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Research paper

Mining beyond earth for sustainable development: Will humanity benefit from resource extraction in outer space?

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ABSTRACT

The concept of sustainable development has been at the forefront of conversations around humankind's shared future for several decades. With expansion into outer space likely to be a prominent feature of that future, it is important to consider how our actions in outer space may impact sustainable development. Definitions of sustainable development share the idea that we must work to preserve our environment, lift people from poverty, and reduce economic and social inequalities, all while looking to ensure inter-generational equality. With many resources becoming increasingly scarce on Earth, providing resources for future generations may mean looking to extraterrestrial bodies such as asteroids, the Moon and Mars to top up our dwindling supplies. There are numerous studies exploring the technical and economic considerations necessary to make resource extraction in outer space a reality; however it is important to also consider the social, socio-economic, and environmental impacts of such an undertaking. This paper discusses whether mining resources from celestial bodies is compatible with the international goal of achieving sustainable development. Mining in space has not yet begun in earnest, providing us with the unique opportunity to establish sustainable mining practices before any resource extraction takes place. As such, we make suggestions for a sustainable off-Earth mining framework, emphasising space mining practices that are environmentally, economically, and socially sustainable.

1. Introduction and background

Since the first person travelled into outer space in 1961, humankind has continued to expand its reach beyond Earth. While the history of human activity has, so far, been dependent on resources extracted from Earth, our growing population and ever-increasing demand for resources brings about concerns that Earth can no longer meet the needs of the population. Thus, it is natural that we might look to space as the "final frontier" to supply Earth with resources necessary for our continued development. Asteroids, the Moon and Mars all contain important indigenous resources that are important for humankind's continued expansion into outer space. While many of these resources will be utilised in space, some may prove useful and/or economical here on Earth too. Innovations will likely continue to reduce the cost of space travel, making the extraction of resources from celestial bodies, in some form, a likelihood in the coming decades. Most of the present discussion surrounding mining off-Earth is focused on the necessary economic and technical considerations to make extracting resources in outer space a reality. However, beyond economic and technical feasibility, if off-Earth mining is to become a reality, it is important to consider how it may or may not benefit humanity.

The 2030 Agenda for Sustainable Development [1] provided clear direction that the world must aim to tread a more economically, socially and environmentally sustainable path. The agenda is focused on improving the quality of life for everyone on Earth through ending poverty, reducing income inequalities between countries, and protecting our environment [1]. With calls for the currently lacking space law to be updated and clarified around the area of resource extraction in outer space, now seems to be the ideal time to discuss how off-Earth mining fits into humanity's shared aim of achieving sustainable development. This paper explores the ways in which mining in outer space could 1) contribute to the shared aim of achieving sustainable development, 2) areas where it may be counter-productive, and 3) what must be taken into consideration to ensure mining off-Earth is carried out

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sustainably.

1.1. Why mine extraterrestrial bodies?

In order to realise affordable, accessible space travel, allowing humans to travel farther into space than ever before and establish settlements on bodies beyond Earth, extraction of necessary resources in space is essential. Extracting water from extraterrestrial bodies is the first step, as not only is it vital for life support, it can also be used to make rocket propellant. Creating rocket propellant in space will result in celestial "gas stations". The mass of propellant that must be launched from Earth can be reduced drastically, which in turn will reduce the cost and facilitate deeper space travel. Seen as the next frontier in human development, deeper space travel will open up a new realm of possible scientific discoveries and further our understanding of the solar system.

Beyond space travel and sustaining a human presence in space, there is an economic imperative for off-Earth mining. There is potential for a self-sustaining cis-lunar economy to develop [2], which will allow companies to turn a profit selling resources in space, and in addition, resources can potentially be returned to Earth for sale within Earth's economy. Extraterrestrial bodies, in particular asteroids, contain large amounts of resources that are scarce on Earth. Of particular economic interest is the platinum group metals (PGMs) contained in metal-rich and some carbonaceous asteroids. PGMs are among the rarest elements on Earth, and have a number of important industrial uses. As siderophile ("iron loving") elements, most of Earth's PGMs have been sequestered into the metallic core, resulting in their scarcity within Earth's crust. Like Earth, some asteroids were differentiated into a crust, mantle and core, and metal-rich asteroids are the remnant cores of these asteroids that remain after collisions with other bodies. This means that these metal-rich asteroids contain much greater concentrations of the PGMs than Earth's crust, which, at today's prices, make some of these asteroids worth trillions of dollars [3].

