a highly populated area and therefore has a greater potential impact.

Solwara 1: Biological controls within the vent communities exist; however, biological controls that benefit humans are unknown and may not be present. There is also the potential for introduced species as a result of the movement of vessels in and out of the mine site.

Discussion: Mining often disrupts natural systems that provide for the biological control of disease, insect populations, and other potential pests. Where no habitat for invasive species or disease exists prior to mining, or where naturally occurring diseases and pests may be under control, mining activities may disrupt these biological control processes and cause a greater incidence of disease, pests and ensuing damage. Compared with impacts at the terrestrial mining sites, biological control impacts to humans at Solwara 1 are less likely because no human communities live near the site.



▲ Cloud forest
Image credit: Carlos Zorrilla

Climate Stability

This service contributes to climate stabilization. Ecosystems help to regulate atmospheric chemistry, air quality, and climate. This process is facilitated by the capture and long-term storage of carbon as a part of the global carbon cycle.

Intag: Climate stability impacts would occur in the form of carbon emissions and in the loss of carbon-sequestering forests. The total carbon emissions of the project have not been carefully calculated, but were broadly estimated and monetized. Carbon emissions are likely to be substantial given the proposed size of the mine. Extensive forests would also be cleared. In addition, carbon offset projects are housed within the Intag area and could be detrimentally affected by the mining operation.

Prominent Hill: The mine has significant carbon emissions, but the area was not heavily forested and thus suffered less damage from clearing than in the Intag case. The low copper concentration in the ore requires significant processing activity, which further contributes to total emissions.

Bingham Canyon: The mine has significant carbon emissions, and forest areas were lost with the mine establishment. The low copper concentration in the ore requires significant processing activity, which further contributes to total emissions.

Solwara 1: Carbon impacts in the form of emissions are present, although on a smaller scale than the previous studies due to the high grade of the mineralized material.[78] The expected carbon footprint of the project has been calculated and is expected to be far less than a terrestrial mine due to the lack of overburden removal required and the reduced processing requirements due to the higher copper grade (See Analysis III).

Discussion: The general reduction in mined ore grades over time has resulted in rising CO_2 emissions/metric ton of copper ore produced globally. Solwara 1 is likely to be an exception to this trend due to its high grade and low overburden. Without a global increase in ore grades or major changes in energy use, carbon emissions per ton of copper produced will continue to rise.

▲ Sunny blue skies
Image credit: Zac Christian

Air Quality

This service relates to the provision of clean, breathable air.

Intag: The loss of cloud forest at the mine site will reduce the provisioning of clean air as the forest is removed. Air pollution in a previously undisturbed area will take place and may degrade air quality for communities in the valley and around the mine site.

Prominent Hill: Impact to air quality likely occurs locally at the mine site due to dust generation and processing emissions.

Bingham Canyon: Impact to air quality likely occurs locally at the mine site due to dust generation and processing emissions.

Solwara 1: The site is 30 km offshore and thus will have no measureable air quality impacts on communities in New Ireland and New Britain. Power generation on the support ship may reduce air quality for crew on the ship.

Discussion: Many copper mines are located near inhabited areas and have a substantial impact on local air quality. This loss of air quality often impacts the health of people living in the mine vicinity. Solwara 1 is distant from any human communities, with the exception of the production ship's crew. The Solwara 1 site also does not contribute to dust generation, which can have impacts on human populations and ecosystem health. This is likely to result in a significant, overall air quality benefit in a shift from terrestrial to deep seabed mining.

▲ Flooded farmland
Image credit: Ecuador Living

Moderation of Extreme Events

This service buffers against storms, floods, fires, drought and other extreme events.

Wetlands, grasslands, riparian buffers, and forests all provide protection from flooding and other disturbances. For example, these ecosystems are able to slow, absorb, and store large amounts of rainwater and runoff during storms, thus reducing flooding. Changes in land use and the potential for more frequent storm events due to climate change make disturbance regulation one of the most important services to economic development.

Intag: The impact is likely to be high at Intag as the mine will remove vegetation that provides storm and flood mitigation. The planned mine site receives 3,000-4,000 mm of rain annually, often in large rainfall events. Like other copper mines with earthen dam impoundments, there is also a danger of dam failure and catastrophic downstream flood damage. If mine tailings are flushed downriver, extreme event damage can be exacerbated.

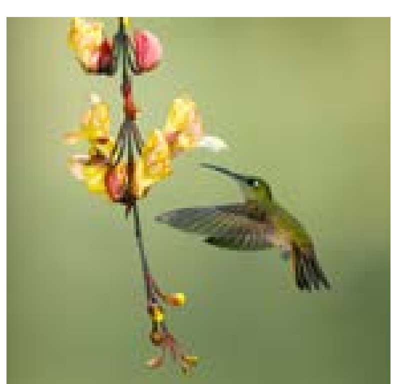
Terrestrial mines often increase the risk of, or exacerbate, disaster damages. Solwara 1 will not reduce the resilience that natural systems in the area provide to people.

Prominent Hill: The impact is low as the mine site is distant from populations in an area of low rainfall.

Bingham Canyon: The impact at this site is significant. Massive landslides occurred at the mine site in 2013, for example.[79]

Solwara 1: This impact is not present. There are no human communities on the downgrade slope from the mine. The Solwara 1 mine will not damage natural capital that provides moderation of extreme events. The mineralized material is also shallow on the ocean floor under tremendous pressure from the water column, and cannot trigger an earthquake or tsunami.[80]

Discussion: Terrestrial mines often increase the risk of, or exacerbate, disaster damages. Solwara 1 will not reduce the resilience that natural systems in the area provide to people.



▲ Hummingbird pollinating a flower
Image credit: Angela Arenal

Pollination

This service provides for the fertilization of plants. Pollination supports wild and cultivated plants and plays a critical role in ecosystem productivity.

Intag: The Intag mine is in an area of cloud forest where pollination for farms within the proposed mine area and outside the mine area occurs. Removal of vegetation for the mine will likely impact pollination services.

Prominent Hill: The impact is likely low. The mine site is distant from agriculture, but pollination of native desert species may occur.

Bingham Canyon: The impact is likely moderate. Nearby forested areas may gain from local pollination, but farms are outside the flight distance of pollinators from the mine.

Solwara 1: Plant pollination is not present at the Solwara 1 deep sea site and no impact is foreseen. Larval recruitment is addressed in the Habitat and Nursery section.

Discussion: Pollination is not only one of the most critical services provided by any ecosystem, but it is also among the most delicate and easily disrupted services. With the exception of Prominent Hill (due to its extremely remote location), our comparison sites negatively impact pollination, which can impact the ecosystem as well as local agricultural productivity. Plant pollination does not occur at the Solwara 1 site, and therefore the proposed mine poses no risk to pollination services.

▲ Eroded bank
Image credit: Wikimedia Commons

Soil Formation and Retention

This service enhances soil fertility and soil retention.

Intag: The mine is likely to accelerate soil erosion and eliminate soil formation at the mine site. The Intag mine will be located on the crest of a very steeply sloped ridge with high and variable rainfall. Communities at lower elevations depend upon the erosion control and could be impacted by uncontrolled erosion, loss of topsoil or a tailings spill.

Prominent Hill: The impact may be significant if topsoil resources are lost. Soil formation is impacted. Downstream areas may be impacted by erosion of rock waste and mine tailings.

Bingham Canyon: The impact is considered high and may extend beyond the mine's life if topsoil resources are lost. Soil formation is impacted. Rock waste and tailings piles overshadow the populated portion of the Salt Lake basin. Downstream areas would be significantly impacted should erosion of rock waste and mine tailings occur.

Solwara 1: The impact is likely to be high, but it is also restricted to a very small area compared with the other studied mines. Sediment and material will be placed downslope from the mine site, impacting only a small area of 3 ha (0.03km2) of deep seabed. Soft sediment will be lost within the mine area, but will also be deposited as a result of mine activities. Biotic communities, but no human communities, will be impacted.

Discussion: Soil serves a vital function in nature. It provides a medium for plant and nutrient growth as well as habitat for millions of micro- and macro-organisms. Healthy soils are able to store water and nutrients, regulate water flow and neutralize pollutants more efficiently than degraded soils. In many areas, vegetation can prevent landslides and harmful erosion. While biotic communities may be impacted at the Solwara 1 site, compared with terrestrial mines, the site will have virtually no impact on human communities.

▲ Mushrooms
Image credit: Carlos Zorilla

Solwara 1 is potentially a unique copper mining project because it has little effect on the waste treatment services of natural systems.

Waste Treatment

This service refers to the conversion and treatment of wastes.

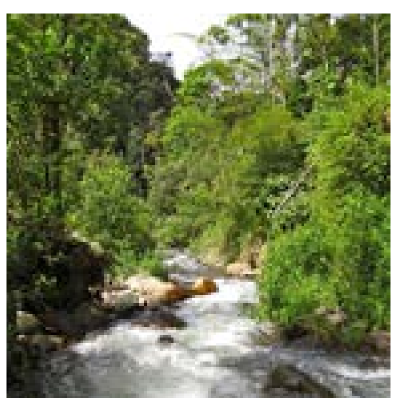
Intag: This impact is expected to be high. Waste treatment is present in the forests, wetlands, and riparian areas of Intag, and it affects the populations living there.

Prominent Hill: The impact is low. This desert area has low waste treatment value.

Bingham Canyon: The impact is significant. Waste treatment is high in the watershed with greater numbers of people living downstream in an area with snow pack and higher rainfall than Prominent Hill.

Solwara 1: No waste treatment benefits are provided to human communities, but natural waste treatment processes are present. Biological activity declines with distance from the chemotrophic vents, and waste treatment value also declines. Waste generation is limited to the surface vessel and will meet international standards.

Discussion: This service is most valuable when associated with human communities. Solwara 1 is potentially a unique copper mining project because it has little effect on natural systems' waste treatment and because it likely generates far less waste per metric ton of copper mined.



▲ River Mindo, Ecuador
Image credit: Ecuador Living

Water Regulation

This service regulates freshwater storage, temperature, flow, quality, and other attributes of water. Traditionally, the focus of this service has been on fresh water.

Intag: The impact to water regulation is likely to be high. The mine is likely to significantly impact surface water resources in terms of storage, temperature, flow, quality and other attributes.

Prominent Hill: The impact is considered low. Low rainfall and the area's topography reduce the impacts.

Bingham Canyon: The site is high in the watershed and impact to surface and groundwater resources impacting storage, temperature, and flow are likely to be significant.

Solwara 1: This mine would have no impact on freshwater regulation.

Discussion: Terrestrial mines such as Bingham Canyon and Intag (excluding Prominent Hill, which is in a desert) can often negatively impact water regulation. Bingham Canyon's location in the mountains above a populated watershed poses a risk to the downstream population. The absence of freshwater in the deep seabed means that Solwara 1 does not have the potential for impacts to this resource.

Supporting Services

▲ Salmon
Image credit: Melissa Doroquez

Solwara 1 will have significant impacts on habitat; however, studies suggest that species in this area have evolved to adapt to regular disturbances, and may recolonize the mined site more quickly than would be the case with a terrestrial mine.

Habitat and Nursery

This service refers to the housing of biodiversity, providing habitat for species continuity and the rearing of young.

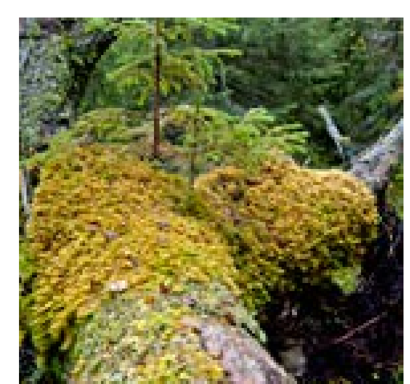
Intag: The impact is likely to be high as the mine would be located in an area that is globally noted for its biodiversity. The proposed mine site traverses significant ecological regions.

Prominent Hill: The impact is considered significant due to surface disturbance, but may not be as high as in mines located in biodiversity hotspots.

Bingham Canyon: The impact is considered high due to surface disturbance as well as the downstream threat from rock waste and tailings.

Solwara 1: The impact is significant, although restricted to a small area. The mine will impact habitat and nursery areas. The site includes vent habitats that are high in biodiversity relative to other deep ocean environments. However, early research by Duke University, Woods Hole Oceanographic Institute and others shows that South Su and nearby vents likely hold the same diversity of life for dominant species as at the mine site, and recolonization of the mine site at the conclusion of mining is expected to reflect the genetic structure of the baseline conditions for all numerically dominant species. This could be achieved if the South Su site provides larvae for the Solwara 1 site.[81]

Discussion: Habitat is the biophysical space and process in which wild species meet their needs. A healthy ecosystem provides physical structure, adequate food availability, appropriate chemical and temperature regimes, and protection from predators. Solwara 1 will have significant impacts on habitat; however, studies suggest that species in this area have evolved to adapt to regular disturbances, and may recolonize the mined site more quickly than would be the case with a terrestrial mine (see the earlier chapter entitled "State of Knowledge of the Bismarck Sea Deep Seabed" for more details).



▲ Nurse log
Image credit: Jonny Hannson

Nutrient Cycling

This service provides local and global cycles for many nutrients including phosphorus, nitrogen, and potassium through living and non-living systems.

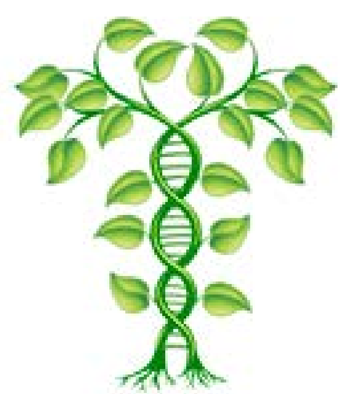
Intag: Nutrient flows will likely be significantly impacted. Further analysis would be required to estimate the quantitative impacts on phosphorus and other nutrients.

Prominent Hill: The impact is considered to be moderately low. Desert systems have low nutrient cycling rates.

Bingham Canyon: The impact is considered to be high. Nutrient cycling is relatively high,[82] and potential downstream impacts from tailings and rock waste are significant.

Solwara 1: The impact is present, but low. Nutrient flows appear to be low for most of the world's deep seabed, although vents are an exception. Vent surveys show that most nutrients remain at the seabed in the deep sea. Chemosynthetic organisms will be impacted by mining. Nutrient flows from the surface will not be impacted by mining. The scale of the mining operation is small.

Discussion: Nutrient cycling is one area of natural capital accounting that can be identified and sometimes quantified, but there are few satisfactory methods for monetization. Values for nutrient cycling are likely to be greater in areas with more vegetation, such as forested environments. Solwara 1 is thus likely to have the lowest impact on nutrient cycling services.



▲ Genetic resources
Image credit: Morley Read via Shutterstock

Genetic Resources

This service relates to the support of species and varieties that hold different combinations of DNA.

Intag: The impact is likely to be high. The cloud forests of the Intag mining site contain high genetic resources that would likely be damaged. A publicly available survey of the Intag site is not currently available.

Prominent Hill: The impact is unknown, although the surrounding habitat is similar to the mine area, which may reduce the impacts. A publicly available survey of the site is not currently available.

Bingham Canyon: The impact is unknown. A publicly available survey of the site is not currently available.

Solwara 1: The mine would impact genetic resources, but the small size of the mine site would likely keep the impact very low. More is known about the genetic diversity and surrounding areas of the deep seabed than is known about many terrestrial mining areas. Independent research shows genetic alignment between the South Su control site and the project site.[83] The project is committed to the establishment of the South Su protected area for the purposes of conserving biological diversity and recolonizing the mine site.

Discussion: Genetic resources will be impacted by the Solwara 1 mine. However, due in part to the proposed deep seabed mining project, the Solwara 1 site is now among the best studied seabed ecosystems on Earth, and genetic resources that may have been unstudied are now better understood (see the earlier chapter entitled "State of Knowledge of the Bismarck Sea Deep Seabed" for more details).

Genetic resources will be impacted by the Solwara 1 mine within the 14 hectare mine site. However, due in part to the proposed deep seabed mining project, the Solwara 1 site is now among the best studied seabed ecosystems on Earth, and genetic resources that may have been unstudied are now better understood.

Cultural Services

▲ Wildflower
Image credit: Isla Chadsey

Natural Beauty

This service provides aesthetic value to people.

Intag: The mine would likely impact the views of Intag Valley residents substantially.

Prominent Hill: The impact is low as the mine is in a very remote area.

