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Astronomical withdrawals: a green criminological examination of extreme energy mining on extraterrestrial objects

Jack Adam Lampkin[1] · **Bill W. McClanahan**[2]

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Abstract
Mining for natural resources on-Earth is commonplace and dates back over a hundred years at an industrial scale. Technological advances in outer space exploration are enabling the mining of extraterrestrial resources to transition from mere science fiction, to a serious possibility. In recent decades, several new start-up companies have arisen with the sole intention of exploiting resources that exist in outer space, such as on Earth's moon, asteroids, meteorites, planets, and various planetary satellites, such as the moons of Mars - Phobos and Diemos. However, despite the increased investment and interest in space mining, criminologists have remained virtually silent on outer space issues. In this paper we adopt a green criminological approach to explain the emergence of outer space mining, and argue that now is the time to be researching and debating the phenomenon of extraterrestrial mining in order to prevent future social and environmental harm (following the precautionary principle of environmental law). To do this, the paper does three things. Firstly, it examines strategies for conducting space mining (such as its feasibility, probable locations, and innovative mining techniques). Secondly, it analyses the terrestrial and extraterrestrial impacts of space mining, unveiling several avenues for the creation of social and environmental harm. Finally, it uses a green criminological approach to justify the rationale for engaging legal scholars and criminologists with problematic space mining issues. The paper concludes that now is the time to discuss these issues, prior to the industrialisation and exploitation of unique celestial bodies.

Keywords Green criminology · Astro-green criminology · Extreme energy · Outer space · Mining.

Extended author information available on the last page of the article

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Introduction

Planet Earth has been subject to intense anthropogenic mining practices since the industrial revolution. In particular, humans have engaged in the widespread extraction of coal, oil and natural gas due to their profitability. Originally this began with low-level inefficient and (comparably) ineffective conventional drilling techniques. In relation to natural gas, the United States (U.S.) based *Mitchell Energy* company combined traditional vertical drilling with horizontal drilling, using vast quantities of water, proppant (sand) and chemicals to facilitate and enhance production in the 1980's (Prud'homme, 2014). This technological innovation led to an exponential growth in the industry (known colloquially as 'fracking,' or formally as unconventional, horizontal, hydraulic fracturing), starting in the U.S. and extending to Canada, Australia, South Africa, China and the United Kingdom (U.K.) (amongst other regions). This new method of natural gas extraction has been dubbed a form of *extreme energy* whereby new and unconventional methods of extraction are adopted to maximise the production potential of gas wells. According to Short et al. (2015: 700), extreme energy refers to 'a range of relatively new, higher-risk, non-renewable resource extraction processes that have become more attractive to the conventional energy industry as the more easily accessible supplies dwindle.' Examples of this include fracking, mountain top removal, hard-rock mining and the exploitation of tar sands.

Whilst the definition of extreme energy is contested (Extreme Energy Initiative no date), Short et al.'s (2015: 700) version refers to extraction processes that are new, high-risk and non-renewable. Largely, new industries are permitted to begin operations prior to the development of appropriate environmental laws and regulations. This can be seen recently in the U.K. whereby the *Infrastructure Act 2015*, which first defined the legal parameters of fracking in the U.K., came after the first unconventional well was drilled at Preese Hall (Lancashire) in 2011 (Green et al., 2012). This contradicts the precautionary principle of environmental law which requires states to consider the impact activities may have on the environment, before such activities are permitted or take place.

In recent years such a risk has emerged from a brand new form of extreme energy extraction known colloquially as *astro-mining* or *space mining*. This can involve extracting natural resources that exist in outer space and returning them to Earth for human consumption. Whilst on-Earth extreme energy extraction processes have received a considerable degree of attention in recent years due to the detrimental impacts of extraction techniques on humans, non-humans and the wider Earth environment (Lampkin, 2018; Short et al., 2015; Stretesky et al., 2014), issues relating to extraterrestrial mining remain virtually unexplored in the criminological literature (see Lampkin, 2021, Rothe & Collins, 2023, and Takemura, 2019 for exceptions). This is in spite of the recent emergence of a number of private companies interested in mining celestial bodies for their commercial value. As Takemura (2019) notes, there are currently four U.S. start-ups pursuing space mining: Moon Express; Planetary Resources Inc; Deep Space Industries; and Shackleton Energy. This suggests that the once abstract notion of space mining may soon become a reality.

This article will explore the potential of space mining prior to the existence of any significant space mining activities. This follows the precautionary principle of environmental law and is undoubtedly a worthwhile endeavour (that is, researching environmental harm before it occurs, rather than reacting to harm that has already transpired) (Lampkin, 2020). In order to analyse the existence, emergence and significance of space mining, we will employ a green criminological perspective. Green criminology is the study of human behaviours that result in environmental harm, regardless of their legality (Lampkin, 2020). This will enable analysis of emerging space mining practices that are currently perfectly legal, despite their potential propensity to generate terrestrial and exo-environmental harm. To that effect, the remainder of this article will cover the three following quintessential areas:

1. Strategies for implementing future space mining.
2. The terrestrial and extraterrestrial impacts of space mining.
3. A green criminological perspective on space mining.