1.2. Is mining extraterrestrial bodies legal, and who owns the resources?

No discussion of off-Earth mining in the context of sustainable development is complete without considering relevant laws and policies, as there is no economic incentive to mine celestial bodies unless ownership can be claimed over the resources that are extracted. The basis of international space law is formed by the Outer Space Treaty which has been in force since 1967 [4]. At present, 107 countries are party to the treaty, which was written with the intention of preventing the militarisation of outer space and limiting the use of the Moon and other extraterrestrial bodies to peaceful activities [4]. The treaty also forbids any claim of sovereignty in outer space, stating the space is the "province of all [hu]mankind" [4]. At the time the treaty was written, prospecting for and extracting resources from outer space was not a serious consideration, and therefore the treaty does not provide any specific guidance on the area of space resources exploitation or ownership. The Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (the Moon Agreement) came into effect in 1979. The Moon Agreement elaborated on the Outer Space Treaty, specifying that the Moon and other celestial bodies should not have their environments disrupted, and that the UN must be informed of any human settlements on these bodies [5]. The Moon Agreement also notes that the Moon's natural resources are the "common heritage of mankind", and prohibits the exploitation of space resources until an international regime to regulate these resources is established, should such resource exploitation become feasible [5]. However, the Moon Agreement has not been ratified by any of the major spacefaring nations, including the United States, the majority of the member states of the European Space Agency, Russia, China and Japan, casting a legal "grey area" over off-Earth mining. While claims of sovereignty by states over celestial bodies are undoubtedly prohibited, off-Earth mining proponents are making the argument that state appropriation only applies to territories, and not resources (e.g., Ref. [6]). The off-Earth mining situation is considered by von der Dunk [7] to be analogous to that of the high seas. The high seas are considered a global commons, and therefore cannot be appropriated, however, the fish caught there belong to whoever caught them (provided they complied with relevant international laws; von der Dunk [7].

Capitalising on such a "grey area", some countries have written their own laws legalising off-Earth mining. The US Spurring Private Aerospace Competitiveness and Entrepreneurship (SPACE) Act of 2015 permits US citizens to "engage in the commercial exploration and exploitation of 'space resources'" [8]. The law entitles US citizens to ownership over any space resources they have obtained, and allows them to do with them as they see fit, including sell them should they so choose. Luxembourg, seeking to be at the forefront of space mining, passed a similar law in 2017—the Law on the Exploration and Uses of Space Resources [9]. Luxembourg's law, however, extends beyond its own citizens to any company with an office in Luxembourg, even if the company is headquartered elsewhere [9].

2. Off-Earth mining through the lens of sustainable development

2.1. Environmental considerations

Off-Earth mining has been hailed by some as the answer to many of the environmental issues associated with mining on Earth (e.g. Ref. [10]), based on the idea that much of the mining that is carried out on Earth could instead be done in space in a bid to reduce pressure on Earth's environment. In a preliminary study comparing the greenhouse gas emissions resulting from mining platinum (Pt) on Earth compared to asteroids, Hein et al. [11] found that mining Pt in space produced considerably less greenhouse gas emissions relative to Earth-based mining. However, this study compared greenhouse gas emissions resulting from 1 kg of mined Pt, and did not compare the impact on other areas of the environment. If asteroids were to supply Earth with all, or even most of the demand for Pt, the assumption can be made that this would require a number of space vehicles carrying materials required for mining infrastructure. While the greenhouse gas emissions associated with space launches may be relatively less than Pt mining on Earth, the cumulative impact of frequent space launches on other areas of the environment is likely to be considerable. Numerous studies have documented the environmental impact of space launches (e.g. Refs. [12–17]), and of particular concern when discussing cumulative launches is depletion of the stratospheric ozone layer. Space rocket launches are the only source of ozone depleting substances deposited directly into Earth's ozone layer, causing concern that an increase in the frequency of launches could have dire consequences for the ozone layer [18]. Aside from global environmental concerns, both Earth-based mining and space launches impact the local environment, with both being associated with emissions to soil, air, and water. However, the scale of emissions from mining is much greater than those associated with space launches, and this would likely remain the case even with a large increase in the frequency of space launches. While more work is needed to quantify the local environmental impact of the Earth-based mining as well as the space launches associated with off-Earth mining, preliminary evidence suggests that space launches result in environmental impacts of a much smaller magnitude (e.g., Ref. [11]). MacWhorter [10] suggests that the environmental benefits to Earth of moving mining for resources used on Earth to other celestial bodies will be so large that off-Earth mining should be incentivised through a legal framework that grants property rights in extracted minerals on a "first-in-time, first-in-right" basis.