Bingham Canyon: The impact is significant. The mine/tailings are within the Salt Lake City catchment.

Solwara 1: The mining activity is likely to have an impact on the natural beauty of vents at the mine site, although no local residents will be impacted.

Discussion: Aesthetic value is often highly valued by local populations, so it is no surprise that sites like Intag and Bingham Canyon, which are both located in scenic areas, have impacts on natural beauty. Prominent Hill's remote location and sparse landscape mean that it has less impact on natural beauty. Solwara 1 is one mile below the ocean and therefore exceptionally remote, making its impacts to natural beauty low.

▲ Basketry tray, Chumash
Image credit: Daderot via Wikimedia Commons

Cultural and Artistic Inspiration

This service provides cultural and artistic value to people.

Intag: Local people currently utilize the proposed mine site for cultural activities which would likely be significantly impacted by the mine.

Prominent Hill: Indigenous cultural values are likely to be present and may be impacted.

Bingham Canyon: Cultural resources were present and impacted.

Solwara 1: No cultural or artistic inspirational values were noted at the site.

Discussion: Cultural and Artistic Inspiration is a value generally associated with the intangible connections between society and nature that permit a society to flourish. Solwara 1's location on the deep seabed means that no indigenous cultures have developed a connection to this area.

▲ River rafting
Image credit: Earth Economics

Recreation and Tourism

This service provides space and ambiance for recreation and tourism.

Intag: Recreational and tourism activities are present in the proposed Intag mine site and would likely be significantly impacted, at least within the mine footprint area and potentially in downstream areas.

Prominent Hill: The impact is low as the mine is in a very remote area, and it is located within the Woomera Prohibited Area (a historic weapons testing area) that is inaccessible to visitors without a permit.

Bingham Canyon: The impact is significant. Nearby forested areas are heavily utilized by people from the Salt Lake area for recreation and tourism.

Solwara 1: No impact to recreation or tourism could be identified.

Discussion: Of all the comparison sites, Bingham Canyon and Intag would most greatly affect recreation and tourism, as the areas disturbed by the other two mines preclude most human activities.

▲ Field trip
Image credit: Metro Parks Tacoma

Science and Education

This service provides learning and information to individuals and humanity.

Intag: There is no scientific agenda associated with the Intag mining plan. As Intag is located in a biodiversity hot spot, the potential for loss of scientific information within the project area is high.

Prominent Hill: Any potential impact is unknown.

Bingham Canyon: The area is relatively well studied, so loss of scientific and educational value is comparatively low as surrounding areas are well utilized.

Solwara 1: Solwara 1: Significant studies have already been carried out on the proposed mine site, and the mine production vessel will house a scientific laboratory to facilitate continued scientific study.

Discussion: Solwara 1 has a unique potential for contributing to a greater scientific understanding of the deep seabed and for examining deep seabed mining impacts and the resiliency of deep sea vent systems.

▲ Petroglyph
Image credit: Martin Padbury

Spiritual and Historic

This service delivers spiritual benefits and historic values to people.

Intag: Spiritual and historic resources are present and expressed by residents of the area, and the impact is likely to be high.

Prominent Hill: The impact is high, as aboriginal cultural sites are present and impacted.

Bingham Canyon: The impact is significant as expressed by indigenous peoples and historic value present.

Solwara 1: No physical links to cultural or spiritual value were found. Local people expressed concern about the project impacting cultural practices such as shark calling, a cultural event in which people attract and harvest sharks in shallow coastal waters. Due to the distance from the shore, the background noise associated with the North Su volcano on the seafloor and fishing vessel activity in the area, it is unlikely that the mining project will impact shark calling or other cultural practices.

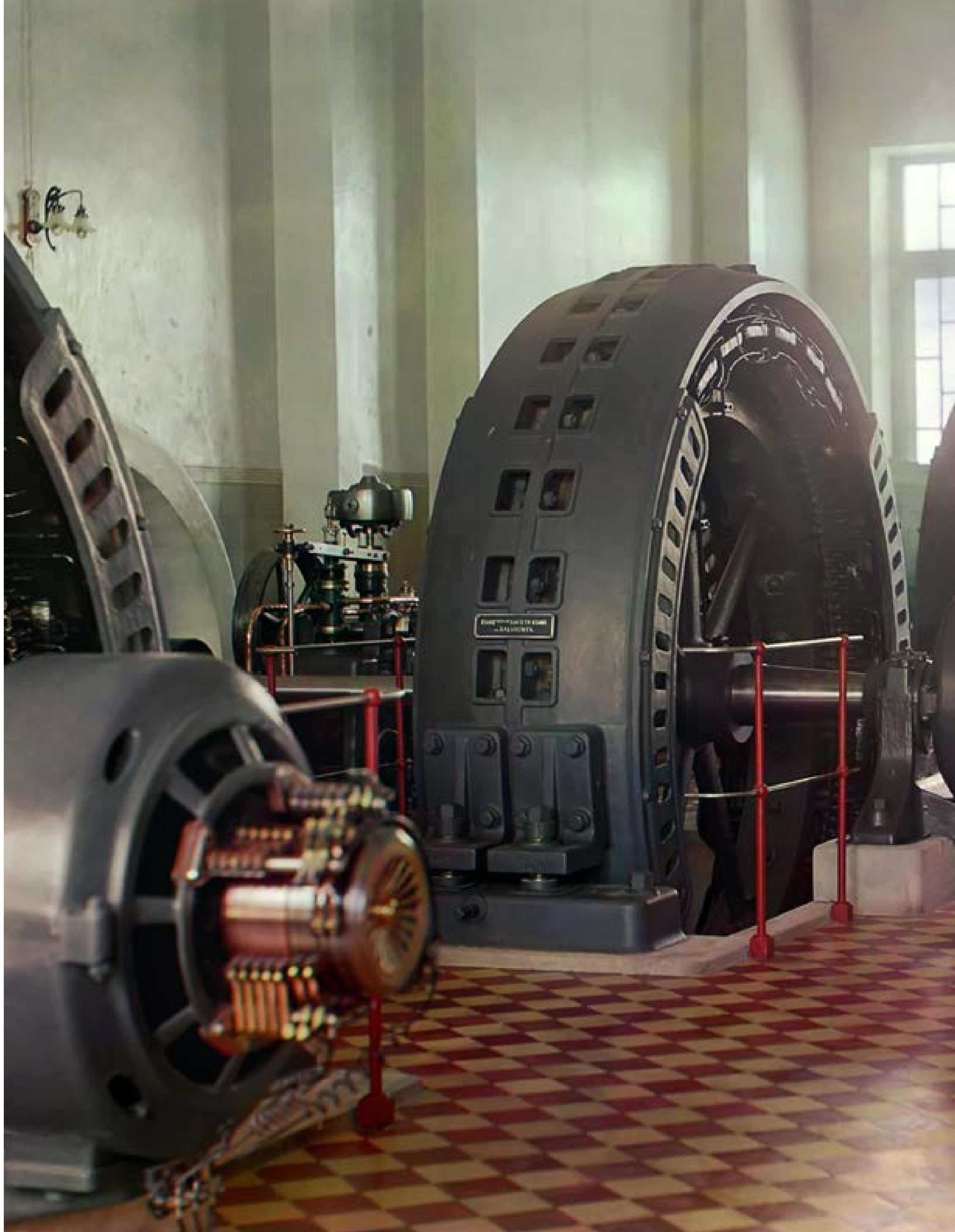
Discussion: Cultural and spiritual resources are tremendously important, and they often become a cause of social conflict. Nautilus has planned community projects in New Ireland and New Britain that include discussions with communities about their concerns and needs (health, reef restoration, education, jobs).[84] Community discussion of shark calling is ongoing and Nautilus plans to review and study this ancient practice in order to further quantify any potential impacts.[85] The lack of terrestrial disturbance is an important factor in limiting the impact of the mine on cultural values, and this represents a significant benefit compared to the terrestrial mines examined.

Conclusion of Analysis II: Identification of Natural Capital Impacts for Solwara 1 and Comparison Mines

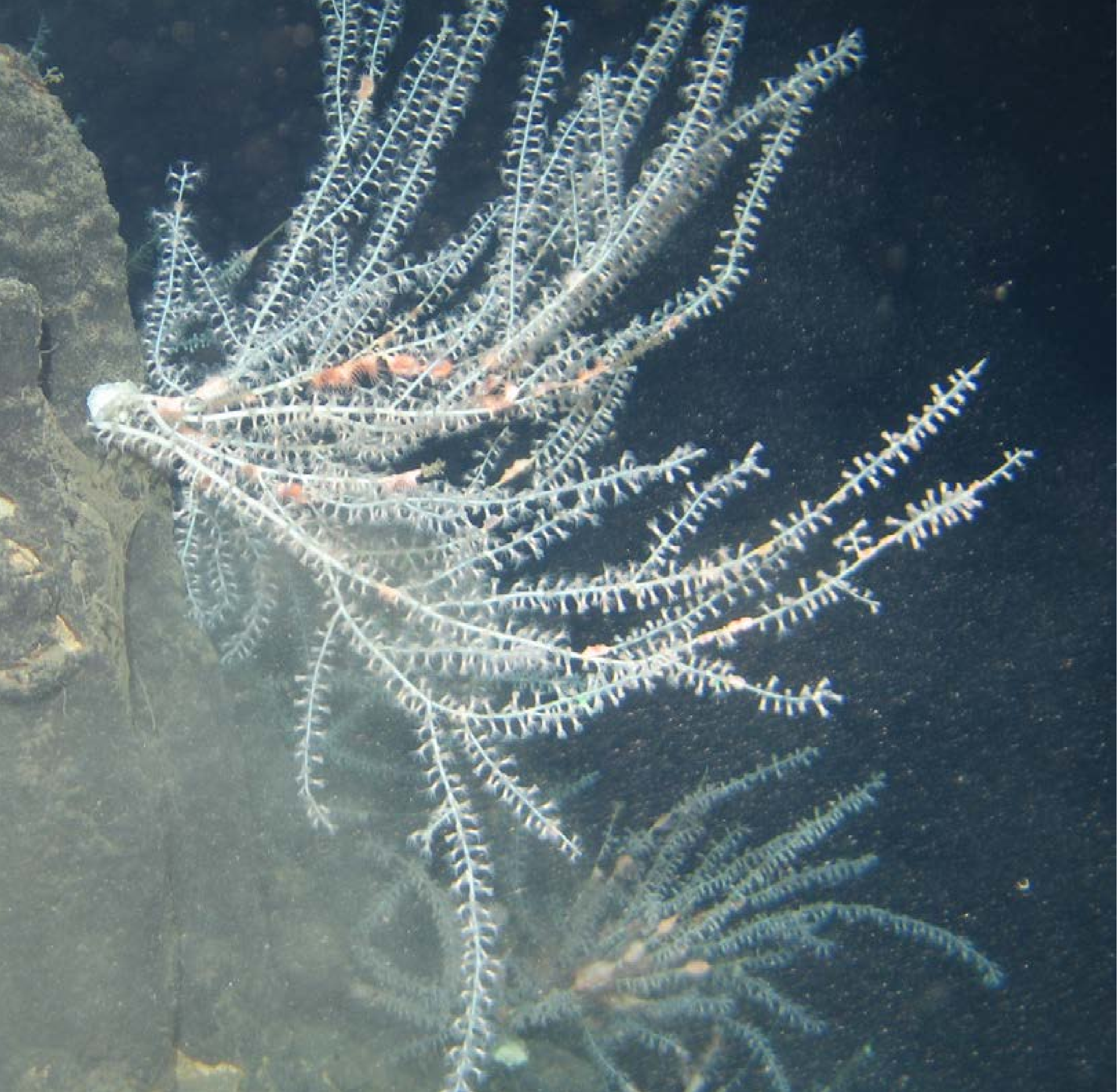
Both the number of ecosystem services and the level of impact on each ecosystem service is likely to be lower overall for the Solwara 1 mine compared with the three terrestrial mines.

This analysis demonstrates that Solwara 1 would have fewer potential impacts to ecosystem services than the proposed Intag mine, or the existing Bingham Canyon and Prominent Hill mines. Both the number of ecosystem services and the level of impact on each ecosystem service is likely to be lower overall for the Solwara 1 mine compared with the three terrestrial mines.

This identification of natural capital impacts provides strong evidence that the Nautilus Solwara 1 project will have far less impact and risk associated with copper mining than existing and proposed terrestrial mines.



► Alternators in a hydroelectric station
Image credit: Sergey Prokudin-Gorsky via Wikimedia Commons



Analysis III: Quantification of Copper Mine Impacts for Bingham Canyon, Prominent Hill, Intag, and Solwara 1

Keratoisis, a deep sea coral that lives at inactive (non-venting) sites
Image credit: Nautilus

The impacts of producing copper can be considered by examining both the natural capital inputs needed for production and the waste by-products associated with each metric ton of copper produced.

Analysis III provides a quantitative assessment of the impact of the proposed Solwara 1 copper mine on natural capital assets and compares Solwara 1 with each of the other three terrestrial mines.

The impacts of producing copper can be considered by examining both the natural capital inputs needed for production and the waste by-products associated with each metric ton of copper produced. This type of analysis should not be based upon per metric ton of copper ore as it reflects dramatically different concentrations of copper. Copper production is the goal, thus refined copper by the metric ton should be the common natural capital efficiency measure. Table 6 provides a full analysis of Solwara 1 and the two active copper mines (Prominent Hill, Australia and Bingham Canyon, USA), and a limited analysis for the proposed Intag mine.

▼ **Table 6.**
Mine Comparisons for Inputs Required for 1 Metric Ton of Copper Output

	Measure	Annual Cu Production	Total Cu Production	Freshwater Use	Energy Use	CO_2 Emissions	Mineral Waste	Area of Disturbance
	Unit	Metric tons	Metric tons	Liters per metric ton of Cu produced	MWh per metric ton of Cu produced	Metric tons of CO_2 per metric ton of Cu produced	Metric tons of tailings & waste rock per metric ton of Cu produced	Square meters per metric ton of Cu produced
COMPARISON MINES	***IMPACT TYPE***							
Solwara 1 (proposed) Total[46,48]	Mine + Refinery	**77,760**[86]	**127,186**[87]	**0**	**4.0**	**3.6**	**1.9**	**5.4**
Solwara 1 Mine	*Mine*			*0*	*4.0*	*3.6*	*1.9*	*1.1*
Tongling Refinery	*Refinery*			*Data not available*	*Data not available*	*Data not available*	*0*	*4.3*
Prominent Hill Total	Mine + Refinery	**73,362**[89]	**2,046,000**[89]	**83,831**[90]	**15.3**[91]	**5.4**[92]	**36.3**[93]	**7.2**[94]
Bingham Canyon Total	Mine + Refinery + Smelter	**194,000**[95]	**19,000,000**[96]	**21,041**[97]	**24.8**[98]	**7.7**[99]	**11.5**[100]	**5.4**[101]
Intag (proposed) Total	Mine	**484,437**[102]	**9,906,472**[103]	*Data not available*	*Data not available*	*Data not available*	**11.5**[104]	**5.4**[105]

This analysis involves two key components: inputs and waste by-products. First, calculations of the freshwater (liters), energy (MWh), and area of disturbance (square meters) as inputs per metric ton of copper produced are estimated. Second, a calculation of two by-products, metric tons of CO_2 emissions and metric tons of waste rock per metric ton of copper produced, are also provided. Because this study is a preliminary analysis, only these five areas of impact were considered. In future studies, additional analyses that would be informative could include examinations of the arsenic and other hazardous materials produced per metric ton of copper, the biodiversity impacted, the level of gold production, worker safety and other measures. However, these figures are not reported in GRI or contained in other reporting requirements. The table is based upon information derived from GRI databases and company sustainability reports. References are provided for each value.

The impacts of copper mining operations should be measured in terms of impacts per ton of refined copper produced, not impact per ton of ore.

Discussion of Mine Impacts

Table 6 shows that Solwara 1 (based on expectations as of the date of this report) is likely to be more efficient at producing copper with fewer overall key physical inputs and fewer overall undesirable by-products than any of the three comparison terrestrial mines. Of the two terrestrial copper mines in operation and the proposed Intag copper mine, none would be comparable to Solwara 1 in producing a metric ton of copper with the least impact on freshwater usage, energy use, carbon emissions, and metric tons of mineral waste.