Strategies for implementing future space mining

Planet Earth is abundant with minerals and resources that are useful to humans, but it is not the only celestial body in the solar system to contain such elements. Moons, planets, comets, asteroids and meteoroids[1] can be found in abundance in our solar system, and they contain a variety of materials that may be useful to humans in a variety of different ways. However, there is a considerable difference between the elements found on Earth and those found elsewhere in the solar system, due to the unique existence of the Earth which boasts liquid water, atmospheric oxygen and, therefore, the existence of diverse biology and geological processes. As Sivolella (2019: 28) recalls:

> there is a substantial difference in the nature of the reserves and ores found on Earth and those currently estimated for the Moon and asteroids. On Earth, mineral reserves are often the result of active geological processes significantly influenced by the presence of liquid water and atmospheric oxygen… On the Moon and asteroids, where liquid water and active tectonic geology have not played a role, this entire realm of aqueous geochemistry never occurred. What is more, the lack of oxygen and life prevented oxidation and denied the role of biology in the formation of ores. Thus, when it comes to resources and ores on extraterrestrial bodies, we cannot expect there to be certain areas with elevated concentrations of a given element or mineral… Generally speaking therefore, resources are expected to be widely spread across the surface and depth of the

[1] It is important here to clarify terminology. According to NASA (2019), a 'meteoroid' is an object in space, a 'meteorite' is a meteoroid that 'survives a trip through the atmosphere and hits the ground,' and a 'meteor' is commonly known as a shooting star - a meteoroid that burns-up in Earth's atmosphere due to friction and a high speed of travel.

> Moon's crust, and to be thoroughly dispersed within an asteroid… (and) this uniformity might ease our mining of the Moon and asteroids.

Due to restrictions on current space travel capabilities, it is not possible to consider mining on every extraterrestrial body. Whilst humans have sent spacecraft to the far depths of our solar system, Earth's Moon is the only extraterrestrial body that humans have set foot on, making it an obvious choice for future space-mining. Humans have also sent spacecraft to Mars, Venus, Mercury, and a number of asteroids which are also being considered as mining locations by private companies. These also happen to exist in (relative) close proximity to Earth, making them obvious logistical choices. Whilst enormous compared to the size and mass of Earth, the gas giants Jupiter, Saturn, Uranus and Neptune, are all logistically problematic where space mining is concerned due to their location far from Earth, but they are also unsuitable due to their gaseous composition. As a result, the main contenders for the first space mining operations are: Earth's Moon; asteroids and meteoroids; Mars; and the two Martian Moons (Phobos and Diemos). Other locations, at this present time, are either two distant that they represent logistical difficulties, or too problematic to mine due to their composition (e.g. the extraordinary temperatures on Mercury, the toxic atmosphere of Venus (Aderin-Pocock et al., 2014) and the unsuitable composition of the gas giants (although several rocky Moons may be considered in the future).

Mining earth's moon

There are a number of different reasons why Earth's Moon is an attractive location for space mining. Very simply, the poles of Earth's Moon contain billions of tons of water ice which can be separated into oxygen and hydrogen - useable as rocket fuel to power spacecraft. Shackleton Energy (no date) suggest that mining these lunar resources will enable 'fuel stations' to be created both on Earth's Moon and in Earth orbit which will enhance the abilities (and possibilities) of future space travel enabling spacecraft to go further. This is essential in sending humans to other locations in space (such as Mars), and setting up fuel stations there (again further enhancing future deep space travel). In fact, there is so much ice on the Moon that estimates suggest there is enough potential fuel existing in oxygen and hydrogen to 'launch one space shuttle per day for 2,200 years' (Anderson et al., 2018: 229). Earth's Moon also contains significant quantities of helium-3 (Sachdeva, 2018) another element that can be used to power spacecraft or, alternatively, to create electricity. Whilst enough helium-3 exists on Earth for research purposes, 'no commercial supplies of helium-3 are present on Earth' (Schmitt, 2004: 59) which again makes Earth's Moon an attractive mining location - for various forms of fuel generation. Furthermore, Rare Earth Elements (REE) exist on Earth's moon which could serve useful purposes for humans on Earth. According to Giraldo and Tobón (2013: 84):

> Other major minerals on the Moon are the rare Earth elements (REE), these elements have become very important for the development of current technologies (from wind turbines and glass for solar panels to use in hybrid cars, and even

guided missiles and other defense- oriented creations) and their existence on the planet Earth is limited.

The advantages of lunar mining (or ISRU - In Situ Resource Utilisation) as opposed to Earth mining (in terms of creating fuel for space travel) revolve around cost. According to Shackleton Energy (no date) it is roughly 20 times cheaper to deliver fuel to Low Earth Orbit (LEO) from the Moon, than it is to do so from Earth. This is because the Moon only has one sixth of Earth's gravity (due to it being roughly one sixth of the size of Earth). Therefore, due to lower gravity, much less fuel is required to lift mass from the lunar surface than from the Earth (Shackleton Energy no date). In addition, regolith[2] on the lunar surface is mineral-rich due to billions of years of asteroid and meteorite impacts (also explaining why the Moon is so heavily cratered). Whilst such impacts have also occurred on Earth, the presence of Earth's atmosphere serves to burn-up small objects due to the friction generated from the speed of the object. 'Wind, water and vegetation' have also 'erased most of these impacts (Peacock, 2017: 23). Earth's Moon has no such atmosphere and, as a result, has no protection against incoming objects resulting in the accumulation of mineral-rich regolith from meteoroid bombardment.