However, the impact of off-Earth mining activities on the extraterrestrial environment must also be considered. It is difficult to predict what impact mining activities may have on the space environment. Implicit in the concept of sustainable development is the consideration of the long term implications of human activities and the impact they may have on future generations. Earth provides the perfect cautionary tale in this regard, as the current generations of humans are left facing numerous environmental challenges resulting from the choices of previous generations. It is imperative that mining in outer space considers the interest of humans not only now, but in the future. Like Antarctica and the deep seabed, outer space is a global commons—"resource domains that do not fall within the jurisdiction of any one particular country, and to which all nations have access" [19], and stewardship for global commons falls to everyone. In addition, a cultural landscape has now developed in space that holds significance to the human race [20]. This means that, as on Earth, heritage areas, such as the Apollo landing sites, exist in space, and these must be considered in any extraterrestrial environmental impact assessment of off-Earth mining activities.

At present there is no clear understanding about the extraterrestrial environmental impacts of human activity in space, and off-Earth mining is likely to have a relatively large impact on the space environment. Kramer [21,22] has called for the establishment of international standards for extraterrestrial environmental impact assessment, suggesting that the standards be industry self-generated and voluntary, to avoid the difficulties associated with creating and enforcing international environmental laws in space. In this scenario, industry based environmental standards would be drafted by relevant industry groups and "enforceable" through pressure from other industry players [21]. While there are many benefits to industry-led standards, there is the risk that standards will not be put into practice if the economic costs of implementing such standards are too high. The environmental impact of mining activities tends to be higher in countries with less stringent environmental regulations in comparison to those countries with a high level of environmental regulation, leading to some mines in developing countries being poorly managed in terms of their environmental impact [23]. This suggests that the best way to manage the environmental impacts of mining activities may be through policy regulation. Along with considering the extraterrestrial environmental impact of off-Earth mining, efficient resource extraction in space is also important.

Ali [24] notes that governance of Earth's natural resources is required for sustainable development, and resources in outer space are no different. The sustainable development principle of inter-generational equity as set out by Harding [25]; requires that humans take a long-term view of environmental management and preservation, to ensure that future generations benefit from Earth's environment, and for this very reason, it is vital we also take a long term view of the management of extraterrestrial environments.

Asteroids are an abundant source of resources, with over 20,000 near Earth asteroids, and many times more than that in the asteroid belt between Mars and Jupiter [26], and as such it may seem tempting to prioritise economic considerations over the efficient extraction of resources. However, future demand for resources from the Moon, Mars, and asteroids may eventually make them scarce [27].

Governing activities in outer space faces the same problem as governance of other global commons, in that the "Tragedy of the Commons" must be avoided. The "Tragedy of the Commons" occurs in situations where there is a shared "common pool resource" and individuals act in their own self-interest, leading to premature depletion of the resource and/or environmental degradation [28]. To avoid this, Elvis and Milligan [29] make an argument for preserving the extraterrestrial environment and preventing the premature exhaustion of space resources by limiting human development to one eighth of our solar system, thereby leaving the remaining seven eighths as wilderness, noting that implementing such a policy at the early stages of space resource exploitation will be easier and more effective. Leaving the majority of our solar system as wilderness, has the advantage of preserving valuable scientific information for current and future generations.