As the table shows, lack of comparability is one of the most significant challenges in this analysis. Bingham Canyon data includes impacts for the mine, smelter and refinery; Prominent Hill data includes impacts for the mine and refinery (but not a smelter); Solwara 1 data was based on the mine's impacts (but not refining or smelting); and it is unknown whether Intag would include a refinery or smelter.

Solwara 1 is likely to be more efficient at producing copper with fewer overall key physical inputs and fewer overall undesirable by-products than any of the three comparison terrestrial mines

In addition, while Rio Tinto Kennecott (Bingham Canyon) and OZ Minerals (Prominent Hill) provide relatively detailed environmental reports on their natural capital inputs and impacts compared with other mining companies, their reports do not yet provide sufficient information to separate their mining operation's impacts from the additional processing (refining and smelting). Therefore, in order to make the comparison between Solwara 1 and the three mines more "fair", and to avoid underestimating the impacts of Solwara 1, estimates for impacts of the Tongling Non-Ferrous Metal Group's (TNFM) refinery were added based on reasonable estimates provided by Nautilus Management (specifically, mineral waste and area of disturbance). It should be noted that the figure for Tongling is valid for a processing plant that processes 400,000 tons of copper per annum, and that the Solwara 1 mineralized material will produce only 77,760 tons of copper per annum, so these figures are an overestimate of the area of disturbance that can be attributed to Solwara 1.

Each impact is discussed in more detail below.

Freshwater Use

The process of copper mining and refining consumes large quantities of water, though the amount of usage can vary widely between mines.[106] Most water usage in a terrestrial mine is for flotation, beneficiation, smelting, and electro-refining, though up to 15% of water is also used for dust suppression at the mine site.[107] The Solwara 1 project is expected to consume virtually no terrestrial water during extraction or refining. Freshwater on the production

0 LITRES

SOLWARA 1 WILL CONSUME VIRTUALLY NO FRESHWATER DURING EXTRACTION OR REFINING

support vessel will be provided using a desalinization process.[108] The smelter where refining will occur has a net negative water balance (i.e. does not discharge water), and salt removal will not result in a requirement to treat and discharge water to the environment.[109] The TNFM smelting facility will use wastewater from other processes, not freshwater, to process the Solwara 1 mineralized material.[110] However, it should be noted that if wastewater was not available from these other processes, freshwater would be required.

Energy Use & CO_2 Emissions

All aspects of copper extraction and refining require electricity. Approximately one third of the total energy use in an average open-pit copper mine is comprised of electricity use, with diesel fuel contributing approximately two thirds. Electricity is required for grinding, crushing, smelting and mine support services.[111] Diesel is typically used for drilling, blasting, ore and waste haulage, earthworks and the powering of production support vehicles. CO_2 emissions are produced as a result of both electricity and diesel use. The Solwara 1 project will use diesel to power the production support vessel and its generators, and to both produce and transport mineralized material.[112]

Compared with the three terrestrial comparison mines, Solwara 1 appears to use significantly less energy and produce moderately less CO_2 emissions per ton of copper produced. While estimates are not available for the TNFM refinery for these impact categories, some idea of the level of impact can be understood by looking at the GRI data produced by other companies. The Canadian company Xstrata, for example, reports that its Canadian Copper Refinery and Horne Smelter use a combined total of 4.8 MWh of energy and emit 0.9 tons of CO_2 per ton of copper produced. Even if these impacts were added to the Solwara 1 mine impacts, its energy usage would remain much lower than the comparison mines, and its CO_2 emissions would remain slightly lower per ton of copper produced.

6X LESS MINERAL WASTE

WILL BE PRODUCED BY SOLWARA 1 PER TON OF COPPER THAN THE TERRESTRIAL COMPARISON MINES

Mineral Waste

Mining operations often move large quantities of waste rock (overburden) before reaching valuable ore. In addition, large amounts of mineral waste (tailings) are produced during ore refining.[113] Compared with a typical terrestrial mine site, the Solwara 1 project will remove minimal overburden before reaching copper mineralized material.[114] In addition, because the copper content of the mineralized

material is so high (approximately 7% copper,[115] compared with Prominent Hill, for example, where the ore is 1.1% copper), a smaller quantity of mineral waste will be produced per ton of copper extracted. Even with the TNFM refinery impacts considered, Solwara 1 produces significantly less mineral waste per ton of copper produced.

181 KM²

SIZE OF THE CONTAMINATED GROUNDWATER PLUME DUE TO THE TERRESTRIAL BINGHAM CANYON MINE

Area of Disturbance

Terrestrial copper mines impact the landscape significantly in several ways. First, all ecosystems, fertile soils, and human communities in the direct footprint of the mine site are removed. Second, a location near the mine pit must be found for storing waste rock and mine tailings, and unless tailings and waste rock are re-deposited in pits (known as "backfilling"), waste storage will also result in the removal of ecosystems (although these systems may be rehabilitated at the conclusion of mining). Finally, downstream impacts due to spills, such as the 70-square-mile (181 square km) plume of contaminated groundwater from Bingham Canyon operations, can be significant.[116] This analysis appears to show that the area of disturbance for the Solwara 1 mine is on par with that of Bingham Canyon and Intag, but lower than Prominent Hill, per ton of copper produced. This result is the only measure in which Solwara 1 does not appear to outperform its terrestrial counterparts. This may be due to the relative shallowness of the Solwara 1 mine compared with a mine like Bingham Canyon, which has reduced the additional surface area impacted by digging a deeper pit. Finally, it is important to remember that while the Solwara 1 site is demonstrably smaller in size and disturbance impact than any of the other mines, the inclusion of the entire footprint of the Tongling facility increases the attributable footprint of Solwara 1 considerably.

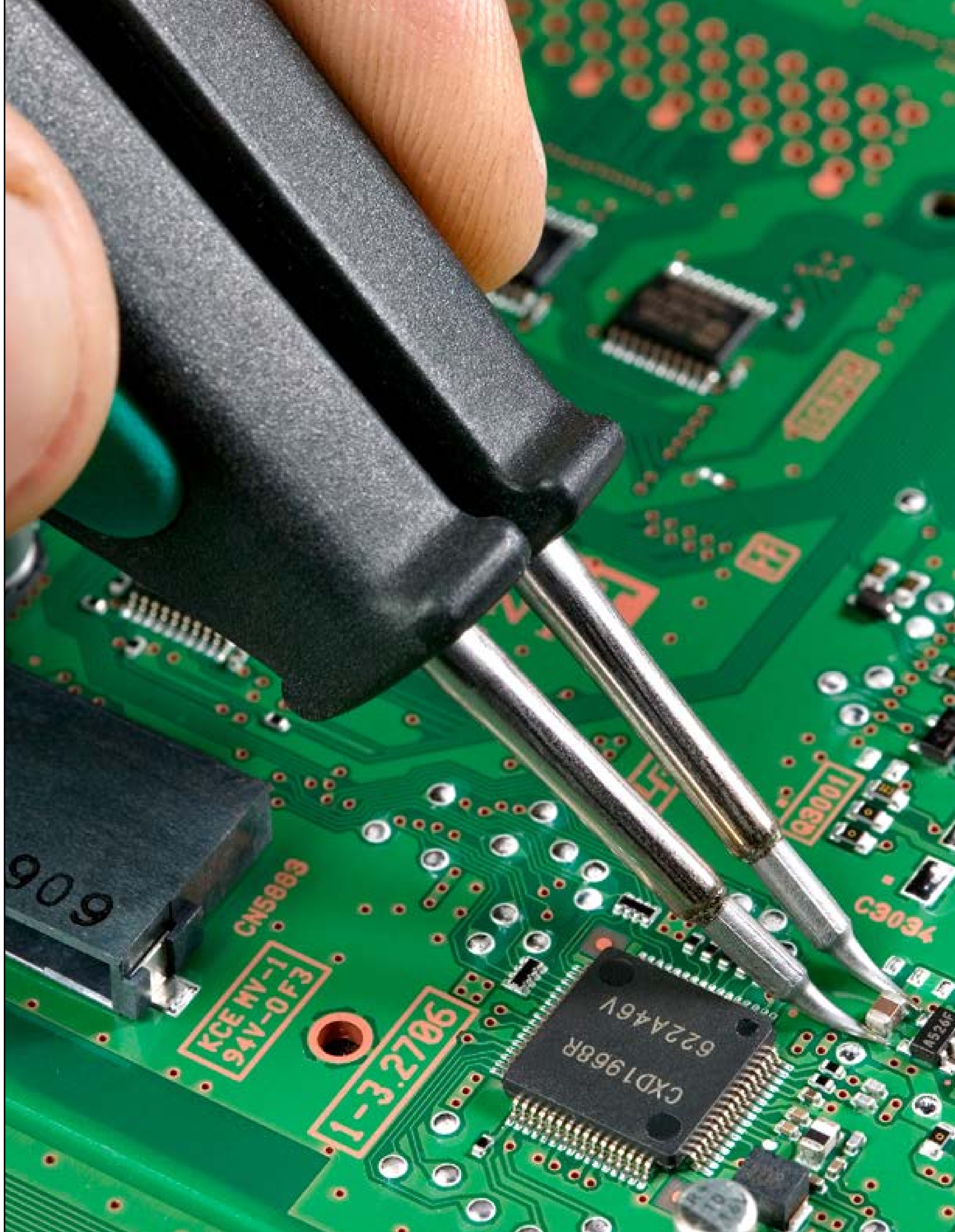
Conclusion of Analysis III: Quantification of Natural Capital Impacts for Solwara 1 and Comparison Mines

It is recommended that a future natural capital analysis be conducted during operation of the Solwara 1 mine, when real data will be available for the mine.

Compared with the three other copper mines analyzed, the Solwara 1 project would clearly have far less impact per metric ton of copper produced both in terms of inputs (fresh water, energy and land consumed) and in terms of waste by-products (carbon and rock waste) produced. This provides a strong sustainability argument that Solwara 1 and projects like it would greatly reduce the current trend in environmental and social impacts of copper mining.

It is recommended that a future natural capital analysis be conducted during operation of the Solwara 1 mine, when real data will be available for the mine (and potentially the TNFM refinery) that can be compared with the projections in Table 6 above. In addition, it is recommended that these impacts continue to be presented in terms of impacts per ton of copper produced.

When comparing the Solwara 1 proposal to other copper mines, the quantification of natural capital inputs and outputs per metric ton of copper produced provides a strong justification for the sustainability of the proposed Solwara 1 project.



▶ Soldering of a capacitor
Image credit: Aisart via Wikimedia Commons

Analysis IV: Monetization of Copper Mine Impacts for Bingham Canyon, Prominent Hill, Intag, and Solwara 1

Image credit:
raalves via iStockphoto

In Analysis IV, the impacts on ecosystem services are monetized for Bingham Canyon, Prominent Hill, Intag, and Solwara 1.

In Section A, the impact associated with a mine's area of disturbance is estimated using land cover-based ecosystem service valuation. Section B presents calculations for the impact associated with carbon emissions.

Section A. Monetizing Impacts to Ecosystem Services

The monetization of natural capital assets requires three key elements: the identification and quantification of assets, methodologies for valuation and a framework for bringing diverse values together. Modern financial analysis commonly tackles the problem of comparing firms with differing units of production (cars, metric tons of wheat, geological services) by translating these units into monetized values. The scientific and sustainability communities are often less familiar and comfortable with monetization; however, comparing monetary values can be an important tool that assists with decisions to allocate monetary resources.

The monetization of natural capital has the same pitfalls as the monetization of built capital assets. Markets and values may change quickly, but natural capital values are often far less volatile than financial assets such as stocks and bonds. Both the cost and price of water is less volatile than real estate, for example. Natural capital accounting and valuation are important tools for assisting many investment decisions, even if they do face the same valuation pitfalls that beset built capital.

One of the greatest potential errors in valuation is that of omission, or not valuing important assets at all. Without monetization, natural capital values are often tallied at zero.

One of the greatest potential errors in valuation is that of omission, or not valuing important assets at all. Over valuing or double counting natural capital assets is a far less common problem. Without monetization, natural capital values are often tallied at zero. Failing to account for the value of natural capital can lead to decision-making that is not fully informed. This document provides a preliminary valuation of natural capital impacts from copper mining in the four cases studied. This analysis largely errs on the side of undercounting the natural capital damage from terrestrial copper mining because many of the natural capital assets identified as clearly degraded by mine wastes or land clearing cannot be not monetized. This is either due to a lack of data, a lack of economic studies to establish the values, or a lack of valuation methodologies.

In the case of Solwara 1, data limitations required the use of terrestrial values to provide an estimate of the value of the seabed. With the exception of copper valuation, there are no existing studies that have established the economic value of deep seabed natural capital goods and services.

Because Solwara 1 is so remote, the potential for ecosystem service beneficiaries is low. In addition, many of the potential impacts found in a surface mine, such as freshwater quality and quantity, are not present at Solwara 1.

In the case of Solwara 1, there are no "comparable" valuation examples because ecosystem service valuation studies of deep seabed ecosystems do not yet exist. Ecosystem services valuation relates directly to the natural system's economic contributions to human economies. Because Solwara 1 is so remote, the potential for ecosystem service beneficiaries is low. In addition, many of the potential impacts found in a surface mine, such as freshwater quality and quantity, are not present at Solwara 1. To address the lack of comparable valuation studies, estimates of the economic damage to deep seabed ecosystems for Solwara 1 were based on terrestrial values identified for cloud forests in the Intag region as both regions are considered unique and sensitive ecosystems with similar qualities.

Overall, the monetization of natural capital assets and natural capital accounting is a rapidly expanding field. Natural capital accounting is increasingly being required by governments and firms to help inform project- and program-related decisions. Earth Economics is recognized as a leader in this field.

This analysis follows the methods of the United Nations Environment Program (TEEB and MEA) in utilizing a landscape and seascape approach to natural capital valuation based on the land cover type and area disrupted.

First, a land cover analysis of Solwara 1 and the three comparison mine sites was conducted. Within the areas directly impacted by each mine site, the total number of hectares of each land cover type was identified. For Solwara 1, the total area of disturbance was estimated based on Nautilus documents. For Bingham Canyon and Prominent Hill, the area of disturbance was estimated using GIS analysis, which is based on satellite imagery combined with company GRI reporting. The area of disturbance for the proposed Intag mine was estimated based on a mine study carried out by the Japanese International Co-operation Agency (JICA).

Next, the original distribution of land cover for each area of disturbance and its value was estimated using benefit transfer methodology. The loss of natural capital (e.g. forest, shrub and other vegetation) was assumed to be complete in the direct footprint of each mine, as open pit copper mining clears the landscape of vegetation, and goods and services such as food, water filtration, biodiversity and storm buffering are completely lost. The dense forest within the

This study uses a highly cautious and "conservative" approach to valuation of Solwara 1 impacts, in the sense that it is more likely to result in an overestimate of impacts than an underestimate.

Intag mine site, for example, will be completely removed with a full loss of the ecosystem goods and services that the forest once provided. Each dollar value in the tables below is tied to a specific valuation study. Appendices A and B provide full references for values in the tables. All values are presented in 2014 US dollars.

Tables 7-10 show dollar estimates for the value of each ecosystem service related to the land cover types occurring at Solwara 1, Bingham Canyon, Prominent Hill, and Intag. All estimates are expressed as dollars per hectare per year. These per hectare values were then summed for each land cover type across the ecosystem services valued for that land cover type, to give an estimate for the total annual value of each land cover type.

It should be noted that the values that were used for Solwara 1 were based on values used for cloud forests, due to the lack of available valuation studies conducted on the deep sea bed. This approach assumes that the deep seabed is at least as valuable as cloud forests in terms of biological control, habitat & nursery, and genetic resources. As cloud forests are some of the most productive and biodiverse ecosystems on the planet, this represents a highly cautious and "conservative" approach to valuation of Solwara 1 impacts, and is more likely to result in an overestimate of impacts than an underestimate.

Just as in the ecosystem services Table 3 in Analysis II, blank cells indicate that impacts to that service are not possible due to lack of presence at the site. Green cells indicate that the ecosystem service is present, and green boxes with a dollar value indicate that appropriate valuation studies were found for that specific service/ land cover combination. Based solely on the number of green cells below and in Analysis II, it can initially be seen that Solwara 1 has fewer potential impacts to ecosystem services (i.e. more blank cells).