In terms of how lunar mining may operate in practice, several different options have been suggested but most revolve around the utilisation of remote 'robotic mining rovers' designed to collect regolith (Peacock, 2017). It is essential that such rovers also have a power source and, as a result, lunar processing plants have been suggested as structures to utilise lunar hydrogen and oxygen from the icy poles to fuel the rovers (Peacock, 2017: 24). In terms of actually collecting regolith remotely, several research projects have studied how such excavation could work in practice. Many designs have been modelled, including the use of robots with various different buckets (ladders and belts), bulldozers, scrapers, wheels, drums, claws, grippers, plates, scoops, blades and rakes (Iai & Gertsch, 2013; Mueller & Van Susante, 2011).

Although surface mining is prevalent within the literature on lunar mining possibilities, underground lunar mining has received some consideration. Whilst the lunar surface consists of regolith varying in depth from 4 to 20 m in thickness (becoming more compact further down) (Sivolella, 2019: 36), beneath the regolith is the lunar crust, approximately 30–46 miles in thickness and composed of 'granite-like silica rock' that 'probably originated as an ocean of molten magma' (Aderin-Pocock et al., 2014: 91). Beneath the crust is the silica-rich outer mantle of solid rock composition containing a high proportion of iron (compared to Earth's mantle) (Aderin-Pocock et al., 2014). The outer mantle is too deep to consider mining making the lunar crust more realistic. This would involve excavation in a similar way to on-Earth practices, by using heavy machinery 'capable of combining drilling, blasting, and ore removal actions… (to) drive a number of drills into the rock face' of an underground lunar tunnel (Sivolella, 2019: 66). A final consideration (or justification) for pursuing lunar mining concerns the need to do so to construct permanent human settlements and/or

[2] The term *regolith* has been defined as 'a general term for the layer or mantle of fragmental and unconsolidated rock material, whether residual or transported and of highly varied character, that nearly everywhere forms the surface of the land and overlies or covers bedrock' (McKay et al., 1991: 285).

mining manufacturing sites on Earth's Moon. Such an outpost could 'support multiple large scale science projects as well as commercial operations' (Baiden et al., 2010), enabling humans to stay on the Moon for greater periods of time.

All-in-all, lunar mining is at a highly theoretical and ultimately nascent stage despite the emergence of private companies interested in the benefits and profitability of lunar mining. There are, however, some strong cases for engaging in lunar mining practices, and three commonly cited reasons have been explored in the section. The first was that lunar mining could provide a valuable fuel source for spacecraft visiting Earth's Moon as a 'fuel station' during space travel (or transporting such fuel to LEO in order to provide a fuel station in Earth orbit). Second, lunar mining could provide valuable elements to humans on Earth in the form of oxygen, hydrogen and helium-3, each of which can be used in energy generation and could reduce our reliance on the consumption of non-renewable fossil fuels on Earth (Schmitt, 2004: 62). Finally, lunar mining could support the development of future infrastructure on Earth's Moon, whether this be for mining manufacturing purposes, or the creation of human settlements (Lucas & Hagan, 2014: 39). Lunar mining, however, is just one credible option for off-Earth mining. The mining of asteroids and meteoroids are also serious possibilities.

Mining asteroids and meteoroids

An asteroid is a 'small, irregular Solar System object, with a diameter of less than 1,000km' consisting of rock and metal (Aderin-Pocock et al., 2014: 244). Meteoroids are usually small pieces of asteroids or comets[3] that may have been created through a collision between an asteroid and another object in outer space[4]. Most asteroids are located in the asteroid belt situated between Mars and Jupiter and this is where the largest asteroid, Ceres, can be found. With a mean radius of 473km, Ceres is recognised as a dwarf planet (Bowling et al., 2019) due in part also to its relatively spherical shape. Such space rocks are potential locations for space mining because of their location (they can be found in relatively close proximity to Earth) and physical composition. Whilst the constituents of asteroids will vary depending upon their history (e.g. how they were formed, whether they have collided with other space objects), many are thought to contain different types of elements. Scientists can study the composition of such rocky objects by analysing meteoroids that have fallen to Earth (Krinov, 1960), or by collecting samples from outer space. In November 2005, the Japanese Hayabusa spacecraft successfully navigated to near-Earth asteroid 25143 Itokawa and later (in June 2010) returned regolith samples from the Muses sea region to Earth (Nakamura et al., 2012; Yano et al., 2006). Similarly, NASA's OSIRIS-Rex spacecraft aims to return samples to Earth from near-Earth asteroid Bennu in 2023 (NASA, 2020b). Such missions demonstrate the viability of sending spacecraft to

[3] A comet is 'a small body, composed mainly of dust-laden ice, that orbits the Sun, typically following an elongated, elliptical path' (Aderin-Pocock et al., 2014: 244).

[4] Or in the case of comets, when a comet's orbit gets 'sufficiently close to the Sun… the volatiles on the surface of their nuclei can sublimate, carrying off particles' (Jopek et al., 2002: 645). Those particles can, therefore, become meteoroids or micro-meteoroids.

asteroids, conducting activities on the surface, and then returning material successfully to Earth. These are also essential components for space mining.