2.2. The space gap, economic growth and mineral economies

The socioeconomic benefits experienced by spacefaring nations as a result of their participation in the space industry are numerous. In a report prepared for NASA in 2013 on the socioeconomic benefits created by the space agency; it was noted that NASA enhances the competitiveness of a number of industries including technology and manufacturing, spurs innovation and growth, promotes international collaboration, contributes to global emerging technologies, expands the scientific knowledge base, and creates employment [30]. Similarly, as noted by the European Space Agency (ESA), citizens of Europe reap the benefits brought about by the space industry daily, including technological advancements, employment opportunities, economic growth and enhanced competitiveness of European corporations in the global economy [31]. A number of important technologies including communications systems, internet, satellite weather forecasts and GPS are reliant on space technology, resulting in unequal access to these technologies between spacefaring states and non-spacefaring states that cannot afford access. Many lower income nations are also non-spacefaring states that miss out on the socio-economic benefits of the space industry, along with access to important space technology, while spacefaring nations are reaping the many benefits of their participation in the space industry. This is known as the "Space Gap". The exploitation of space resources is one of the next logical steps in humankind's development. However, if only high-income, spacefaring nations participate in off-Earth mining and therefore profit from space resources, the space gap, i.e., economic inequality between states, is likely to widen. This is contrary to the United Nations 2030 Agenda for Sustainable Development, which sets out reduced inequalities as one of it's 17 Sustainable Development Goals [1]. At a UN general assembly meeting in 2014, it was determined that the those living in poverty must benefit from the progress made in space science and technology, noting that space benefits should not be a cause of increasing economic and social inequality between nations [32].

Off-Earth mining may not only provide a lucrative resource stream to countries with spacefaring capabilities, but also reduce high-income countries reliance on importing certain minerals from middle or low-income countries. The International Council on Mining and Metals has identified 25 mineral economies—countries where mineral exports comprised 20% or more of total merchandise exports or over 10% of GDP between the years 1995 and 2015 [33]. Given their dependence on mineral exports, mining resources in space and returning them to Earth has potentially serious economic and social implications for these mineral economies. Of the 25 countries with mineral economies identified by ICMM, only four have high income or upper-middle income economies, while 9 have lower-middle income economies, and the 12 remaining nations have low income economies [33]. This means that the majority of countries that have mineral economies are classified by the World Bank as middle-low to low income countries, while the majority of spacefaring nations are high-income countries [34], (Fig. 1).

A reduction in mineral exports is likely to have serious economic and social implications for mineral economies. For example, South Africa supplies the majority of the world's PGMs [35], and if importing nations begin to extract PGMs from metal rich asteroids and return them to Earth, this is likely to have significant economic consequences for South Africa on both the national and community levels. Reduced income from mineral exports will have knock-on effects for the economy, and at the local level a reduction in mining operations could result in unemployment and a reduction in services within mining communities, such as health care and education.

Saletta and Orrman-Rossiter [36] suggest looking to Earth models of resource leasing for examples of the best way to regulate the benefits from the exploitation of outer space resources, in particular the Alaska Permanent Fund (APF). The APF is a natural resource fund, financed by revenues from the sale of natural resources such as oil and deposits and/or royalties collected from leasing arrangements for mine sites or

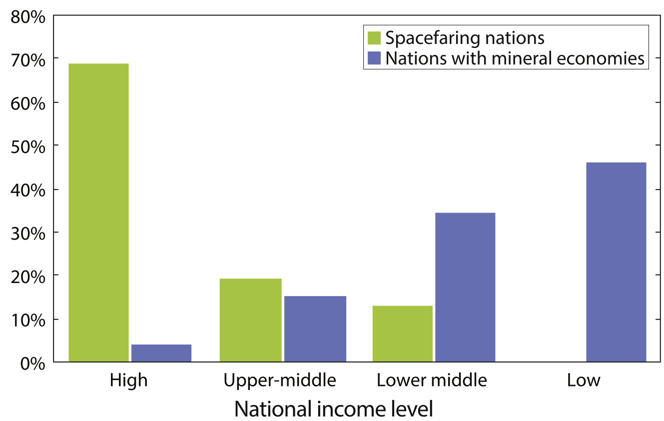

Fig. 1. Proportion of countries with mineral economies (blue) and spacefaring countries (green) that fall into high, upper-middle, lower-middle and low national income brackets, as defined but the World Bank. Data from World Bank (2018), [33]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