	Seabed (based on Intag Cloud Forest values)
Ecosystem Service	Value ($/hectare/year)
Food	
Medicinal Resources	
Ornamental Resources	
Energy & Raw Materials	
Water Supply	
Biological Control	$26
Climate Stability	
Air Quality	
Moderation of Extreme Events	
Pollination	
Soil Formation	
Soil Retention	
Waste Treatment	
Water Regulation	
Habitat & Nursery	$1,464
Nutrient Cycling	
Genetic Resources	$277
Natural Beauty	
Cultural and Artistic Information	
Recreation and Tourism	
Science and Education	
Spiritual and Historic	
Total	$1,766

Table 7. Annual Ecosystem Service Impacts of Solwara 1 (proposed) Mine by Ecosystem Service and Land Cover

	Mixed chenopod, samphire
Ecosystem Service	Value ($/hectare/year)
Food	
Medicinal Resources	
Ornamental Resources	
Energy & Raw Materials	
Water Supply	
Biological Control	
Climate Stability	$23
Air Quality	
Moderation of Extreme Events	
Pollination	
Soil Formation	
Soil Retention	
Waste Treatment	
Water Regulation	
Habitat & Nursery	$828
Nutrient Cycling	
Genetic Resources	
Natural Beauty	
Cultural and Artistic Information	
Recreation and Tourism	$481
Science and Education	
Spiritual and Historic	
Total	$1332

Table 8. Annual Ecosystem Service Impacts of Prominent Hill Mine by Ecosystem Service and Land Cover

Key	
	Ecosystem Service Not Present
	Ecosystem Service Present but No Valuation
$	Ecosystem Service Present with Valuation Studies

Table 9. Annual Ecosystem Service Impacts of Bingham Canyon Mine by Ecosystem Service and Land Cover
Source: Derived from Thurber et al., 2014, Table 1. Key on facing page.

Ecosystem Service	Developed, Open Space/M-low Density	Deciduous Forest	Evergreen Forest	Mixed Forest	Shrub	Grasslands	Pasture/Hay	Cultivated	Woody Wetlands	Emergent Herbaceous Wetland
	Value ($/hectare/year)									
Food			$78	$39		$90		$22,560		$877
Medicinal Resources										
Ornamental Resources										
Energy and Raw Materials		$48	$10	$29				$356		
Water Supply										
Biological Control										
Climate Stability										
Air Quality	$579	$670	$410	$540				$251		
Moderation of Extreme Events	$319		$1,682	$841					$18,270	$7,694
Pollination										
Soil Formation										
Soil Retention			$2	$1		$18	$15	$325		
Waste Treatment			$516	$258					$14,064	$38,684
Water Regulation	$1,083					$4		$121	$2,644	$6,503
Habitat & Nursery			$9,496	$4,748	$828	$87	$12	$736	$35,791	$14,688
Nutrient Cycling										
Genetic Resources										
Natural Beauty	$57,805	$1,217		$609			$13	$217	$17,683	$15,559
Cultural and Artistic Information										
Recreation and Tourism		$742	$15,922	$8,332	$481	$285		$68	$18,646	$13,121
Science and Education										
Spiritual and Historic										
Total	$59,785	$2,678	$28,116	$15,397	$1,309	$484	$40	$24,634	$107,097	$97,126

Table 10.
Annual Ecosystem Service Impacts of Proposed Intag Mine by Ecosystem Service and Land Cover

Key	
	Ecosystem Service Not Present
	Ecosystem Service Present but No Valuation
$	Ecosystem Service Present with Valuation Studies

Ecosystem Service	Agricultural Lands	Pasture	Bamboo	Native Andean Alpine Grasslands	Cloud Forests Value ($/acre/year)	Rivers and Lakes	Pasture and Agricultural
	Value ($/hectare/year)						
Food	$11,459			$62	$2,899	$742	$94
Medicinal Resources							
Ornamental Resources							
Energy and Raw Materials	$2,753		$498		$3,732		
Water Supply			$613	$16	$12	$742	
Biological Control				$36	$26		$37
Climate Stability	$844		$670	$433	$679		
Air Quality							
Moderation of Extreme Events							
Pollination	$457			$39	$714		$31
Soil Formation	$15	$742	$737	$2	$16		$2
Soil Retention	$15			$48	$1,045		
Waste Treatment			$251	$137	$283	$742	
Water Regulation				$5	$84	$742	
Habitat & Nursery			$624	$3	$1,464	$742	
Nutrient Cycling	$59				$1,468		
Genetic Resources					$277		
Natural Beauty							
Cultural and Artistic Information							
Recreation and Tourism	$79				$835	$56,242	$69
Science and Education							
Spiritual and Historic							
Total	$15,681	$18	$3,393	$782	$13,531	$81,947	$232

Tables 11-14 show the acreage value of each land cover type within the mine area examined, the total monetized value for all ecosystem services valued per hectare for that vegetation type and the total value (acres multiplied by ecosystem service value per acre).

Table 11. Total Annual Ecosystem Service Impacts of Solwara 1 (proposed) Mine

Land Cover Type	Area (hectares)	Value ($/hectare/ year)	Value of Impacts to Ecosystem Services ($/year)
Seabed	14	$1,766.03	$24,724
Total	**14**		**$24,724**

Table 12. Total Annual Ecosystem Service Impacts of Prominent Hill Mine

Land Cover Type	Area (hectares)	Value ($/hectare/ year)	Value of Impacts to Ecosystem Services ($/year)
Mixed chenopod, samphire	1,466	$1,332	$1,952,330
Total	**1,466**		**$1,952,330**

Table 13. Total Annual Ecosystem Service Impacts of Bingham Canyon Mine

Land Cover Type	Area (hectares)	Value ($/hectare/ year)	Value of Impacts to Ecosystem Services ($/year)
Open Water	4	$0	$0
Developed, Open Space	129	$59,785	$7,697,270
Developed, Low Intensity	205	$59,785	$12,262,929
Developed, Medium Intensity	183	$0	$0
Developed, High Intensity	49	$0	$0
Barren	179	$0	$0
Deciduous Forest	242	$2,678	$648,584
Evergreen Forest	524	$28,116	$14,724,095
Mixed Forest	1	$15,397	$12,282
Shrub/Scrub	838	$1,309	$1,096,636
Grassland/Herbaceous	242	$484	$117,206
Pasture/Hay	302	$40	$12,153
Cultivated Crops	96	$24,634	$2,364,458
Woody Wetlands	27	$107,097	$2,862,971
Emergent Herbaceous Wetlands	11	$97,126	$1,066,274
Total	**3,031**		**$42,864,859**

Table 14. Total Annual Ecosystem Service Impacts of Intag (proposed) Mine

Land Cover Type	Area (hectares)	Value ($/hectare/year)	Value of Impacts to Ecosystem Services ($/year)
Agricultural Lands	33	$15,681	$522,791
Bamboo	18	$3,393	$62,635
Cloud Forests	592	$13,531	$8,013,450
Native Andean Alpine Grasslands	42	$782	$33,238
Pasture	184	$18	$3,266
Pasture and Agricultural	329	$232	$76,230
Rivers and Lakes	1	$81,947	$85,975
Total	**1,200**		**$8,797,585**

0.08 – 0.2

RELATIVE IMPACT OF SOLWARA 1 ON ECOSYSTEM SERVICES PER TON OF COPPER PRODUCED COMPARED WITH BINGHAM CANYON, INTAG, AND PROMINENT HILL

Tables 11-14 show there are a number of ecosystem services present but not monetized for each mine site. In other words, there is a lack of valuation studies (comparable areas with peer reviewed valuation studies) to apply to the sites. These gaps imply that the estimates may be underestimates of the true natural capital values per hectare for each land cover type.

In addition, the calculation of impacts to ecosystem services for Prominent Hill, Bingham Canyon, and Intag conservatively assumes there are no off-site environmental impacts. However, many previous examples show that downstream impacts can be significant if rock waste and mine tailings are deposited downstream (as in the PNG Ok Tedi copper mine),[117] or if an earthen tailings/waste rock retention dam fails (as in the Marinduque copper mine).[118]

From these annual losses, a net present value of these losses can be calculated and is shown in Table 15 with a discount rate of 4% over 100 years (Nobel laureate economists advise lower discount rated for natural capital net present value analysis[119]).

Table 15. Present Value of Ecosystem Service Impacts to Solwara 1 and Comparison Mines

Mine	Annual Value of Ecosystem Service Impacts	Net Present Value of Ecosystem Service Impacts	Total Copper Production for Lifetime of Mine (metric tons)	Relative Impact on Ecosystem Services per Ton of Copper Produced
Solwara 1 (proposed)	$24,724	$605,871	127,186	1.0
Prominent Hill	$1,919,065	$47,026,675	2,000,000	4.9
Bingham Canyon	$42,864,859	$1,050,403,319	17,000,000	13.0
Intag (proposed)	$8,797,585	$215,584,802	9,906,472	4.6

Section B. Monetizing CO_2 Emissions Impacts on the Economy

Emitting a carbon into the atmosphere adds to climate change-related impacts such as changes to net agricultural productivity, human health, and property damages from increased flood risk. This impact is referred to as the "social cost of carbon", and the U.S. Environmental Protection Agency has estimated that every ton of CO_2 emitted results in approximately $57.30 in damages (in 2013 dollars). Table 16 compares the annual social cost of carbon emitted due to the Solwara 1 project and the three comparison mines, as well as the cost per ton of copper produced. Results indicate that Solwara 1 results in significantly lower impacts per ton of carbon

Table 16.
Present Value of Ecosystem Service Impacts to Solwara 1 and Comparison Mines

Mine	Annual Copper Production (metric tons per year)	Annual CO_2 Emissions (metric tons per year)	Social Cost of CO_2 Emissions ($ per ton)	Annual Value of CO_2 Impacts ($ per year)	Relative Impact of CO_2 Emissions per Ton of Copper Produced
Solwara 1 (proposed)	77,760	346,051*	$57.30	$19,828,722	1.0
Prominent Hill	73,362	396,513	$57.30	$22,720,195	1.2
Bingham Canyon	194,000	1,490,000	$57.30	$85,377,000	1.7
Intag (proposed)	484,437	Unknown	$57.30	Unknown	Unknown

US pennies
Image credit: Roman Oleinik

Discussion of the Environmental Impacts of the Solwara 1 Copper Concentration and Smelting Processes

Tongling Non-Ferrous Metals Group copper smelter
Image credit: nerin.com

Once the mineralized material is transferred to the shipping vessels, the Tongling Non-Ferrous Metals Group has custody of the material, its copper products, and process by-products. Tongling operates one of the larges, and cleanest, smelters in the world.

This section presents a discussion of the environmental impacts of the proposed concentration and smelting processes for the Solwara 1 project.

It does not compare the chosen smelter for Solwara 1 with any other smelter operations as there is limited confirmed data available in relation to the chosen smelter for Solwara 1.

The Solwara 1 mineralized material will be sold to the Tongling Non-Ferrous Metals Group (TNFM) located in the city of Tongling in the Anhui Province of the People's Republic of China. The Earth Economics team did not visit the TNFM site and relied on interviews with Nautilus management. No direct comparison between the TNFM facility and other potential smelters was conducted.

Nautilus is legally responsible for the mineralized material during mining and up to the transfer of the material from the production vessel to the Handy Max-sized shipping vessels, at which point the mineralized material is 'purchased' by TNFM and is no longer within the control of Nautilus. The previous analyses of the mine site in this report included the mining process for which Nautilus has custody. Once the mineralized material is transferred to the shipping vessels, the client has custody of the material, its copper products, and process by-products.

Copper concentration and smelting is both capital- and time-intensive. A comprehensive description of the concentration, smelting and refining process can be found in the World Copper Factbook 2013.[120] As of 2002, there were 124 copper smelters in the world.[121] Appendix D provides a few of the many cases of local contamination from older copper smelters.

Mineralized Material Shipping Transfers

Once Nautilus brings the mineralized material up the riser system to the production support vessel and accomplishes dewatering, the copper will then be transferred to 25-30,000 Metric ton Handy Max sized vessels for shipping to China about every 7-10 days.[122]

From there, the material will be transferred from the Handy Max vessels to barges in Nantong or Nanjing. Subsequently, the material will be offloaded from barges in Tongling at the TNFM port facilities. The material will be transferred directly from the port facilities to the concentrator by truck. There will be no temporary stockpiling at the port. Dust control during discharge and handling of the material will be accomplished using water sprays. Stockpiles and barge cargos will also be covered when necessary.[123]

There are significant environmental risks associated with transferring ore at export terminals. For example, Colombia recently closed a BHP Billiton Ltd. Coal export terminal, which used to be the second largest supplier

of coal to Europe, because the barge and crane system was spilling coal and materials into marine water and harming coastal ecosystems.[124]

The choice for transferring ore from the Handy Max vessels to barges in either Nantong or Nanjing will be made by TNFM on a shipment by shipment basis, taking into account operational constraints at each of the port facilities. Both Nantong and Nanjing are major Chinese ports subject to environmental performance standards of the People's Republic of China and local port authorities. TNFM is still in discussion with port authorities over the ore transfer procedures to be applied.

Tongling Non–Ferrous Metals Group Concentrating and Smelting Facilities

The primary objective of Tongling Non-Ferrous Metals Group is to process the Solwara 1 mineralized material to produce only saleable products with no waste that has to be stored or disposed of. This is feasible in Tongling as there are other industries such as cement works, steelworks and underground mines in close proximity to their smelter that can make use of tailings and leach residues generated during processing.

Copper ore is often concentrated close to its mine source. However, in this case, TNFM will handle both the concentration and smelting processes. The facilities are all located along the Yangtze River in Tongling, China. TNFM doubled its capacity in 2014 with one of the most modern, and one of the largest, copper smelters in the world. This new smelter has a production capacity of 400,000 metric tons of copper per year.

The primary objective of TNFM is to process the Solwara 1 mineralized material to produce only saleable products with no waste that has to be stored or disposed of. This is feasible in Tongling as there are other industries such as cement works, steelworks and underground mines in close proximity to their smelter that can make use of tailings and leach residues generated during processing. TNFM has recently been recognized by the Anhui provincial government for their achievements in terms of this recycling philosophy. The process is described in further detail in the following paragraph.

On arrival at the TNFM facility, the mineralized material will be concentrated by flotation into two products, a copper concentrate containing 20% copper content and a pyrite concentrate containing high levels of iron and sulphur. The tailing from the flotation plant represents 15-20% by mass of the mineralized material. This tailing is mostly comprised of "Gangue minerals", which are undesirable minerals that often occur with copper material. The venting environment at Solwara 1 is such that the concentration of copper is very high and the concentration of gangue minerals is very low. This means that the relative tonnage of tailings produced when processing the mineralized material is also relatively low. This material will either be used as backfill in TNFM's underground mines or as landfill on construction sites. There is no tailings storage requirement and no tailings storage facility will be built for the Solwara 1 concentrator. Pyrite produced in the concentrator is processed through a roast / leach plant. This plant produces acid and precious metals. If the leach residues have an iron content in excess of 50% iron, then they are sold as feed for steel-making plants. Residues with a lower iron content are sold to cement works as cement additives. The pyrite produced from the Solwara 1 mineralized material is likely to have a high iron content and will therefore be used in the steel-making industry.

The traditional smelting process for copper sulphides such as those contained in Solwara 1 mineralized material involves first roasting and then smelting in reverberatory furnaces (or electric furnaces for more complex materials). This process produces copper matte (copper-iron sulphide), and converting for the production of blister copper (98% copper content). Blister copper is further refined through electrolysis to cathode copper (greater than 99% pure copper). These traditional processes produce air pollutants such as SO2 and particulate matter (potentially including arsenic) as well as liquid effluent and solid by-products. Fortunately, this traditional process route with its inherent environmental issues will not be used for Solwara 1 mineralized material.

At TNFM, the copper concentrate will instead be processed through TNFM's new smelter with a Flash Smelting and Flash Converting process that was first commissioned in 2013.[125] This process is also used at the Bingham Canyon mine in Utah, USA by Rio Tinto Kennecott. Using this new technology, TNFM has the opportunity to provide copper to the market with fewer environmental externalities in the smelting process.