Asteroids and meteoroids can be classified into different types concurrent with their taxonomy. The majority of meteoroids are known simply as ‘stony’ objects consisting largely of chondrites (approx. 75%) and achondrites (approx. 12%) (Sivolella, 2019: 45). There also exist ‘stony-iron’ and ‘iron’ meteoroids containing (amongst other things) mesosiderites, pallasites, hexahedrites, octahedrites and ataxites (Sivolella, 2019). Examining the usefulness and production potential of these materials is beyond the scope of this paper, but it is worth noting first that they exist, second that there is a potential for them to be extracted (as the Hayabusa example above demonstrates), and third that they could serve a useful purpose to humans. According to Martínez-Jiménez and colleagues (2017: 73) for example, asteroids contain ‘large amounts of valuable resources including platinum group metals, iron, nickel, rare Earth elements (REE) and water.’ Such resources may be sparse on Earth and, therefore, the production of such resources on asteroids could sustain the market economy of such elements over longer timescales (Martínez-Jiménez et al., 2017: 74) subject to continuing technological advancement and investment that makes such mining possible. Asteroids and meteoroids, however, are just one viable option, particularly those that exist near-Earth. Other rocky planets and moons may also be suitable for extreme energy mining.

Mining mars and the martian moons

Mars is just half the diameter of Earth and, similarly to Earth’s Moon, lacks the gravity to hold on to a dense atmosphere (Aderin-Pocock et al., 2014). The fact humans have never physically visited the Martian system may induce scepticism regarding the viability of mining the red planet. On the 50th anniversary of the 1969 lunar landings, however, NASA and the ESA announced plans for manned missions and permanent human outposts on both the moon and Mars by 2040 (Naser, 2019). It is also clear from previous human endeavours that travel to Mars is possible, signified by the many Martian exploration missions[5]. Some of these remain in Martian orbit (such as Mariner 9 and the Mars Global Surveyor orbiter), and some have successfully landed on Mars and conducted scientific experiments (Garber, 2015).

When considering extraterrestrial mining, there must be resources available to mine to make such an endeavour worthwhile from a commercial perspective. Mars has a complex geological history with evidence of the previous existence of water, and a high number of meteorite impacts. This strong meteorite history suggests that Mars may contain:

[5] In terms of notable Martian operations, the first successful mission to Mars was the U.S. Mariner 4 which flew by Mars in 1965 taking the first close-up pictures of the planet. The U.S. Viking 1 and 2 missions landed on Mars in 1976 returning detailed on-surface images. More recently, Curiosity (a U.S. Mars rover) successfully landed on Mars in 2012 and continues to explore the Martian surface to test whether the planet has ever had an atmosphere capable of supporting small microbial life forms (Garber, 2015). Similarly, NASA’s perseverance rover was launched on 30th July 2020 with the purpose of seeking ‘signs of ancient life and collect(ing) rock and soil samples for possible return to Earth’ (NASA, 2020a).

> 'valuable elements like magnesium, aluminium, titanium, iron, chromium and trace elements like lithium, cobalt, nickel, copper, zinc, niobium, molybdenum, lanthanum, europium, tungsten, and gold are relatively common. (As a result), it is quite possible that in some places these materials may be concentrated enough to be mined' (Giraldo & Tobón, 2013: 85).

Despite the existence of such elements on Mars the reasons for engaging in mining practices on the red planet vary. One reason may be to extract REE for human use, as discussed in the mining of the Earth's moon. However, the extreme weather conditions on Mars provoke an additional justification for mining. If space agencies are intent in sending humans to Mars (regardless of whether this be for scientific or commercial reasons) mining and constructing an underground human settlement would be advantageous in order to provide 'refugia for habitation from extreme surface conditions' (Cockell et al., 2019: 158). Finally, mining Mars is attractive from a scientific point of view in order to learn more about the history and present geological conditions there. This will aid any future Martian missions, as well as enabling us to gain a greater understanding of planetary history, formation, geology and evolution, beyond studying our own planet.

Mining of the Martian system, however, may not just stop at the red planet. Mars has two small, irregularly shaped rocky moons, Phobos (17 miles long) and Deimos (9 miles long) (Aderin-Pocock et al., 2014). Exactly how these moons formed is still unknown and subject to debate (Deutsch et al., 2018). They could simply be asteroids caught by Mars' gravity (Pajola et al., 2013), they could be left-over remnants from Mars' formation, or they could have been ejected from Mars via some sort of giant impact (Citron et al., 2015). Whatever the case may be, it is the constituents of the moons that determines their attractiveness for mining. In this respect, the actual composition of Phobos and Deimos remains unknown and a 'lander' is needed to analyse samples from the surface of these satellites in order to fully understand their in situ resources (Fraeman et al., 2014). Such a landing mission would also enable the history of the moons to be ascertained, which will enable scientists to determine whether the Moons originated as asteroids, or as Mars formation debris. This would further clarify whether the materials on the Martian moons are similar to those on Mars, or more similar to those of an asteroid. This is significant because it would determine the mining potential of the moons in terms of which elements may be potentially useful to humans. As Deutsch and colleagues (2018: 2174) suggest:

> Phobos and Deimos are potentially valuable destinations, providing a wealth of science return, as well as telecommunications capabilities, resource utilization, radiation protection, transportation and operations infrastructure, and may have an influence on the path of the martian exploration program.