oil and gas operations. As of 2018 the APF was worth USD$63 billion, with regular dividend payments made from the fund to Alaskan residents [36]. Dividend payments of USD$2074 and USD$1100 were made in 2015 and 2017 respectively [36]. Saletta and Orrman-Rossiter [36] propose the idea of an "international space resources fund" managed by the World Bank, whereby the benefits of space resource exploitation are shared by all of humanity without constraints on the commercial side of off-Earth mining. The space resources fund would involve space mining operators paying for the rights to a resource lease, the revenue from which would be invested, and the dividends paid to residents of Earth. The space mining operators will still reap the majority of the benefits, so this does little to close the space gap and reduce inequalities between space-faring and non-spacefaring nations. However, an international fund of this nature has the benefit of equally distributing at least some of the economic benefits of off-Earth mining, staying true to outer space being considered the "common province of all mankind". Similarly, Barnes [37] suggests the commons be held in a trust. Those using the commons would be required to make payments to the trust that vary with level of pollution produced by their activities. In this model, all citizens would be paid dividends from the trust.

Paxson [38] suggests a scheme where a certain amount of lunar mining credits are allocated to all countries, allowing the holder of these credits to engage in mining a certain mass of natural resources on the Moon over a given time period. In theory, this could be extended beyond the Moon to include other celestial bodies in addition. This scheme would distribute credits on the basis of population, with a potential allowance to increase allocations for developing nations, and would allow credits to be sold and purchased between countries [38].

An example of the management of profits from common resources on Earth is the United Nations Convention on the Law of the SEA (UNCLOS), which established the International Seabed Authority (ISA) to oversee all seabed resource prospecting, exploration and extraction activities [39]. Article 82 of UNCLOS obligates coastal nations to make payments to the ISA "on the basis of equitable sharing criteria", and the ISA would be responsible for distributing these "taking into account the interests and needs of developing States, particularly the least developed and land-locked among them" [39]. A similar provision could be made for space resources, allowing developing nations that are not in a position to participate in the extraction of resources to receive financial benefits from countries participating in off-Earth mining. However, Article 82 of UNCLOS has not been triggered, and the way in which benefits would be distributed has not yet been agreed upon, so this concept remains untested [40].

Given that distributing the benefits of space exploration across all of humanity is an important facet of space law, it seems important that a framework for ensuring that all countries, even those without spacefaring capabilities, are able to participate in off-Earth mining. However, if a "first in, first served" approach is taken to space resource extraction, then mining in space is likely to reinforce, or even widen the income gap between countries, regardless of whether dividends were paid. Paxson [38] notes that due to the high expense incurred from outer space activities by spacefaring nations, these nations may be reluctant to share the economic benefits of their space programs with developing countries in order to ensure their space programs continue to be economically viable, while developing nations will benefit most from the highest possible sharing of benefits.

2.3. International collaboration

In addition to a space resources fund, international collaborations are likely to be another benefit of off-Earth mining. Dennerley [41] notes that space law is underpinned by the principle of international cooperation, and that cooperation between states on the scientific and legal aspects of outer space activities should therefore be encouraged. While international collaborations on space missions are already reasonably common, collaboration typically takes place between existing spacefaring nations (e.g., Ref. [42]). The "Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries" was a resolution adopted by the United Nations General Assembly in 1996 [43]. The resolution encourages countries with space programs to collaborate with other countries, particularly developing nations, to foster the development of space programs in these nations. It largely came about due to the dissatisfaction developing countries felt regarding their lack of participation in international space cooperation [43]. The resolution allows countries to participate in this international agreement as they see fit, and does not apply to private space enterprises, many of which are involved in off-Earth mining projects. For off-Earth mining to contribute to sustainable development, private space enterprises and government space agencies must *both* work to collaborate with developing nations. The promotion of international collaboration and cooperation throughout space law and multilateral agreements on the use of outer space is promising, and off-Earth mining will provide a new pathway to facilitate such cooperation.