The Flash Smelting Furnace and Flash Converting Furnace (FSF/FCF) process is based on sealed furnaces, which enable better control of gas flows together with higher production efficiency, more flexible processes and more efficient capture of solid, liquid and gaseous contaminants. The flash process is more energy efficient because during sulphur oxidation, the ore releases energy that can be utilized by the furnace, thereby reducing energy inputs. According to TNFM, SO2 emissions are effectively controlled through acid production. The double flash technology produces a higher concentration of SO2 in off-gasses when compared to conventional smelters, and this allows higher efficiency for the acid plant and a commensurately lower level of final SO2 emissions. The acid plant currently achieves emission levels of 99.8 ppm SO2 compared to Chinese and International standards of 200 ppm and 140 ppm respectively. The acid produced is used in a range of chemical industries, such as fertilizer production.[126]

Deleterious Elements in the Solwara 1 Mineralized Material

Copper naturally occurs with both inert and dangerous elements and minerals.

In general, there is no greater concern associated with the copper material from the Solwara 1 site than would surround copper ores from other mines. Copper naturally occurs with both inert and dangerous elements and minerals. At the Solwara 1 site, hot geothermal waters dissolve copper, gold, arsenic, sulphur, iron and other elements. These hot, element-rich waters move through vents at around 1,000 degrees Celsius and are

expelled into cold seawater at the deep seabed. At lower temperatures, the water can no longer hold the metals and they are instantly precipitated out as sulphide minerals such as chalcopyrite. Copper ores differ in concentrations of arsenic, sulphur, iron, gold, silver, and selenium between and within deposits. Arsenic and salt are two aspects of the Nautilus mineralized material that deserve consideration in smelting and disposal.

Arsenic has been a present, persistent problem around copper smelting areas since the Bronze Age.

Arsenic

Arsenic occurs in copper sulphide minerals including chalcopyrite ores. Indeed, arsenic has been a present, persistent problem around copper smelting areas since the Bronze Age.[127] Arsenic concentrations in ore are not reported under the GRI. A terrestrial copper sulphide mine would likely emit more arsenic per metric ton of pure copper produced, but have a lower concentration of arsenic per metric ton of copper than Solwara 1. China limits the allowable concentration of arsenic in imported ore and concentrates, and requires testing and tracking for the levels of arsenic in ore and concentrates shipped to the country. Every shipment from Solwara 1 will be tested for arsenic concentrations. Copper material from Solwara 1 must be below the required limit of 0.5% arsenic in order to be shipped to China.

TNFM reports that arsenic fed to the smelter leaves the process by two different routes. Approximately 70% of the arsenic reports to the final slag (the slag produced after taking into account slag retreatment). The arsenic in the slag is in an inert form that poses no danger of remobilization. This slag is sold as feed to local cement works. The remaining 30% of the arsenic reports to a concentrate with a grade of approximately 20% arsenic. This concentrate is produced from acid purification circuits in the acid plant. The concentrate is sold to specialist arsenic refining companies which produce arsenic compounds for use in various chemical and processing industries. The shipments of Arsenic concentrates are monitored and tracked by Chinese environmental agencies. Both the buyer and the seller have to be registered to produce and ship arsenic. These registrations are required at both state and provincial government levels, and there appears to be a high level of scrutiny to ensure all arsenic is adequately accounted for throughout the process.

Salt

Copper material from Solwara 1 requires the removal of salt water. Most of the salt is removed when the water is drained off from the mineralized material (dewatered). However, some salt is present in the residual water that remains with the mineralized material after dewatering. Test work has indicated that this salt will not have any significant negative impact on the flotation or smelting process.[128]

The TNFM site operates with a net negative water balance as a result of high rates of evaporation during the cooling of slag. This means that fresh water is always being added to the process with no need for discharge of treated water

The Tongling refinery site operates with a net negative water balance, which means that fresh water is always being added to the process with no need for discharge of treated water to local water courses.

to local water courses. The site can accommodate treatment of the Solwara 1 mineralized material and still maintain a net negative water balance. The only impact on the site will be an increase in the levels of chlorides in the slag and in some of the other product streams produced by the smelter complex.

Solwara 1 has a social and environmental benefit advantage over terrestrial mining because there is no damage in the upper catchment to surface and groundwater resources. In addition, arsenic is far better contained because it is not distributed throughout millions of tons of waste rock and tailings piles, where it may interact with or impact on communities. Gangue minerals and damaging associated elements such as selenium are very low in Solwara 1 mineralized material.

Arsenic and salt are contained within the material handling concentrating and smelting process. This does provide the opportunity to isolate hazardous materials like arsenic more effectively.

Nautilus and TNFM are continuing to plan details for the processing of copper mineralized material from Solwara 1. Nautilus aims, where possible, to work with TNFM to ensure the mineralized material and byproducts are handled in a best practices, responsible manner.[129] Nautilus is setting a higher-than-industry standard by following the product stewardship line and including environmental and social impact criteria for smelter selection.

An analysis of the efficiency (pollutants/ton of copper ore produced) could not be conducted at this time for either TNFM or other smelters. The TNFM smelter complex is likely in the top 10%, if not the top 1%, of least air-polluting smelters per metric ton of copper produced, due to new technology, production efficiencies, and closed systems.

The TNFM smelter is new, and is likely to operate at full capacity. At the smelter scale, copper mineralized material from Solwara 1 will displace copper ore from terrestrial mines rather than be additive.

Even with modern facilities, copper smelting is not a pristine process. Currently, there is no advertised "clean copper" standard and no assurance that it would fetch a higher price if such a standard were in place. However, if a future analysis shows that the TNFM is comparatively better than other concentration and smelter sites, reducing impacts and effluents, this may contribute to upgrading the overall sustainability of copper production.

Conclusion to the Discussion of Copper Shipping, Concentrating, Smelting and Disposal

All copper concentrating and smelting processes have effluents and dangerous by products, such as arsenic. Nautilus has chosen one of the most modern facilities in the world with a greater opportunity to reduce the amount and toxicity of tailings. The TNFM smelter is currently the newest copper smelter in the world, utilizing the latest technology. The Solwara 1 mineralized material has a high concentration of chalcopyrite and has few gangue minerals.[130] The TNFM smelter is close to associated industries, such as iron, chemical, and concrete production. Thus, most of the pyrite other by-products can be utilized in other industries, greatly reducing waste material. Some end waste materials, including traces of arsenic, will be disposed of as backfill in associated underground copper mines very close to Tongling, TNFM.[131]

Though some details regarding the ultimate disposal of tailings and smelting slag remain to be settled, there seems to be both the opportunity and willingness on the part of Nautilus to pursue the most environmentally sound options.

Setting aside conservation areas such as South Su, investing in baseline data such as a thorough survey of life at the site and beyond the mining impact area, providing information willingly and ensuring close independent monitoring from the life-of-the-mine through reclamation are all ingredients to avoid the dramatic errors made in terrestrial mining.

Other Issues

Finally, several issues likely to be more fully examined in future reports are included here.

Setting Standards

As Solwara 1 is developed, Nautilus and the Government of PNG will manifest the world's first deep seabed mining operation. As such, Nautilus and the PNG Government will play a critical role in defining the standards for deep seabed mining at both the national and international scales. As the first deep seabed mining project, Solwara 1 can set a high sustainability standard for the International Seabed Authority. Setting aside conservation areas such as South Su, investing in baseline data such as a thorough survey of life at the site and beyond the mining impact area, providing information willingly and ensuring close independent monitoring from the life-of-the-mine through reclamation are all ingredients to avoid the dramatic errors made in terrestrial mining.

IFC Standards

International social and environmental standards for investments exist. The most widely accepted standards have been set by the International Finance Corporation (IFC) of the World Bank Group. Although not required to

Nautilus and the PNG Government have an opportunity to dramatically reduce the social and environmental impacts of mining and surpass many elements of the IFC standards.

meet IFC standards, Solwara 1 should surpass IFC social and environmental standards for mining in many areas. The IFC mining requirements were set in 2007 and should be up-dated. In addition, IFC requirements provide no guidance for deep seabed mining. Nautilus and the PNG Government have an opportunity to dramatically reduce the social and environmental impacts of mining and surpass many elements of the IFC standards. For example, Solwara 1 does not require the relocation of communities and does not impact cultural resources. There is no freshwater contamination, upper watershed tailings, or rock waste. In addition, the Nautilus proposal will have community projects, but not as mitigation for any impact to communities. The mine should only have positive impacts on communities in New Ireland and New Britain. This approach may set a new standard for "best practices" in mining that greatly surpasses the current IFC requirements.

Transforming Mining Processes

Deep seabed mining is a transformational approach to mining. The mine production vessel and three remotely-operated mining vehicles would displace hundreds of vehicles and much heavy equipment common to terrestrial copper mines. Much of the equipment is unnecessary because the mineralized material is on the surface of the seabed, meaning that the removal of millions of tons of overburden is avoided and mine efficiency is improved. Much of what is considered mining would be converted into a shipping activity. A vessel far above the mine site is being designed to enable enormous mining equipment to be easily and directly pulled out of the mine. This is impossible in any underground or open-pit terrestrial copper mine. This advancement alone would save downtime, increase efficiency and save on repair and mining costs. In a typical mine, road building is a gargantuan undertaking, yet this necessity does not exist in this deep seabed proposal. Additionally, weather at the sea floor is consistent, facilitating smooth, continuous operations. In March 2015, all mining stopped at Chuquicamata (the world's largest copper mine) and five other large copper mines in Northern Chile due to a heavy rainstorm that washed out the mine roads and flooded open pits. This sort of disturbance would not be a problem in deep seabed mining.[132] The Bismarck Sea is also protected from typhoons and tropical storms. There is a great deal of opportunity for engineering and efficiency improvements in mining at the deep sea floor that should be addressed in future analyses.

Reduced Mine Employment

Increased efficiency in any industry often results in less employment. As noted by Nautilus staff, there are also social downsides to the mining transformation that seabed mining brings forth. There would be far fewer mining jobs in Solwara 1 as opposed to a traditional mine that removes a similar quantity of copper. Prominent Hill copper mine employs about 1,400 people,[133] and Bingham Canyon employs 2,800 people.[134] There would likely be less than 200 people working on the Solwara 1 mine site on the production vessel.

As noted by Nautilus staff, there are also social downsides to the mining transformation that seabed mining brings forth. There would be far fewer mining jobs in Solwara 1 as opposed to a traditional mine that removes a similar quantity of copper.

Falling employment in mining is nothing new, however. It has been a function of increased technology and mechanization for the past 150 years. The ability to produce more output with less labor is a global phenomenon in every area of commodity and manufacturing production. This certainly deserves greater attention. Increased employment with Nautilus community projects could partially outweigh this net employment loss and could contribute to increased sustainability (coral reef restoration projects, for example). Counterbalancing the loss of employment (which has been a long-standing trend) is the fact that increases in productivity form the basis for rising real wages and a higher quality of life.

Impact on Copper-Exporting Nations

Copper exports provide a significant part of several countries' GDP. For example, copper exports account for 20% of Chile's GDP and 60 % of Chile's exports. At the scale of Solwara 1, the impact would be relatively small, but competition with expanded seabed mining could have a significant impact on the global copper market and particularly copper dependent countries like Chile and Zambia.

Opening the Seabed to Metals Mining

Most of the earth's solid surface resides in the deep seabed. Opening this area to metal mining, and thereby allowing higher concentrations of mineralized material to be mined with dramatically fewer impacts to communities, surface area, and social and natural capital assets, would be a historic achievement for Solwara 1. Copper ore concentrations have been declining dramatically in the last 100 years. Copper is becoming more and more energy-, water-, landscape- and pollution-intensive. "Peak copper", the idea that copper production will become so expensive that world production will decline, has become a mantra in some circles.

Mining selected copper resources at the deep seabed while still carefully conserving biodiversity promises to move copper concentrations back to 6% and open an area far larger than all terrestrial lands to mining. Yet, with higher copper concentrations and virtually no overburden, far less of the ocean floor would need to be disturbed to recover a ton of copper.

Mining selected copper resources at the deep seabed while still carefully conserving biodiversity promises to move copper concentrations back to 6% and open an area far larger than all terrestrial lands to mining. Yet, with higher copper concentrations and virtually no overburden, far less of the ocean floor would need to be disturbed to recover a ton of copper. The physical extent of the proposed Solwara 1 mine is 14 ha, the same area as a typical Walmart parking lot. As is the case for all mining, living systems will be disturbed and destroyed. Some copper mines displace the highest biodiversity ecosystems on the planet. Ok Tedi in PNG is astride a ridge in one of the earth's biodiversity "hot spots" and has impacted ecological systems from cloud forest to coral reef. The deep seabed, especially vent systems, have specialized ecosystems that must be conserved; however, mining high-grade mineralized material allows for less overall disturbance. Mining the deep seabed avoids the inevitable reality of mine waste and tailings eroding, contaminating and flooding the entire length of riparian systems to the continental shelf of the ocean.

Conclusions

◀ Community engagement
Image credit: Nautilus

Expert Recommendation

Pursuing a global economy that is more sustainable and provides greater services for the world's poorest requires more copper. Copper is necessary for wind, hydro, wave, geothermal, and tidal power production. If terrestrial mining could be reduced, Solwara 1 would still be preferred over new or existing terrestrial mines because it entails fewer social and natural capital impacts as shown by Analyses II-IV.

Four analyses were conducted in this report, as well as a high-level summary of deep seabed science in the Bismarck Sea and a discussion of copper smelting relevant to Nautilus' proposed activities.

Analysis I showed that recycling and substitutes cannot be sufficiently increased to displace copper mining. Recycling is likely limited to around 35% of the supply because copper has a long productive life, high prices, and efficient recycling markets. Substitutions for some copper applications are taking place. For example, the replacement of long-haul copper communication lines with fiber optic cables is market driven. At the same time, the demand for copper for new applications is also increasing. Expanding global renewable energy supplies (copper generator windings), clean water provisioning (copper plumbing) and communications technology requires millions of tons of copper. Pursuing a global economy that is more sustainable and provides greater services for the world's poorest requires more copper. Copper is necessary for wind, hydro, wave, geothermal, and tidal power production. If terrestrial mining could be reduced, Solwara 1 would still be preferred over new or existing terrestrial mines because it entails fewer social and natural capital impacts as shown by Analyses II-IV.

Analysis II identified goods and services that are impacted by terrestrial and deep seabed copper mining. The displacement of communities, food production, impact to water supplies and the risk of failing waste structures are all impacts that are present in terrestrial mining, but not present in deep seabed mining. By impacting fewer categories of natural capital, Solwara 1 is far superior to existing (and proposed) terrestrial mines that entail far greater environmental and social impact and risk.

Analysis III demonstrated that Solwara 1 will produce more copper with fewer natural capital inputs, fewer damaging outputs, and a smaller area of impact for every metric ton of copper produced. Quantifiable physical impacts were measured per ton of copper produced. Solwara 1 outperforms the other copper mines in terms of fresh water required, mineral waste, carbon dioxide emissions and energy use per ton of copper produced. This reflects the physical efficiency of copper production, and the likely lower natural capital impacts of Solwara 1.

Analysis IV estimated the dollar value of natural capital assets impacted to be far lower for Solwara 1 than for a comparable terrestrial mine. There are no ecosystem service valuation studies for the deep seabed. Some ecosystem services can be accurately

valued at zero because they do not exist at the deep seabed, such as fresh water filtration and supply. Other ecosystem services exist at the Solwara 1 site, but are scarce or low-functioning compared with terrestrial systems. A proxy for estimating deep seabed ecosystem services that exist is to use high terrestrial values, likely overestimates, for the values provided in the deep seabed, and this was applied. Solwara 1 has far lower natural systems impact values than terrestrial mines. For terrestrial mines, mines located in deserts appear to perform better than mines located in forests.

A discussion of the proposed shipping, concentrating, and smelting process for Solwara 1 shows that it is likely a far better process than those offered at other smelting facilities. The TNFM smelter is the world's most modern smelter (completed in 2014). However, there are concerns that are present for all sulphide copper ores, such as arsenic wastes and salt in the ore. Nautilus is not responsible for the mineralized material once sold to a smelter. However, the company has contracted with one of the world's newest smelters and requested an accounting from TNFM of the fate of all copper concentrating and smelting byproducts. This establishes a new best practice in the copper mining and production industry.

Solwara 1 can also set a high bar for deep seabed mining. This includes the establishment of conservation sites based on careful science to protect the biodiversity and promote post-mining larval recolonization. There are currently eight other deep seabed mining leases which have been approved globally. Setting a high standard in PNG provides a model for the International Seabed Authority and other countries when considering regulation of seabed mines.

In a world of over 7.3 billion people, copper is needed. The current path is to expand terrestrial mining of copper ore with declining concentrations of copper, higher costs, increased long-term risks and greater social and environmental impacts. This environmental and social benchmarking study demonstrates the clear benefits of developing the first deep seabed copper mine.