This section has highlighted several different locations that may be suitable for future space mining, including Earth's moon, near-Earth asteroids, meteoroids and comets, the planet Mars and its two moons Phobos and Diemos. Whilst much has been written about the potential of mining outer space resources in terms of the practicalities, economics and overall feasibility, much of this (perhaps unsurprisingly) has originated from the scientific and astronomical communities. Social scientists and, in particular, criminologists and green criminologists have remained virtually silent on such issues. This may be because outer space mining does not fit the traditional conceptions of crime, criminals, nor criminal behaviour. Furthermore, despite the recent emergence of a number of private companies and start-ups taking an interest in such extraterrestrial mining activities, to date, commercial space mining has not yet materialised. Therefore, it may seem premature to be critical of future mining operations. Such discussions, however, are pertinent to green criminology and these issues will be discussed further in this article. But first, it is important to discuss what harms already exist, or may transpire in the future, before analysing these through a green criminological lens.

The terrestrial and extraterrestrial environments of space mining

Terrestrial impacts

Humans have conducted mining on planet Earth in order to exploit an array of resources, the most common being coal, oil, natural gas, and rare and precious metals (e.g., gold, diamonds). These extraction processes, particularly where fossil fuels are concerned, are often accompanied by high levels of environmental harm (Jackson et al., 2014; Lampkin, 2020; Long et al., 2012; Stretesky et al., 2014). Harm also occurs when such resources are consumed and greenhouse gases are released into the atmosphere. Prolonged periods of this production-consumption cycle have been scientifically proven to contribute to climatic change whereby 'burning fossil fuels… (has) changed the carbon cycle, loading the atmosphere with extra carbon dioxide' (Summerhays and Zalasiewicz 2018: 194).

If resources mined on extraterrestrial bodies are transported to Earth for use by humans, there may still be implications for Earth's atmosphere when they are consumed and burned (for resources that are utilised as a source of fuel). This means that resource consumption could be viewed as a very expensive way to create more of the same atmospheric harm on planet Earth, as is the case with current fossil fuel use. Harnessing renewable energy in outer space could overcome the climatic consequences of mining for fuel on Earth, but this too is very problematic due to the differing degrees of sunlight and wind.

This is not to say that searching extraterrestrial environments for fuel sources is a totally harmful endeavour, however. There are resources abundant in outer space that are scarce on planet Earth and the ability to utilise such resources could have monumental implications for human societies. As Schmitt (2004: 58) suggests:

> The unique atomic structure of helium-3 promised to make it possible to use it as fuel for nuclear fusion, the process that powers the sun, to generate vast amounts of electrical power without creating the troublesome radioactive byproducts produced in conventional nuclear reactors. Extracting helium-3 from the moon and returning it to Earth would, of course, be difficult, but the potential rewards would be staggering for those who embarked upon this ven-

ture. Helium-3 could help free the United States—and the world—from dependence on fossil fuels.

Not only does such resource extraction have the potential to provide huge quantities of power to be consumed by humans, but the location of space resources far from Planet Earth inevitably avoids the on-Earth environmental harms associated with traditional fossil fuel mining techniques. Furthermore, on-Earth resource extraction is associated with harms to humans in terms of the public health impacts of mining to production workers, but also those working and residing within close proximity to extraction sites (Lampkin, 2018). Harms can occur from various processes, including exposure to hazardous substances employed during extraction activities (Hein et al., 2018). Such consequences simply would not exist for energy mining in outer space, which led Sivolella (2019: 191) to claim that 'in the lifeless vacuum of space, resource mining is environmentally harmless.'

Despite such appealing harm-reduction advantages of extraterrestrial mining, there are clearly important ethical and moral considerations for exploiting off-world resources for human consumption on Earth, which renders Sivolella's (2019: 191) claim of 'harmless' space mining an oversimplification. For example, there is inevitably a carbon cost associated with the manufacturing and transportation of extraterrestrial resources. This is apparent in the on-Earth design and construction of mining and transportation equipment which entails a carbon cost. In addition, the burning of rocket fuel required in order to send such apparatus into space, resulting in harmful emissions being released into the atmosphere.

Extraterrestrial impacts

The impact that mining may have on extraterrestrial environments is currently a contested area (Mallick & Rajagopalan, 2019). Earth is unique in that it has a distinctive atmosphere and climate capable of supporting an abundance of different life forms. This is a characteristic that (to date) is unique to Earth. The potential contenders for space mining discussed above (such as the Moon, Mars and meteoroids) do not have the life-supporting atmosphere that planet Earth has. Therefore, it can be argued that the negative externalities of space mining would be less pressing (at least from an atmospheric and anthropocentric perspective) on celestial bodies outside of planet Earth (Sivolella, 2019), simply because there is no (or very little) atmosphere to damage. Despite the lack of atmosphere argument, there are several important considerations regarding the exploitation of off-world resources. The first is that resources are often non-renewable, which presents a finite quantity of resources that are available to be extracted.