2.4. Industrial resource supply

The supply of natural resources on Earth is unlikely to be able to meet the ever increasing demands of our growing population. Extraterrestrial bodies, particularly asteroids, are abundant sources of many resources that are growing increasingly scarce on Earth. PGMs for example, have many industrial uses. Aside from their primary use in catalytic converters, they are being increasingly used as catalysts in fuel cells for clean energy and transport [44]. With the demand for these technologies growing, terrestrial reserves may only meet demand for a few decades [45,46], without high recovery recycling programs in place. Metal rich asteroids likely contain many times the PGMs foundin Earth's crust [47], which would not only supply technologies like fuel cells for many years to come, but may also lead to the development of new green technologies.

Nuclear fusion power has been proposed a potential future clean energy source that would generate electricity through heat produced by nuclear fusion reactions. Unlike current nuclear power produced by nuclear fission, fusion would result in greatly reduced operational radioactivity and very little nuclear waste. Helium-3 (^{3}He) has been identified as a potential future fuel for nuclear fusion power generation, however, it is very rare on Earth, but relatively abundant on the Moon [48]. Taylor and Kulcinski [49] suggest that harvesting ^{3}He (implanted by solar wind) from the lunar regolith could potentially supply Earth with enough ^3He to provide fusion energy for over a thousand years. Clean sources of energy and transportation are vital for a sustainable future and achieving the climate goals set out by the UN. Space resources may facilitate new developments in this area, as well as topping up Earth's dwindling reserves of resources that currently have other important industrial uses.

2.5. Resources for development

While resources from space may play an important role in topping up supplies on Earth, the distribution of these resources is an important consideration. A country's material footprint is the total amount of raw materials extracted globally to meet that country's consumption demand [50]. From 2007 to 2017, the developed world had twice the material footprint of developing countries, with extraction of raw materials in developing countries facilitating this trend through material exports [50]. Lifting the standard of living in developing countries requires an increase in their material footprints [50], and with developed countries being reluctant to decrease their reliance on raw materials, it is difficult for global supplies to meet the required amount to sustain developing nations' increasing material footprints. The addition of resources from space could be key to overcome this challenge, if resources were distributed to those nations around the world that really need them. However, along with the many potential benefits to Earth that could result in a greater supply of many important resources comes the responsibility of managing the exploitation of these resources. Unlike the Outer Space Treaty, other international agreements governing global commons such as the Antarctic Treaty and the Law of the Sea Convention make explicit mention of resource exploitation [51–53]. Zell [54] suggests that we could look to the ISA as a model for managing outer space's common resources, proposing a Space Resource Authority (SRA) that would have responsibility for “approving and regulating exploration and exploitation working plans”. The proposed SRA permitting process would work in the same way as the ISAs, whereby prospecting is free but an exploration permit would be paid for, along with an additional fee if exploitation took place [54]. The permitting process would go some way to preventing the over-depletion of resources by limiting the number of mining operations in outer space. However, added fees and royalties may limit developing nations' capacity to take part in off-Earth mining and benefit from the resources.

2.6. Scientific value

Space is often referred to as the “final frontier”, and exploring space further is seen as the next step in human development. Much of the human interest in exploring space arises from the quest for knowledge and the desire to better understand the origins of our planet, the solar system, and beyond. The prospecting and exploration stages of a mine on Earth always involve gathering a great deal of data, and space-based mining will be no different in this regard. When it comes to mining extraterrestrial bodies, the data gathered in the stages before and during mining will have a great deal of overlap with more traditional space science objectives. Space mining prospecting will involve gathering geological and geophysical data of the body of interest [55], data that will also be of great value to scientists seeking to understand the formation and development of the bodies within our solar system. Water on the Moon, Mars and asteroids is of high scientific interest, as evidenced by the numerous studies in this area (e.g., Refs. [56–65]). Due to its use in life support for manned missions and human settlements and for making rocket propellant, water will almost certainly be the first resource that will be extracted in space. Thus, prospecting for water in space may provide scientists with valuable data collected in-situ. Human knowledge of the extraterrestrial environmental is relatively limited, and furthering our understanding of our planet, solar system and beyond is a key motivation for travelling farther into outer space, and will be facilitated by resources extracted from celestial bodies.