What sets Solwara 1, Nautilus, and the PNG Government apart is the implementation of deep seabed mining. Copper mining has been exclusively terrestrial for 7,000 years. Expanding metal mining to the deep seabed opens most of the earth's solid surface to mining for the first time. The technological transformation associated with the mining technology, machinery and production vessel is remarkable. History records few technological developments with such capacity for change, economic advancement, and transformation toward greater sustainability.

In a world of over 7.3 billion people, copper is needed. The current path is to expand terrestrial mining of copper ore with declining concentrations of copper, higher costs, increased long-term risks and greater social and environmental impacts. This environmental and social benchmarking study demonstrates the clear benefits of developing the first deep seabed copper mine. Solwara 1 provides an opportunity to expand mining to 7% copper,135 with fewer social and ecological impacts and long-term risks. It provides an opportunity to meet the copper demands for expanding sustainable energy production, rural electrification, better and more widespread telecommunications, safe drinking water and a plethora of modern products. Providing these goods and services that require copper is essential to improving the quality of life for over a billion people living in severe poverty. In a world of declining terrestrial copper concentrations, Solwara 1 provides a path toward producing copper with higher concentrations in the 21st century and beyond.

Overall, Earth Economics finds the Solwara 1 proposal to be a clear opportunity to dramatically reduce the social and environmental impacts of copper mining.

▶ Traditional fishing
Image credit: Photo: AusAID

Appendix A: Land Cover, Ecosystem Services, Authors and Values for Monetization Analysis

The land cover, ecosystem services, and authors with dates and values utilized for the ecosystem service monetization analysis are included in the table below. The full references for the studies in this Appendix are included in Appendix B.

Solwara 1 Land Cover, Ecosystem Services, Authors, and Values

Land Cover	Ecosystem Service	Author(s) (Primary)	Value ($/hectare/year)
Seabed	Biological Control	Krieger, D.J.	$25.67
	Genetic Resources	Godoy, R. et al.	$276.69
	Habitat Refugium & Nursery	New Jersey Type A Studies 2006	$1,463.67

Prominent Hill Land Cover, Ecosystem Services, Authors, and Values

Land Cover	Ecosystem Service	Author(s) (Primary)	Value ($/hectare/year)
Mixed Chenopod, Samphire	Habitat & Biodiversity	Costanza, R., et al	$828.01
	Recreation	Bennett, R., et. al.	$481.04
	Climate Stability	EE calculation	$22.69

Bingham Canyon Land Cover, Ecosystem Services, Authors, and Values

Land Cover	Ecosystem Service	Author(s) (Primary)	Value ($/hectare/year)
Cultivated	Food	Faux, J.	$577.54
		Piper, S.	$112.84
		Sandhu, H.S., Wratten, S.D., Cullen, R., Case, B.	$22,559.58
			$16,710.80
		Zhou, X., et al.	$267.32
	Water Regulation	Sandhu, H.S., Wratten, S.D., Cullen, R., Case, B.	$121.29
			$61.21
	Habitat and Biodiversity	Sandhu, H.S., Wratten, S.D., Cullen, R., Case, B.	$563.39
			$736.47
			$97.88

Land Cover	Ecosystem Service	Author(s) (Primary)	Value ($/hectare/year)
			$87.13
	Soil Retention	Moore, W.B	$11.55
		Pimentel, D. et al	$325.42
			$296.07
		Wilson, S. J	$5.59
	Aesthetic Information	Bergstrom et al.	$216.94
	Nutrient Cycling	Wilson, S. J	$24.72
	Soil Formation	Pimentel, D.	$17.42
		Sandhu, H.S., Wratten, S.D., Cullen, R., Case, B.	$109.81
			$416.56
			$607.29
			$13.15
			$10.74
		Wilson, S. J	$6.37
	Biological Control	Cleveland, C.J., et al	$498.47
		Pimentel, D.	$203.57
			$140.15
		Pimentel, D. et al	$76.36
		Sandhu, H.S., Wratten, S.D., Cullen, R., Case, B.	$119.36
	Energy and Raw Materials	Sandhu, H.S., Wratten, S.D., Cullen, R., Case, B.	$267.37
			$355.70
	Air Quality	Canadian Urban Institute	$248.55
		Sandhu, H.S., Wratten, S.D., Cullen, R., Case, B.	$250.68
	Pollination	Costanza, R. et al	$34.06
		Pimentel, D.	$254.03
		Ricketts, T.H. et al.	$484.63
		Sandhu, H.S., Wratten, S.D., Cullen, R., Case, B.	$622.51
			$543.10
		Winfree et al	$4,832.07
Deciduous Forest	Recreation and Tourism	Prince, R. and Ahmed, E.	$133.86
		Shafer, E.L. et al	$1,406.26
			[illegible]
			$255.54
		Willis	$1,359.07
	Aesthetic Information	Standiford, R., Huntsinger, L.	$1,217.22
	Biological Control	Krieger, D.J	$26.06
		Pimentel, D.	$11.16
			$74.44
	Energy and Raw Materials	Pimentel, D.	$46.20

Land Cover	Ecosystem Service	Author(s) (Primary)	Value ($/hectare/year)
	Air Quality	Wales, W., Reyes, J.	$969.97
Desert	Recreation and Tourism	Richer, J.	$151.62
	Air Quality	Dolfino, K., et al.	$2.16
Emergent Herbaceous Wetland	Food	Allen, J., et al.	$976.56
	Water Regulation	Brander, L.M., et al.	$6,502.96
			$250.55
			$2,920.04
			$1,574.05
	Habitat and Biodiversity	Everard, M.	$33.63
		Gren, I.M. and Soderqvist, T.	$44.50
		Loomis, J.	$14,867.94
		Pearce, D. and Moran, D.	$10,637.22
			$708.51
		Woodward, R., and Wui, Y.	$4,320.69
	Recreation and Tourism	Brander, L.M., et al.	$2,119.16
		Cooper, J. and Loomis, J.	$333.62
		Farber and Costanza 1987	$941.26
		Gren, I.M. and Soderqvist, T.	$543.14
			$596.21
			$7,793.62
		Kreutzwiser, R.	$521.06
		Lant, C.A. and Roberts, R.S.	$509.06
		Stoll et al. 1989	$1,531.57
		Whitehead	$15,559.41
		Willis, K.G., Garrod, G.D. 1991. An individual travel cost method of evaluating forest recreation. Journal of Agricultural Economics 42, 33-42	$97.24
			$300.56
		Wilson, S.J.	$310.26
		Woodward, R., and Wui, Y.	$61.06
			$967.66
			$12,252.96
	Aesthetic Information	Mahan, B.L., et al.	$98.64
		(Blank)	$15,559.41
	Waste Treatment	Brander, L.M., et al.	$6,889.51
		de Groot, D.	$38,883.13
		Gosselink et al.	$15,408.88

Land Cover	Ecosystem Service	Author(s) (Primary)	Value ($/hectare/year)
		Gren, I.M. and Soderqvist, T.	$1,045.42
			$983.72
		Grossman, M.	$30.64
		Lant, C.A. and Roberts, R.S.	$509.06
		Meyerhoff, J. and Dehnhardt, A.	$2,354.42
		Olewiler, N.	$2,751.78
		Wilson, S.J.	$5,284.43
			$515.98
		Woodward, R. and Wui, Y.	$6,059.22
	Moderation of Extreme Events	Brander, L.M., et al.	$5,509.87
		Costanza, R., et al.	$5,753.72
			$5,252.27
		Gupta, T.R. and Foster, J.H.	$1,101.22
		U.S. Army Corps of Engineers 1971	$1,136.60
		Woodward, R. and Wui, Y.	$7,634.43
Evergreen Forest	Food	Lampietti, J.A. and Dixon, J.A.	$78.37
	Water Regulation	Adger, W.N., et al.	$0.19
	Habitat and Biodiversity	Brander, L.M., et al.	$17.65
			$3,495.92
		Costanza, R., et al.	$1,656.01
		Haener, M.K. and Adamowicz, W.L.	$16.39
	Recreation and Tourism	Bamrock, K., et al.	$16,921.57
		Boxall, P.C., et al.	$0.54
		Costanza, R., et al.	$6,570.09
		Haener, M.K. and Adamowicz, W.L.	$0.15
		Harvey, N.D.	$294.74
		Walsh et al. (1978)	$103.25
		Wilson, S.J.	$316.07
	Soil Retention	Moore, W.B.	$2.03
	Waste Treatment	Olewiler, N.	$92.17
		Wilson, S.J.	$515.98
	Biological Control	Wilson, S.J.	$26.27
	Energy and Raw Materials	Haener, M.K. and Adamowicz, W.L.	$0.61
	Moderation of Extreme Events	Wilson, S.J.	$1,682.07
	Air Quality	Wilson, S.J.	$409.98
	Pollination	Costanza, R., et al.	$607.58
		Wilson, S.J.	$1,053.47

Land Cover	Ecosystem Service	Author(s) (Primary)	Value ($/hectare/year)
			$564.60
Grasslands	Food	US Dept of Comm (1995)	$89.60
	Water Regulation	Jones, O.R., et al	$3.99
	Recreation and Tourism	Brookshire, D., et al.	$0.75
		Butler, L.D., and Workman, J.P.	$265.11
		Pearce, D. and Moran, D.	$0.69
	Pollination	Wilson, S. J.	$1,053.47
Shrub	Habitat and Biodiversity	Costanza, R., et al	$928.01
	Recreation and Tourism	Bennett, R., et al	$461.04
		Costanza, R., et al	$3,327.41
	Pollination	Costanza, R., et al	$17.26
Woody Wetlands	Water Regulation	Brander, L.M., et al	$844.69
			$2,643.65
	Habitat and Biodiversity	Brander, L.M., et al.	$2,564.30
		Mayer and Anderson 1987	$35,791.08
		van Kooten, G.C. and Schmitz, A.	$42.69
			$98.69
		Wilson, S. J.	$6,347.74
	Recreation and Tourism	Gupta, T.R., and Foster, J.H.	$963.57
		Kozak, J., et al	$1,342.75
		Whitehead, J.C.	$17,682.41
	Aesthetic Information	van Vuuren, W. and Roy, P.	$3,569.03
		Whitehead, J.C.	$17,682.41
	Waste Treatment	Grossman, M.	$23.64
		Jenkins, W.A., et al	$1,349.79
			$1,439.48
		Thibodeau, F.R. and Ostro, B.D.	$14,063.94
	Moderation of Extreme Events	Brander, L.M., et al	$7,778.15
		Leschine, T.M., et al	$15,772.53
		Loomis, J. and Ekstrand, E.	$13,269.63
		Qiu, Z., et al	$14,777.50
		Streiner, C., Loomis, J.	$1,292.41
		Wilson, S. J.	$4,296.26
Pasture/Hay	Habitat and Biodiversity	Bastian, C.T., et al	$11.90
			$4.60
	Recreation and Tourism	Boxall, P.C.	$0.09
	Soil Retention	Canadian Urban Institute.	$15.37
		Wilson, S. J.	$5.89

Land Cover	Ecosystem Service	Author(s) (Primary)	Value ($/hectare/year)
	Aesthetic Information	Bastian, C.T., et al	$12.84
	Nutrient Cycling	Canadian Urban Institute	$56.93
		Wilson, S. J.	$24.72
	Soil Formation	Canadian Urban Institute	$15.37
		Pimentel, D., et al	$19.10
		Wilson, S. J.	$6.37
	Biological Control	Pimentel, D., et al	$45.82
		Wilson, S. J.	$43.28
	Pollination	Wilson, S. J.	$1,053.47
Desert	Energy and Raw Materials	Delfino, K., et al	$72.19
Grasslands	Habitat and Biodiversity	Gascoigne, W.R., et al.	$87.17
	Soil Retention	Gascoigne, W.R., et al	$17.97
	Aesthetic Information	Ready, R.C., et al	$0.01
			$0.02
Urban	Water Regulation	Brosey, R.A.	$490.05
		McPherson, G.	$22.43
			$22.44
		Trust for Public Land	$490.00
			$1,052.60
	Recreation and Tourism	Bishop, K.	$5,741.26
		Brander, L.M., et al	$16,221.68
		Breffle, W., et al	$25,224.22
		Tyrvainen, L.	$5,587.44
			$5,296.13
			$10,516.27
	Aesthetic Information	Beltzer and Netusil	$57,605.30
		McPherson, G. and Simpson	$5,466.86
		Nowak, D.J., et al	$15,909.37
			$15,051.69
			$20,478.65
			$21,481.74
			$22,936.37
			$22,610.92
			$24,201.01
			$44,114.25
		Opaluch, R.J., et al	$7,655.97
		Qiu, Z., et al	$5,373.64
		Thompson, R., et al	$26,135.49
	Moderation of Extreme Events	McPherson, G. and Simpson	$310.86
	Air Quality	Brosey, R.A.	$978.63
		McPherson, E.G., et al	$76.92
		McPherson, G.	$510.29
			$618.58

Land Cover	Ecosystem Service	Author(s) (Primary)	Value ($/hectare/year)
		McPherson, G. and Simpson	$425.11
	Climate Stability	McPherson, G.	$3,258.33
Cultivated	Recreation and Tourism	Costanza, R., et al.	$78.53
		Knoche, S. and Lupi, F.	$63.29
Deciduous Forest	Recreation and Tourism	Bennett, R., et al.	$461.04
		Maxwell, S.	$466.22
	Waste Treatment	Zhongwei, L.	$707.25
			$710.20
Emergent Herbaceous Wetland	Food	Woodward, R., and Wui, Y.	$24,743.75
	Habitat and Biodiversity	Meyerhoff, J., and Dehnhardt, A.	$23,110.65
	Aesthetic Information	Mazzotta, M.	$36,862.63
		Opaluch, R. J., et al.	$24,776.52
	Moderation of Extreme Events	Thibodeau, F. R. and Ostro, B. D.	$18,896.73
		U.S. Army Corps of Engineers 1978	$20,467.05
Grasslands	Soil Retention	Rein, F. A.	$9,361.56
			$97.10
			$3,806.27 $569.29
	Aesthetic Information	Mazzotta, M.	$9,215.66
		Opaluch, R. J., et al.	$7,855.97
			$12,359.37
		Qiu, Z., et al.	$3,280.67
	Waste Treatment	Rein, F. A.	$54,177.17
		Zhongwei, L.	$16,696.97
			$29,954.46
	Biological Control	Rein, F. A.	$60.90
			$776.79
	Moderation of Extreme Events	Rein, F. A.	$10,253.62
			$670.41
Lake	Recreation and Tourism	Cordell, H. K. and Bergstrom, J. C.	$4,910.20
		Costanza, R., et al.	$4,961.47
		Ribaudo, Marc, et al.	$2,157.02
		Ward, F. A., et al.	$11,743.11
		Young, C. E. and Shortle, J. S.	$17.28
	Aesthetic Information	Berman, M. A., et al.	$611.60
		Young, C. E. and Shortle, J. S.	$4.46
	Waste Treatment	Bouwes, N. W. and Schneider, R.	$3,777.02

Land Cover	Ecosystem Service	Author(s) (Primary)	Value ($/hectare/year)
		Young, C. E. and Shortle, J. S.	$5.67
Riparian	Food	Knowler, D. J. et al.	$1,961.07
		Knowler, D.J., et al.	$128.33
	Habitat and Biodiversity	Amigues, J. P., et al.	$1,810.12
		Berrens, R. P., et al.	$10,907.59
		Berrens, R.P., et al.	$91.70
		Haener, M. K. and Adamowicz, W. L.	$38.23
		Wu, J. Skelton-Groth, K.	$7,614.09
	Recreation and Tourism	Everard, M.	$38.76
		Lant, C. L. and Tobin, G.	$5,496.82
	Moderation of Extreme Events	Zavaleta, E.	$158.12
River	Water Regulation	Gibbons, D.C.	$7,036.95
			$5,246.29
			$1,822.07
			$5,733.23
	Recreation and Tourism	Loomis, John B., et al	$56.81
			$491.77
		Mathews, Leah Greden, et al	$35,768.09
		Shafer, E. L., et al.	$11,581.99
			$44,236.61
	Aesthetic Information	Berman et al.	$1,252.99
		Kulshreshtha, S. N. and Gillies, J. A.	$2,129.51
		Rich, P. R. and Moffitt, L. J.	$20.05
		Sanders, L. D., et al.	$30,760.03
Woody Wetlands	Aesthetic Information	Thibodeau, F. R. and Ostro, B. D.	$364.74
	Moderation of Extreme Events	Leschine, T.M., et al.	$19,437.74