The issues discussed in this section have highlighted several potential environmental implications of space mining. Some impacts may be environmentally positive, and some may bear an environmental burden. In order to bring these arguments together, a summary of the main themes provided in this section are presented in the Table 1 below:

Table 1 The terrestrial and extraterrestrial impacts of space mining

Negative Terrestrial Impacts	Negative Extraterrestrial Impacts
Resources that are brought to Earth for consumption as fuel will still produce emissions that are damaging to Earth's atmosphere, leading to global warming and climate change.	Like on-Earth mining, resources in outer space are non-renewable. This raises moral and philosophical questions over the best usage of off-Earth resources.
There is a carbon cost associated with designing and constructing off-Earth mining equipment. In addition, rocket fuel must be used to propel such apparatus into space.	Pursuing outer space mining for non-renewable resources could be seen as a method of delaying the transition to more renewable forms of energy generation, and, consequently, prolonging human over-reliance on fossil fuels.
Rockets can fail on their journey into outer space or on their return to Earth. This could cause crash (or splash) landings, leading to the contamination of land and marine environments with debris, including hazardous rocket fuels.	Utilising resources in outer space will limit the use of such resources for future generations of humans.
Positive Terrestrial Impacts	**Positive Extraterrestrial Impacts**
Utilising fuels originating from outer space that are rare on Earth could overcome global reliance on fossil fuels, such as helium-3 used for generating electrical power, found in abundance on the moon.	Utilising fuel resources on the moon could help to develop future 'fuel stations' there, or other exo-locations (Mars, LEO etc.). This could enhance space exploration possibilities by enabling spacecraft to go further.
The lack of people and atmosphere on other extraterrestrial bodies means the social and environmental impacts of space mining are lower than terrestrial mining impacts.	Fuelling and launching from outer space would avoid the negative environmental impacts of launching rockets from Earth.

As identified in this section, there are several different human actions that could contribute to environmental harm through engaging in space mining activities. Therefore, these are pertinent issues for green criminologists.

A green criminological perspective

Traditionally, the discipline of criminology has been devoted to the study of behaviours that violate criminal laws with the *crime* and the *offender* as central areas of focus (Lampkin, 2020). Some criminologists, however, have realised that concentrating specifically on imperfect notions of crime and criminality can often fail to encompass similarly *harmful*, yet legal acts. Issues pertaining to the environment (and human interactions with it) often fall into this trap because many environmentally damaging human endeavours are perfectly legal, albeit ecologically catastrophic

(Wyatt, 2013). This crime-harm conundrum applied to the environment has resulted in the establishment of an 'environmentally sensitive' version of criminology – *green criminology* – which proclaims to study environmentally harmful acts regardless of legality (Ruggiero & South, 2013: 360). As a result, green criminology could be seen as related to the criminological subfield of *zemiology* - the study of social harms, law and crime (Hillyard & Tombs, 2017).

Perhaps unsurprisingly, human interactions with outer space also have 'environmental' consequences. Much academic literature, for example, has been devoted to the increasing dangers associated with orbital space debris (Migaud, 2020). Space-related activities can also have an environmental impact both on-Earth (such as harmful emissions or marine pollutions) and off-Earth (the deterioration of extraterrestrial resources and environments) (De Lucia & Iavicoli, 2018; Race & Kramer, 2018). Despite these environmentally harmful impacts, there is very little by the way of environmental law to prevent such consequences. Because no person or nation can own or appropriate outer space, there are no enforceable laws pertaining to outer space. There are, however, a number of international agreements and treaties devoted to the use of outer space. The most influential of these has been the 1967 Outer Space Treaty developed by the United Nations Committee on the Peaceful Use of Outer Space (UNCOPUOS), designed to address political tensions between the U.S. and Soviet Union during the cold war era. Even this important treaty, however, did not consider the environmental impact (terrestrial or otherwise) of humans' interactions with outer space. As a result, outer space has been described as a frontier ready to exploit, rather than an environment in need of protection (Takemura, 2019).

Therefore, due to both the potential for environmental harm, and the severe lack of environmental law pertaining to outer space, a vacuum exists between people, companies and nations undertaking environmentally harmful acts, on the one hand, and the existence of laws designed to manage human interactions with outer space, on the other. A traditional, orthodox version of criminology would consider such issues as beyond the 'purview of the discipline' (Stretesky et al., 2014: 1) owing to the lack of violations of criminal laws. Few are yet to make this realisation, although some important early steps are currently being made (Lampkin, 2020, 2021; Takemura, 2019). This paper can be seen as adding another important contribution to this area.

The issue of space mining presents a perfect example of an environmentally harmful human endeavour worthy of (green) criminological attention. There are no laws pertaining to what humans can and cannot do regarding mining on extraterrestrial bodies (Shaw, 2013). This is the result of the remote location of such mining and the prohibition of the national appropriation of space in Article II of the OST. Although prohibiting the ownership of off-Earth resources was initially designed as a mechanism to prevent powerful states from claiming bodies in outer space, it could be argued that national appropriation may at least subject that nation to the environmental laws enacted by its legislature. The lack of environmental law, however, coupled with the potential profitability of space mining has led to the emergence of several companies invested specifically in the exploration and production of off-world resources (Takemura, 2019), meaning space mining may soon transition from science fiction into reality.