As discussed above, mining in outer space is likely to generate a large amount of scientific data. However, humanity will only reap the scientific benefits of off-Earth mining if the data collected by space mining organisations are shared with scientists. While government space agencies will be gathering data to be used for research in the course of space mining prospecting and exploration, there is a concern that private off-Earth mining enterprises may not be forthcoming with the data they have gathered, considering it proprietary information. If private off-Earth mining companies gather data that are not shared with the planetary science community, there is a chance that valuable knowledge may be lost forever. Off-Earth mining activities may result in irreversible changes to extraterrestrial bodies, making it impossible for certain scientific information to be recovered after exploration and mining activities have taken place. However, by addressing these concerns, off-Earth mining provides an opportunity for international collaboration between private space enterprises and research institutes. An Earth based analogy is the UNCLOS, which makes provisions for sharing knowledge and expertise gathered as a result of deep sea mining prospecting in order to expand human knowledge of the seabed Jaeckel et al. [66]. The ISA is responsible for promoting and overseeing the dissemination of these non-monetary benefits United Nations (1994).

3. Recommendations for a sustainable off-Earth mining framework

There has been considerable discussion in the literature as to what the legal regime for off-Earth mining should look like (e.g., Refs. [7,52,67,68]). On the basis of this and the discussion above, we suggest recommendations for a framework for sustainable off-Earth mining, that could be used to inform a future legal regime:

1. International collaborations must be encouraged for off-Earth mining to contribute to sustainable development goals, particularly between states involved in off-Earth mining and developing countries. Ideally, collaborations will help developing countries create niches within the space industry, making collaborations mutually beneficial and profitable for all parties involved. Research has shown that international scientific collaboration is a highly effective way to improve the scientific capacity of developing nations [69], and resource extraction in outer space provides a unique opportunity to collaborate across a number of areas of scientific research. Countries with mineral economies, particularly those with dwindling resources, could, through international collaboration, benefit economically through participation in the space industry and the exploitation of space resources. Along with the economic benefits of participating in space activities, developing nations will also then be able to share in the benefits brought about by space technology, and spin off technologies used on Earth.
2. Mining permits or licences should be required for mining in outer space, similar to the way in which mining tenements are required in many countries on Earth. An international body, akin to the International Seabed Authority, would be required for managing these mining permits, and taking royalty payments for leasing the land to mining operators. The number of leases each country can hold could be decided based on population, with exceptions made for extra leases to be given to countries that would benefit most from the associated economic benefits. Royalties could then be used in assisting lower income nations in developing spacefaring capabilities, for example. The annual number of mining permits given out could be limited, along with limits to the mass of material that can be extracted from a defined permit area. Environmental planning and consent would be required within the terms of the permit. This would go some way to managing the extraterrestrial environmental impacts by limiting the amount of mining and preventing the

premature exhaustion of resources through inefficient extraction methods. The Society of Mining Professors [70] notes that operational efficiency must be encouraged for future mining operations, and off-Earth mining operations should be no different.