Intag Land Cover, Ecosystem Services, Authors and Values

Land Cover	Ecosystem Service	Author(s)	Value ($/hectare/year)
Agricultural Lands	Aesthetic & Recreational	Bergstrom, J., Dillman, B. L. and Stoll, J. R. 1985	$78.51
	Erosion Control	Canadian Urban Institute.	$15.43
	Gas & Climate Regulation	Smith, W.N. et al.	$74.59
		Wilson, Sara J.	$843.66
	Nutrient Cycling		$59.36
	Pollination	Robinson, W. S., Nowogrodzki, R. and Morse, R. A. 1989	$34.35
		Southwick, E. E. and Southwick, L. 1992	$6.55
		Ricketts, T.H., Daily, G.C., Ehrlich, P.R., and Michener, C.D.	$457.36
	Raw Materials	Martinez, A.	$1,077.63
		Valverde, M. and Gaybor, A.	$2,751.56
	Soil Formation	Canadian Urban Institute.	$15.43
		Sandhu, H.S., Wratten, S.D., Cullen, R., and Case, B.	$15.43
	Food Production	Martinez, A.	$11,456.75
		Valverde, M. and Gaybor, A.	$5,102.63
Pasture	Soil Formation	Pimentel, D. 1998	$17.76
Bamboo	Gas & Climate Regulation	Tianhong, L. et al.	$670.36
	Habitat Refugium & Nursery	Tianhong, L. et al.	$624.41
	Raw Materials	Tianhong, L. et al.	$497.96
	Soil Formation	Tianhong, L. et al.	$737.50
	Waste Treatment	Tianhong, L. et al.	$250.91
	Water Supply	Tianhong, L. et al.	$612.72
Native Andean Alpine Grasslands	Biological Control	Pimentel et al., 1995	$24.65
		Pimentel et al., 1997	$36.35
	Erosion Control	Barrow (1991) (Calculated 1992)	$48.39
		Costanza et al. 1997	$45.60
	Gas & Climate Regulation	Costanza et al. 1997	$10.37
		Fankhauser and Pearce (1994)	$10.26
		Wilson, Sara J.	$433.33
		Wunder, S. et al.	$325.66
	Habitat Refugium & Nursery	Asquith et al.	$3.38
	Pollination	Pimentel et al., 1995	$27.26
		Pimentel et al., 1997	$39.31
	Soil Formation	Costanza et al. 1997	$1.57
		Sala and Paruelo (1997) (Calculated 1994)	$1.32
	Waste Treatment	Pimentel et al., 1997	$136.79
		Wunder et al.	$16.30
	Water Regulation	Costanza et al. 1997	$4.71
		Jones et al. (1995) (Calculated 1992)	$5.47
	Water Supply	Asquith et al.	$3.38
		Wunder, S. et al.	$16.30
	Food Production	US Dept of Comm (1995) (Calculated 1992)	$62.16
Cloud Forests	Aesthetic & Recreational	Prince, R. and Ahmed, E.	$5.12
	Biological Control	Gossling, S.	$335.01
		Costanza et al. 1997	$6.19
		Krieger, D.J.	$75.67
	Erosion Control	Chopra 1993	$1,045.19
		Costanza et al. 1997	$149.14
		Chomitz, K.M., and Kumari, K.	$899.17
		Magrath, W.B., and Arens, P.	$9.89
	Gas & Climate Regulation	Pimentel, D. 1998	$35.90
		Adger et al. 1995	$133.58
		Mates, W., Reyes, J. 2004	$679.09
		New Jersey Type A Studies 2006	$35.90
		Kumari, K.	$546.06
		Grieg-Gran, M. et al.	$147.31
	Genetic Resources	Adger et al. 1995	$169.72
		Pearce, D., and Moran, D.	$37.57
	Habitat Refugium & Nursery	Godoy, R. et al.	$276.60
		Amigues, J. P., et al.	$658.95
		Amigues, J. P., et al. 2002	$772.42
		Garber et al. 1992	$1,292.11
		Haener, M. K. and Adamowicz, W. L.	$28.07
		Kenyon, W. and Nevin, C.	$1,476.71
		Shafer, E. L. et al.	$8.03
		New Jersey Type A Studies 2006	$1,463.57
		Asquith et al.	$3.38
	Nutrient Cycling		$1,467.85
	Pollination	Wilson, Sara J.	$531.01
		New Jersey Type A Studies 2006	$713.76
		Asquith et al.	$3.38
	Raw Materials	Costanza et al. 1997	$28.84
		Shone and Caviglia-Harris 2006	$46.22
		Grimes, A. et al.	$3,731.91
	Soil Formation	Gram, S.	$23.09
		Costanza et al. 1997	$15.54
		Pimentel et al. 1997	$10.91
	Waste Treatment	Pimentel et al. 1997	$94.64
		Adger et al. 1995	$282.68
	Water Regulation	Loomis, J.B. 1988	$27.44
		Olewiler, N.	$33.55
	Water Supply	Asquith et al.	$3.38
		Kumari	$11.53
	Food Production	Costanza et al. 1997	$77.68

Land Cover	Ecosystem Service	Author(s)	Value ($/hectare/year)
		Adger et al. 1995	$2,898.55
		Godoy et. al. 1993	$170.05
Rivers and Lakes	Aesthetic & Recreational	Burt, O. R. and Brewer, D.	$1,318.52
		Cordell, H. K. and Bergstrom, J. C.	$4,053.18
	Nutrient Cycling		$59.36
	Pollination	Robinson, W. S., Nowogrodzki, R. and Morse, R. A. 1989	$34.55
		Southwick, E. E. and Southwick, L. 1992	$6.55
		Ricketts, T.H., Daily, G.C., Ehrlich, P.R., and Michener, C.D.	$457.36
	Raw Materials	Martinez, A	$1,077.63
		Valverde, M. and Gaybor, A.	$2,751.56
	Soil Formation	Canadian Urban Institute.	$15.43
		Sandhu, H.S., Wratten, S.D., Cullen, R., and Case, B.	$15.43
	Food Production	Martinez, A.	$11,458.75
		Valverde, M. and Gaybor, A.	$5,102.65
Pasture	Soil Formation	Pimentel, D. 1995	$17.76
Bamboo	Gas & Climate Regulation	Tianhong, L. et al.	$670.36
	Habitat Refugium & Nursery	Tianhong, L. et al.	$624.43
	Raw Materials	Tianhong, L. et al.	$497.96
	Soil Formation	Tianhong, L. et al.	$737.30
	Waste Treatment	Tianhong, L. et al.	$250.91
	Water Supply	Tianhong, L. et al.	$612.72
Native Andean Alpine Grasslands	Biological Control	Pimentel et al. 1995	$24.65
		Pimentel et al. 1997	$36.55
	Erosion Control	Barrow (1991) (Calculated 1992)	$48.39
		Costanza et al. 1997	$45.60
	Gas & Climate Regulation	Costanza et al. 1997	$10.37
		Fankhauser and Pearce (1994)	$10.26
		Wilson, Sara J.	$433.33
		Wunder, S. et al.	$325.66
	Habitat Refugium & Nursery	Asquith et al.	$3.35
	Pollination	Pimentel et al. 1995	$27.26
		Pimentel et al. 1997	$39.31
	Soil Formation	Costanza et al. 1997	$1.57
		Sala and Paruelo (1997) (Calculated 1994)	$1.31
	Waste Treatment	Pimentel et al. 1997	$136.79
		Wunder et al.	$16.30
	Water Regulation	Costanza et al. 1997	$4.71
		Jones et al. (1995) (Calculated 1992)	$5.47

Land Cover	Ecosystem Service	Author(s)	Value ($/hectare/year)
		Kealy, M. J. and Bishop, R. C.	$36.92
		Kreutzwiser, R.	$517.48
		Piper, S.	$685.78
		Ward, F. A., Roach, B. A. and Henderson, J. E.	$5,477.74
		Young, C. E. and Shortle, J. S.	$233.69
		Loomis J.B. 2002	$56,241.74
		Postel & Carpenter 1997	$250.71
	Habitat Refugium & Nursery	Loomis 1996	$46.14
	Waste Treatment	Gibbons (1986) (Calculated 1980)	$2,606.23
	Water Regulation	Gibbons (1986) (Calculated 1980)	$7,048.46
	Water Supply	Bouwes, N. W. and Scheider, R.	$1,762.88
		Croke, K., Fabian, R. and Brenniman, G.	$1,615.70
		Gibbons (1986) (Calculated 1980)	$1,371.07
		Henry, R., Ley, R. and Welle, P.	$1,225.68
		Howe & Easter (1971) (Calculated 1971)	$15,959.60
		Piper, S.	$87.11
		Ribaudo, M. and Epp, D. J.	$2,408.07
	Food Production	Postel & Carpenter 1997	$44.68
Pasture and Agricultural	Aesthetic & Recreational	New Jersey Type A Studies 2006	$69.41
	Biological Control	Costanza et al. 1997	$36.52
	Pollination	New Jersey Type A Studies 2006	$30.54
	Soil Formation	Costanza et al. 1997	$1.54
	Food Production	Costanza et al. 1997	$94.03

Appendix B: Ecosystem Service Valuation Study References

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Appendix C: Analysis I: Copper Recycling and Substitution

Is copper mining necessary? Some advocates, including Greenpeace, assert that copper recycling provides an alternative to seabed mining.[136] Copper prices are high, providing a strong incentive for recycling globally. Recycling currently provides a significant portion of the total annual copper supply. Though sources differ on the exact amount, it is likely above 30%. Increasing recycling is a goal that should be pursued globally. Copper is too valuable to be sent to a landfill. However, copper also has a long, useful life in most products. Mining today provides the vast majority of the copper supply. Demand for copper continues to rise, but is highly sensitive to economic downturns, particularly in the housing market. How best to mine copper with the fewest negative externalities or damaging impacts to communities, biodiversity, water quality, and natural systems is a critical question.

Mining seabed copper ore could displace terrestrial mining because the return per hectare of disturbance is high (disturbance is very low), saving communities, biodiversity, energy, and greenhouse gas emissions, and more. If increased copper recycling can be achieved, it should displace the most destructive copper ore mining. The following discussion examines recycling and the more potent option of substituting other technologies and materials for copper. The implications of recycling for the Solwara 1 proposal are also discussed.

Copper is virtually 100% recyclable; as an element, copper does not decay. Copper does not lose physical, chemical, or performance properties with recycling processes. Recycled copper is no different from copper smelted from ore. Recovering and recycling copper for reuse helps meet global demand, conserves natural resources, and improves sustainability by reducing environmental and social externalities. The process of recycling copper, called secondary production, uses far less energy—up to 85 % less—than primary production (mining). The current level of copper recycling saves an estimated 100 MW of electrical energy and 40 million metric tons of CO_2 each year.[137]

Recycled copper has remained a relatively stable portion of the growing copper supply, consistently supplying between 30% and 40% of the total copper supply since the 1950s. The demand for copper has increased dramatically from 2.5 million metric tons in 1950 to between 21 and 24 million metric tons in recent years, at an annual growth rate of 3.4%. This is despite dramatic copper price fluctuations, economic booms and busts, and some changes in copper applications. Of the estimated 24 million metric tons of copper used around the globe in 2010, 35% was sourced through recycling.[138] Part of the recent increase in the demand for copper comes from an increase in demand for end-of-life products such as laptops and cell phones, as well as the demand for plumbing and wiring with the growth in construction in developing countries.

Recycled copper can come from "old" scrap (end-of-life products found in electronics, households, cars, and industrial) and "new" scrap (factory scrap waste from the copper production process). Around 9 million metric tons of copper per year comes from both "old" and "new" scrap.[139]

A recent article in Environmental Sciences and Technology examined the total stock of copper in the global built capital economy. The article states: "Based on the global copper stocks and flows model, recently developed by the Fraunhofer Institute, it is estimated that two-thirds of the 550 million metric tons of copper produced, since 1900, are still in productive use."[140] This approximately 360 million metric tons of copper is equivalent to a 17-year supply of copper at the current demand of 21 million metric tons per year. Yet, this copper is largely unavailable for recycling because it is still productively employed in buildings, equipment, generators, ships and other built capital assets.

Experts project that additional copper recycling will be necessary to keep up with the growing demand, but also expect that this will not relieve the full demand for copper from mining.[141] For recycling to effectively increase, there will need to be innovation in education. Cultural adoption must increase to raise recycling rates. Improvements in product design to facilitate recycling must proceed. Incentives motivating recovery must be implemented. Specific, proven catalyst programs will be required to achieve higher copper recycling rates, if copper recycling is to partially decrease the demand for mining sourced copper.[142]

Copper recycling has limitations. Fraunhofer and the International Copper Association have pointed out that there are copper losses during the smelting process, semi-finished production processes, with dissipation and abandonment of products, losses in scrap collection and losses in scrap separation processes. They do not estimate how much additional copper in the current global flow of copper could be additionally recycled. One of the difficulties of estimating copper availability for increased recycling is the lack of data concerning the amount of copper in the built capital stock that could be available for recycling, such as the copper contained in an obsolete generator in a farmer's barn, versus the copper stock in built capital that is fully utilized, such as an operating generator in a farmer's barn. Copper prices are high. The global recycling market is large, brisk and efficient. There is strong global awareness that recycling copper provides income. It appears that there is no easily available vast stock of copper simply waiting to be recycled.

Further research will be required to understand the full potential of copper recycling, but it is the opinion of Earth Economics that it is very unlikely to provide much more of the global copper supply than it currently provides within the next decade.

Overall, there is no question that mining is required to meet growing copper demand and to ensure that many people living in poverty can avail themselves of modern power, drinking water and electronic goods. Copper is generally applied in long-lived applications, such as house plumbing or generator windings. This is unlike an aluminum beverage can, which has a short life between recycling events. Copper applications have useful lifespans that can easily last decades as in power station generators. In addition, much of the copper consumption provides new services such as rural electrification, residential construction, and industrial applications, particularly in China and India. Thus, according to the International Copper Study Group (ICSG), "recycled copper alone cannot meet society's needs."[143] The only opportunity for greatly increasing copper recycling would be to displace copper currently in use with substitute materials.

For many applications, copper is a difficult material to replace because it performs so well as a power and heat conductor. Copper has been a necessity for applications in domestic and industrial infrastructure and high technology for decades, and will continue to be essential to both developed and developing nations. There has, however, been growing research and development in alternative materials and substitutes for copper. Carbon-based conductor replacement materials are on the technological horizon.[144]

Carbon-based conductor replacement materials are being researched for applications in aerospace, oil platforms, and optoelectronic devices. Carbon nanotube conductor cables, currently under development, show promise. They have been shown to carry four times as much current as copper wire of the same mass, but at a fraction of the weight.[145] Overall, however, there is currently no satisfactory substitute for copper commercially available for many applications. If price-competitive carbon-based nanocomposite products can be produced at a large enough scale, then the demand for copper in power distribution cabling could be reduced. According to a report by BCC Research, "Global consumption of nanocomposites is expected to grow in unit terms from nearly 225,060 metric tons in 2014—an estimated value of over $1.2 billion—to nearly 584,984 metric tons in 2019— $4.2 billion in value—at a compound annual growth rate (CAGR) of 21.1 % for the period of 2014 to 2019."[146] This growth represents the application of nanocomposites to far more than copper replacement applications.

Copper recycling rates could be increased if many products were redesigned to facilitate cost-effective copper recovery (and the recycling of other materials). This is happening more rapidly in some industries, such as computer manufacturing. It is important to keep scale in mind. Cell phones have a relatively short lifespan for copper applications, and they are not designed for easy mineral recovery. In addition, a vast increase in recycling of cell phones would not move the world market in copper. For one million cell phones gone to waste, 1.6 metric tons of copper has also gone to waste, however.[147] This is a relatively insignificant amount of copper. Few cell phones are going to waste. Every phone is worth recycling, not only for the copper, but also for the gold, cobalt, niobium and more. The entire global stock of roughly 4 billion cell phones contains about 6,400 metric tons of copper. This amount would be dwarfed by the stock of copper plumbing currently in buildings if it were recycled, yet most copper plumbing is still in use. Copper plumbing is difficult to replace, and the cost of replacement far exceeds the income that would be generated by copper recycling.