Some criminologists would undoubtedly argue that scholarship debating space mining is premature at best, owing to the fact space mining is not yet a fully commercial enterprise. Ultimately, there are no active space mining operations and, therefore, discussing any ensuing environmental harms could inevitably be interpreted as only a subjective and theoretical exercise (particularly if space mining fails to ever come to fruition). In addition, there are undoubtedly more pressing green criminological matters, particularly those associated with global warming and climate change (White, 2020). These are certainly important issues and ones that have a more immediate social, human and ecological impact.

We argue, however, that this mode of thinking is a reactive response to environmental harms that have already occurred. For example, whilst researching the environmental impacts of the fossil fuel industry is vitally important in understanding the lasting impacts of such technology (and therefore may influence public policy into altering, restricting or prohibiting such practices in the future), it is clearly a reaction to damaging events that have already occurred. As a result of researching such environmental harm, some destruction must have taken place previously. Therefore, whilst green criminological scholarship has made excellent inroads into exposing (and occasionally curbing) environmental harms, such research is a response to harm that may already be irreversible.

As a result, we contend that considering future environmental harms is in fact a worthwhile endeavour, despite the lack of harm materialisation. Whilst such an approach may be construed as radical within criminology, it is commonplace within other disciplines where initial prevention is deemed as vital. For example, in law, the precautionary principle suggests that states 'take action where a risk to human health or the environment exists, but there is evidential uncertainty as to the existence or extent (magnitude) of the risk' (Wolf & Stanley, 2014: 16). This is clearly the case with space mining at this embryonic stage whereby companies are still exploring the technological possibilities that may enable the extraction of space resources to take place in the future.

Dealing with issues that are yet to materialise may result in the prevention of destructive practices in the future (Lampkin, 2020). However, considering future human-space relationships and their potential to impact on and off-world environments raises puzzling philosophical questions of a dark-green criminological nature. Human activities in outer space could be considered 'invisible spaces' that may consequently be vulnerable to exploitation due to their remote location. Whilst cameras, social media and modern technology may make visible some human activities (such as those onboard the International Space Station), only a few humans have ever travelled into outer space to witness and engage in human-related activity there. We argue, however, that outer space represents an invisible environment for most humans, and the potentially damaging environmental impacts of space mining may constitute a dark figure of environmental harm. Remote (i.e., human-less) mining is a good example of how human endeavours in outer space may become invisible (and therefore open to exploitation).

Although robust international laws may go some way to help prevent or limit such harm, other philosophical questions arise pertaining to the importance and value of extremely remote places. As Milligan (2016: 129) purports:

> 'we need grounds for protection of a more robust sort and this will require us to think in terms of the importance of places and geographical features as warranting stewardship or otherwise having importance in their own right. But this is easier to propose than to justify. It is open to charges of sentimentality and/or anthropomorphism, the projection of value onto that which is *just there*.' [*Emphasis* in original].

Milligan (2016), then, is perhaps displaying the argument that we are over-thinking our relationship with outer space and that the remoteness of extraterrestrial bodies, therefore, does not merit extra scholarship as the activities there do not affect humans on Earth. As a result, just because an object exists in deep space, it does not necessarily mean that we need to protect it or refrain from exploiting it.

These questions surrounding off-Earth ecologies also indicate, to us, that the discipline of green criminology, itself, might be pressed in useful, critical, and inevitable directions. Since its inception, green criminology has been troubled by the role of *green* in its analysis. Halsey (2004), for example, has raised critical questions about the dominant framings of 'nature' at work in green criminology, arguing that dominant disciplinary modes of thought from liberal environmentalism to Marxist ecology all suffer from the failure of all modernist thought to render 'nature' accurately or adequately as a coherent concept or object. For Halsey, 'the term "green" should be jettisoned from criminological discourse', in part because it fails to 'adequately capture the *inter-subjective, inter-generational, or inter-ecosystemic* processes which combine to produce scenarios of harm' (Halsey, 2004: 835, *emphasis* added). Here we can note that each dimension of Halsey's apt critique can be satisfied, at least somewhat, by incorporating an astro-green perspective within green criminology. Inter-subjective and inter-generational harms, of course, are an essential dimension of any criminological consideration of space mining as the practice itself, as outlined above, is far-off in terms of both time and space. The concern surrounding inter-ecosystemic harms, meanwhile, is highlighted plainly by the material facts of an emerging, extreme, and largely speculative form of extraction like space mining.

Lampkin (2020) has also critiqued the persistence of 'green' in green criminology, describing the ways in which the disciplinary adherence to green sometimes indicates a narrow view of human ontology and, at the same time, fails to adequately capture the vast complexities of relations between material humanity, culture, and the other-than-human world. Both Halsey (2004) and Lampkin (2020) claim that so-called green thinking binds any analysis which it infects to a certain form of anthropocentrism in which subjectivity is restrictively and unnecessarily confined to Earth, itself an object constructed from human-centred thought. While this issue seems determined and destined to hound green criminology—which, to be clear, is not suffering from any failure to recognize these limitations—it seems to us that it can be addressed at least somewhat by exploring speculative and looming issues like space mining that impact off-Earth ecological systems and objects. Outside of criminology, significant attention to the sorts of philosophical questions presented by space mining has already developed, most notably from within contemporary ecotheory and ecocriticism. Here green criminology might contribute to the ongoing development of perspectives like those outlined in Wilson's (2014) *melancology*, with its constant attention to the ways humanity is able and inclined to conceptualize our relation with the cosmic and astronomical, and those offered by contemporary ecocritics like Levi Bryant (2013), whose 'black ecology' is deeply suggestive of the cosmic encounters likely to emerge from space mining as a material practice.