3. There must be a provision for the protection of both the Earth and space environments. An assessment of the impact that off-Earth mining will have on these environments should be part of the mining permit process, with requirements for environmental risk assessments and planned mitigation measures to be included. The cumulative environmental impact to Earth of launches associated with mining in outer space must be considered, particularly with regard to the release of ozone depleting substances from rocket engine emissions. Guided by the precautionary principle, the impact resource extraction will have on celestial bodies is an important consideration for any off-Earth mining activities. The most widely used definition of the precautionary principle comes from Principle 15 of the 1992 Rio Declaration: “In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation” [71]. The principle underpins much of international environmental law, with the intention of obliging decision makers to consider the potentially harmful consequences of their activities on the environment, before pursuing these activities [72]. In the case of off-Earth mining, it is particularly important to abide by the precautionary principle given that there are many limitations in our understanding of the extraterrestrial environment and the impact that human activities could have on it. Central to the principle are four core ideas; that preventive action must be taken where there is uncertainty, public participating is vital in the decision making process, alternatives to potentially harmful actions must be considered, and that the proponents of activities must bear responsibility by assessing the risk and taking precautionary action [73]. In addition, assessing the impact that off-Earth mining could have on the extraterrestrial environment may lead to the identification of opportunities where the extraction of a particular resource on Earth results in a large environmental impact, but has a minimal impact to the extraterrestrial environment when extracted there, thus creating a pathway to reducing environmental degradation on Earth. Some mechanism for assessing the extraterrestrial environmental activities should be in place before the exploitation of resources in space commences.
4. As noted by the precautionary principle, public participation in making decisions about activities that effect the environment is important. We suggest that stakeholder participation in general will be as important for the success of off-Earth mining projects as it is with mining projects on Earth. On Earth, an important factor for a mining operation's success is that the mine operator obtains a social licence to operate. A social licence to operate differs from formal mining licences obtained from governments, in that a social licence is the ongoing acceptance of a mining project by communities that will be impacted by it. In instances where mining goes ahead without a social licence, community opposition to the project often results in costly conflicts and delays [74]. With its status as the “common heritage of mankind”, public involvement in decisions regarding off-Earth mining activities is important, as all humankind are stakeholders in the shared resources in outer space. Public participation on a global scale is difficult, but could be managed through national representatives. Stakeholder engagement and adding shared value between stakeholders and mining operators are important for successful mining activities on Earth [75]. Harding [25] notes that all members of society do not have equal access to participating in environmental decision making, but that in order to achieve intra-generational equity (an important principle of sustainable development) disadvantaged individuals, groups and nations must be part of decision making processes. In addition to the public at large, scientists are important stakeholders in off-Earth mining operations, and a framework that makes provisions for (at least non-proprietary) data collected by private off-Earth mining organisations to be disseminated to the scientific community for creating shared value. The asteroid mining company Planetary Resources suggests a framework should be developed that will allow the planetary science community to reap the benefits of asteroid prospecting activities without the mining company having to give up proprietary information [55]. Cultural groups, for which certain celestial bodies—most often the Moon—hold significance, are also stakeholders in off-Earth mining operations. While mining on the Moon is unlikely to change how it appears from Earth, working with relevant cultural groups to ensure their perspectives are taken into account should be part of the mine planning process.

4. Conclusions and the way forward

Off-Earth mining provides us with the unique opportunity to continue to supply Earth with natural resources that are growing scarce on our planet by creating a sustainable resource supply stream from space. However, as the world works towards achieving sustainable development by reducing inequalities between nations, it is easy to foresee a scenario where the economic, environmental and social benefits of mining in outer space are not felt beyond the borders of countries with spacefaring capabilities. While it may be some time before resources are extracted in space and returned to Earth, given the long time frame required for drafting and implementing international regulations, now is the time to discuss what provisions should be made for ensuring off-Earth mining is carried out as sustainably as possible and in line with international sustainable development goals. While it is uncertain exactly what shape resource extraction in outer space will take, it seems as though it is a question not of if, but when it will take place. A scenario where access to resources is on a “first in, first served” basis would not serve to achieve the goal of sustainable development. Space resource appropriation must be carried out responsibly and sustainably, and there is a clear need for either an amendment to existing regulation or the creation of new international space laws to ensure this is the case. It is important that before any resource extraction takes place in space, there is a global discourse around the most acceptable, and ideally beneficial manner of off-Earth mining for all of humanity. For off-Earth mining to be truly sustainable, we must consider the impact it will have across humanity, ensuring that the benefits are felt by all and that any adverse impacts are minimised wherever possible.

Declaration of competing interest

The authors declare no conflict of interest.

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