Existing residential and commercial building communications wiring throughout the developed world could be viewed as a vast 'copper mine'. In the case of telecommunications, substitutes with less cost and greater productivity exist. Pulling wires from buildings is far less costly than pulling plumbing. Most voice and data communications can now be conducted over fiber optic networks or wireless systems. While telecommunications used to be the largest market for copper in the U.S. forty years ago, the use of copper in telecommunications cables has since declined sharply with the rise of fiber optic and wireless technology.[148] Fiber links are proven to be a more efficient application for communications, providing over 1,000 times as much bandwidth and 100 times the distance capability, not to mention the capacity to handle more information at a faster rate and with a clearer signal.[149] If the US government were to upgrade its inventory of 436,000 buildings with wireless & fiber networks and reclaim the now obsolete copper wiring, thousands of metric tons, but not millions of metric tons, of copper could be recycled.

Counterbalancing substitution away from copper is the phase out of other metals or materials, such as lead solder, where copper may be part of the replacement for more toxic or lower performance materials. Increased use of copper is the solution in some applications, particularly copper in alloys that are less toxic, more conductive, or more durable substitutes.

There is also growing demand for copper in renewable energy. Over the last decade, increasing investment of renewable resource energy infrastructure and technologies in the U.S. has increased four-fold, from $10.4 billion in 2004 to over $44.2 billion.[150] To increase renewable energies, wind, wave, geothermal, tidal and photovoltaic (PV) solar power systems all use copper in their wiring, tubing, cables, and generators (PV has no generators). Offshore wind energy systems use up to 9.5 metric tons of copper per MW of power. Land-based wind energy systems use

2.5 to 7 metric tons of copper per MW, and PV solar panels use over 2 metric tons of copper per MW of power produced.[151] Copper demand for this sector is increasing sharply. [Offshore wind power photo]

President Obama's 2013 Climate Action Plan committed to double US wind and solar generation by 2020. This alone could increase the usage of copper between 80,000 and 140,000 metric tons. China has far more ambitious plans for expanding wind power as well as coal, gas and nuclear power plants, which all require vast amounts of copper. When it comes to renewable energy systems, copper is a preferred material. It is reliable, efficient and long lived, with high performance qualities.[152]

The global demand for copper is dominated by Asia and China in particular. China consumes 40 % of the world's annual copper production. Demand in Asia has expanded fivefold over the last 30 years, to about 13,739 million metric tons in 2013. More than half the total global copper consumption was in Asia in 2013.[153] For copper recycling to have a significant impact in reducing the demand for mining, there would need to be a large transfer of copper stock from North America, Europe and Japan to China. Because China is expanding copper use in residential and industrial sectors, power distribution, generators, renewable energy and other areas, China has little historic copper stock to tap for recycling.

Globally, and very broadly, the end use of copper has the following sector breakdown: 30% building construction, 30% equipment, 15% infrastructure, 13% transport, and 12 % industrial. Construction accounts for 55% of copper consumption in China. Domestic non-construction consumption accounts for 29% of copper consumption in China. Exports account for 16% of China's copper consumption.[154]

Displacing built infrastructure copper uses with substitutes and pulling copper from existing in-use buildings could open up a significant supply of copper for recycling. Substitutes exist, for example, copper plumbing could be replaced by Pex plumbing systems. Copper wiring could be replaced by aluminum wiring. Copper-based communications wiring could be replaced by fiber optic and wireless. However, these scenarios are not yet economical for much of the copper stock in place. When a wireless system is put into an existing house, the redundant copper wiring is left in place.

Some of these substitutes have significant environmental impacts as well, and may not result in a net gain for sustainability. For example, aluminum replacement of copper wiring requires bauxite mining and is far more energy-intensive in the smelting process. Aluminum has replaced copper in aircraft and some transmission applications, but is not expected to replace the bulk of copper wiring. In addition, aluminum has a larger heat expansion coefficient and has been tied to an increased rate of house fires over copper wiring. Pex plumbing systems are based on high quality plastic pipes with copper fittings. Pex is currently more expensive than copper plumbing. Pex also requires crude oil, refining, plastics and chemical production with the attendant environmental and social impacts. Optic fiber has a far superior performance over copper for communications uses. This technological advantage and market forces have driven the replacement of copper by optic fiber. Despite this significant substitution, global demand for copper has expanded.

Finally, new systems designs that could more closely twin previously segmented parts of the economy might reduce copper consumption. For example, the twinning of renewable power such as windmills with smaller distributed data centers located at the windmill sites could cut copper use as this pairing would integrate the power grid with communications and internet systems, using more robust fiber optic networks. In this case, there would be a shift from moving electrons to moving photons. Instead of moving 24 MW of power from a power plant to a large data center (currently the power demand for a large-scale four hectare data center), which involves large power losses, a distributed data center system would locate appropriately sized data centers at the power sources. Data centers already have substantial battery capacity, 24 MW for two minutes at a four-hectare data center, with additional diesel generating capacity that stands idle awaiting a possible power outage. In this case, the data center batteries could also be used to store wind power for sale in peak periods as part of the power grid. With a power consumer at the windmill site, power efficiency increases greatly as do the economics for the windmill owner. The micro data centers could purchase off-peak power, as well as store and sell power at peak loads. The network of micro data centers could be managed just as a large 10-hectare data center is managed today, optimizing use across the processor pool. In this case, unlike a traditional data center, battery usage could also be optimized. This would facilitate moving photons down fiber optic cables rather than electrons down power cables. The substitution would reduce the need for copper in transmission lines and cabling in data centers. However, there is an enormous stock of large data centers globally, and no rapid transition to a radically integrated power and communications network is currently underway.

Overall, copper recycling is at a high global rate. Copper stocks in built capital assets, such as buildings and generators, are in use. Recycling cannot be dramatically increased in the short-term. The stock of copper in the world's built capital is colossal. The need for an increased stock of copper in performing built capital such as residential houses, renewable power and electronics is growing, and must continue to grow if much of the world's population is to escape abject poverty.

Substitution and the urban mining of this copper stock for recycling in the future could provide a significant and less costly source for the copper supply. However, this transition would be disruptive, such as pulling copper piping from existing buildings to replace with Pex, and is neither economically viable today, nor is it on the near horizon.

Even if there were the ability to mine large built capital copper stocks, two questions would remain. First, with the level of copper mining yet required, though it may be a lower level, where could that copper best be mined with the least natural capital and social impacts? This study supports the projection that seabed copper mining will likely dramatically outperform terrestrial copper mining (open-pit or below ground). Second, are large-scale substitutes such as aluminum wiring, Pex plumbing, or fiber optic actually more sustainable than copper? Optic fiber is unquestionably a superior substitution for copper and markets have powered this substitution. Other substitutes remain more costly, with less performance value, and may not be more sustainable than copper.

There is potential for increased copper recycling. Significantly increasing copper recycling could have two paths. First, redesigning products so that more copper can be pulled from these products when their useful life is complete. Second, the only route to significantly large-scale recycling would be the substitution of other materials and technologies for a significant portion of the copper stock currently in use. This would require a system for replacing the services of copper and cheaply mining built capital copper stocks without damaging in-use buildings and other facilities.

Though this may be viable in the future, it is not here today. In addition, studies on the environmental and social impacts of substitutes would need to be conducted.

There are important conclusions.

1. Copper recycling and the substitution of other materials and technologies for the current in-use copper stock will not be realized in the near future (the next two decades), thus, demand for copper ore will remain high and copper mining will likely expand globally.

2. Even if mining a significant portion of the estimated 360,000 million metric tons of copper serving the current global built capital stock became feasible, copper ore mining would still be required to meet global demand, and seabed mining appears to be an option that could outperform terrestrial copper mining with far less environmental and social impacts, garnering far higher ore concentrations.

Appendix D: Additional Smelter Impact Case Studies

ASARCO Smelter, El Paso, Texas

Once called “Smeltertown”, El Paso, Texas had no tracking of tailings and mining wastes. Material was dumped illegally in fields. The EPA closed the smelter and ordered immediate remediation due to high levels of lead and arsenic.[155] However, the majority of the smelter’s ash plume was oriented to the south, impacting Juarez, Mexico, less than half a mile away from the smelter. Juarez was not included in the environmental remediation.[156]

ASARCO Smelter, City of Tacoma, United States

Operating from the early 1900s, the ASARCO smelter in Tacoma was once the world’s largest copper smelter (1975)[157] before it contaminated 1,000 sq. km. of the Puget Sound region with elevated levels of arsenic, lead and other heavy metals.[158] The soils of nearby Vashon Island are still contaminated to such an extent that the EPA has warned residents against eating garden grown vegetables.[159] The smelter was closed and remediation of the Superfund site is being completed. It is one of 20 sites that ASARCO manages. In 2009, after a legal battle, ASARCO agreed to pay $94.6 million for the City of Tacoma’s restoration of the smelter site.[160] The wider remediation has involved digging up all of the topsoil in many neighborhoods of the city.

Chemetco, City of Hartford, Illinois

With a peak production of nearly 120,000 tons of copper production per year in the early 1990’s, Chemetco produced roughly half of all US copper production.[161] However, the company emitted more airborne lead than any other firm in the US.[162] Chemetco was convicted of evading and violating environmental protection laws. A surprise EPA inspection uncovered a hidden pipe discharging high levels of zinc oxide, lead, cadmium and other regulated hazardous materials directly into Long Lake, a tributary of the Mississippi River.[163] Court proceedings showed that with every rainfall, over 1,500 gallons of hazardous waste sludge was pumped from the smelter into the Mississippi River.[164] Ultimately, lower profitability, an aging smelter, and legal battles led to bankruptcy and closure of the smelter.

Kabwe, Zambia

Kabwe translates to “Smelting Place,” a fitting name for a site that produced roughly 7,600 metric tons of copper ore annually at its peak during the 1970’s. Eventually, declining ore grades and poor maintenance led to the uneconomical plant’s closure in 1994. During its lifetime, the plant operated without pollution standards. No plans were made for remediation. The plant site continues to leach arsenic, lead, and chromium into the soil and water. With the closure of the smelter, “artisanal smelting” has developed. People manually smelt ore, risking their own and the community’s health with ongoing and unregulated or unmonitored hazardous material discharges.[165] Much of this work is performed by children.[166]

Appendix E: Additional Copper Mine Case Studies

Marcopper, Marinduque, Philippines

The Marcopper Mining Corporation operated a highly profitable copper mine. During this period, approximately 200 million tons of mine tailings were piped and dumped into the Calancan Bay (16 years).[167] In 1996, a break in the tailings drainage tunnel flushed 1.6 million cubic meters of acidic tailings containing arsenic into a 27km length of the Makulapnit-Boac River. Dozens of villages were submerged beneath hazardous tailings sludge. The tailings spill isolated roughly 20,000 people, requiring the Philippine Government to declare a national disaster and airlift food, water, and medicine into the area.[168] Lands along the river remain uninhabitable and because the coral reefs were smothered, coastal fisheries collapsed.[169]

La Oroya, Peru

The capital of Peru’s Yauli Province, La Oroya, has produced an average of 70,000 metric tons of copper annually since 1922. In 1999, testing showed local villagers’ blood contained roughly 85 times the World Health Organization maximum limit for arsenic, 41 times for cadmium, and 13 times the limit for lead. After a decade of remediation, the firm that owns the mine, the Doe Run, claims to have substantially reduced levels of harmful pollution, yet there is no independent certification of the remediation performance.[170]

Kabwe, Zambia

Kabwe, once at the core of Zambia’s copper production, has been labeled “Africa’s most polluted city.”[171] Deemed too uneconomic to continue commercial production, the mine was closed in 1994. However, villagers began their own illegal artisanal mining without safety precautions and utilizing rudimentary tools. Destitute villagers dig for minerals under the most primitive of conditions.[172] An average child in Kabwe has roughly 200 ug/dl of lead in their blood; the U.S. Centers for Disease Control and Prevention considers any concentration above 5 ug/dl to be extremely serious.[173]

Grupo Mexico—Buenavista Mine and the Sonora River

Grupo Mexico operates the Buenavista copper mine near the Sonora River, Mexico. On August 7, 2014, Grupo Mexico SAB disclosed that thousands of gallons of sulphuric acid had leached into the Bacanuchi tributary to the Sonora River, severely impacting a 40-mile reach of the river and contaminating the drinking water of 20,000 people.[174] Grupo Mexico had underestimated the extent of multiple spills. The Sonoran State Environmental Protection Agency subsequently ordered the company to establish a $150 million trust fund before closing the mine. The heaviest rainy season in 40 years, coupled with Hurricane Odile, flushed highly acidic material into the river, which overflowed into surrounding farmland. The government declared all land within 1,600 feet of the riverbanks as contaminated.[175] It is estimated that 90% of agricultural production in the area has ceased in a province where agriculture constitutes 20% of all economic activity.[176]

Appendix F: About the Authors

David Batker is Founder and Executive Director of Earth Economics. He is a leader in the field of Ecological Economics. An acclaimed speaker, leader, educator and advocate, Dave co-founded the non-profit Earth Economics to catalyze a global shift of investment to sustainable practices. His work has been quoted in the Washington Post, LA Times, and 40 other newspapers as well on radio and television. David is also a trained geologist.

Some of David's and the Earth Economics Team's recent accomplishments include:

• Improving the Federal Emergency Management Agency (FEMA) benefit/cost analysis for hurricane and flood mitigation (80% of FEMA's mitigation expenditures) to include environmental benefits.

• Examining the socio-economic impacts of multi-billion dollar projects for the restoration of the Mississippi River Delta.

• Analyzing the Yosemite Rim Fire for the San Francisco Public Utilities Commission: The first natural asset fire loss analysis. California Gov. Brown used this for his disaster declaration; work completed in 60 days.

• Helping improve lending standards including environmental assessment, information disclosure and indigenous people's rights at the World Bank, Asian Development Bank, InterAmerican Development Bank, export credit agencies and private banks.

• David also co-authored the acclaimed book: What's The Economy For, Anyway? published by Bloomsbury Press. The New York Book Review ranked the book in the top ten economics and business books in 2011.

Rowan Schmidt leads Earth Economics' 21st Century Utility program with the goal of expanding water utility funding mechanisms for watershed health. Areas of the program include: providing accurate valuation of drinking water watersheds to inform utility investment decisions; updating national accounting standards to recognize watersheds that provide and filter water; improving asset management approaches for natural infrastructure; enhancing bond disclosure standards to include watershed and natural capital conditions; and adjusting water utility rate structures to support natural capital investments. Rowan also works on projects to advance the methods and applications of ecosystem service valuation in source water protection, benefit-cost analysis, return on investment analysis, and other areas of policy making.

Recent areas of work include:

• Co-editing a World Resources Institute report on source water protection strategies and contributed chapters on natural capital finance mechanisms and accounting rules for water utilitiesPlanning and executing several workshops that brought together leaders from major water utilities to discuss natural capital valuation, accounting, and finance mechanisms for source water protection.

• Working with Duke University, three partner utilities, and a number of expert advisors to develop approaches to capturing the value of utility natural infrastructure using a traditional balance sheet format.

• Coordinating research, writing and economic valuation of damages due to the California Rim Fire near Yosemite Park and Hetch Hetchy Reservoir – a key drinking water source for San Francisco – which were used to support the State of California's successful application for FEMA assistance.

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[48] Nautilus’ Annual Information Form (AIF) dated March 28, 2014 contains the following cautionary disclosure under the section entitled “Risk Factors” (page 52) (capitalized terms are defined in the AIF, which

is available at www.sedar.com): "No pre-feasibility study or feasibility study. Nautilus does not intend to complete a pre-feasibility study or feasibility study or define a large, long life resource or reserve before proceeding with the construction of equipment and commencement of production at the Solwara 1 Project. Management considers the Company's best interests would be served by first demonstrating that existing offshore technologies could be adapted to cut and recover high grade seafloor massive sulphides from the deep ocean. Furthermore, the cost estimates in the Cost Study are not current as of the date of the Technical Report, the Solwara 1 and 12 Report or this AIF and should not be relied on as reflecting the current costs associated with Nautilus' present production plans. The Technical Report and the Solwara 1 and 12 Report do not update the cost estimates in the Cost Study. Accordingly, no independent Qualified Person has confirmed the amount of these costs or recommended that these costs be incurred. There is significant risk with this approach and no assurance can be given that the proposed production at the Solwara 1 deposit will successfully demonstrate that seafloor resource development is commercially viable."

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