Among the many criminological concerns emanating from space mining identified by Takemura (2019), perhaps the most speculative are those relating to nonhuman extraterrestrial life. On Earth, of course, we only need to glance across the global landscapes of energy production and extraction - extreme or otherwise - to see the sorts of harms that come along with it: from the dynamited mountains of Appalachia in the U.S. subjected to mountaintop removal mining, to the vast extractive geography of the Canadian tar sands; from the bloody violence of the Niger River Delta's oil fields, to the informal mining of rare-Earth minerals required for batteries in the Brazilian and Colombian Amazon. Ultimately, where extreme energy projects are undertaken, harm follows. Because of the long history of extraction as a key dimension of colonial expansion, where extraction was developed into a mode of social discipline and a fundamental source of colonial wealth, green criminologists like Takemura are right to speculate about the predictable effects of space mining on extraterrestrial life. Put simply, green criminology should not limit itself to a concern for forms of ecological life we know and recognize, but those we might encounter later. By expanding the scope of its inquiry to include extraterrestrial extraction and extreme energy practices like space mining, green criminology can also recall and reaffirm its relationship with social and environmental justice: in the earliest calls for a criminology attuned to environmental harm, critical concerns for issues like colonial power and the need to understand environmental health and stability as elementally connected to social and political power, race and racism, gender and sexuality, class, and geography (see: Lynch, 1990; South, 1998).

Finally, green criminology might find itself enriched by making space for the subject of what White and Heckenberg (2011) have called the discipline's need and tendency to 'horizon scan,' to keep a speculative eye on those ecological developments and devastations that may be looming over the future. Space mining, perhaps more than any other significant development, represents the horizon of extreme energy extraction, and so if it is to remain relevant, green criminology must take up the challenge of thinking through the likely outcomes. Faced with the looming problem of space mining, green criminology might have the opportunity to do two things. First, by scanning the horizon for the sorts of foreseeable harms presented by space mining, green criminology makes good on White's call that we do not abandon our speculative concerns (White, 2016; White & Heckenberg, 2011). Second, we can take seriously the critical claims of ecocritics like Tabas (2020), who joins Takemura (2019) in questioning the colonial implications of the 'post-planetary culture' suggested by space mining and who notes that despite being 'seen as providing a lifeboat against the unsustainability of the economy,' it is understood that space mining 'will permit the perpetuation of the growth and production-oriented paradigm of capitalism' (Tabas, 2020: 64), a critique that if taken up might affirm green criminology's critical origins in environmental justice.

Aside from these important questions, green criminology can also consider other aspects of space mining. There are many unanswered questions surrounding, for example, the construction and implementation of environmental laws designed to curb environmental harms associated with outer space activities. It has not yet been decided who should be able to engage in space mining and for what purpose they may/should be allowed to do so (e.g. to extend scientific understanding, to make commercial profit from a natural resource that already exists and is not subject to ownership). Other simple questions have also been left unanswered, many that implicate both the material and philosophical issues outlined above. For example, who does, or who should, own resources in outer space? Should we (as humans) be using such resources for scientific or commercial gain? What impact may doing so have on future generations of humans, and on other potential extraterrestrial life forms? What impact, if any, may exploiting off-Earth resources have for planet Earth itself (in terms of contributing to pollutions and other harmful emissions)? There exists, currently, a wealth of green criminological research and understanding on environmental harms that have occurred on Earth (Brisman & South, 2020), but there is comparably very little pertaining to off-world environmental harm despite the existing (and possibly future) environmental harms. As a result, we hope this article may inspire other criminologists to engage with astro-green criminological issues, thereby advancing Takemura's (2019) recent call for such a discipline.

Conclusion

This article has done three things. First, it has briefly outlined the current state of space mining which included an exploration of mining possibilities on Earth's Moon, asteroids, meteoroids and other planetary objects. Second, the article has examined some of the potentials for on and off-Earth environmental harm that could result from human-space interactions. Finally, a green criminological lens has been applied to space mining activities, including a call for green criminologists to engage with issues pertaining to environmental harms and outer space, off-Earth ecologies, and questions relating to colonial power. Further, this paper has expanded upon Takemura's (2019) original call for an astro-green criminology, and Lampkin (2021) subsequent development of that call which included in its analysis the pressing need to research and understand the social and environmental impacts of space mining.

Importantly, this paper has argued that now is precisely the right time for social scientists to be engaging in complex discussions about space mining. There appears, for example, a so-far undebated social issue about the philosophy and morality of conducting space mining. Could, for example, mining in outer space prevent some of the negative effects of on-Earth mining (in terms of direct, and often negative, impacts on public health, the environment and non-human animals)? Or could utilising non-renewable resources gleaned from outer space exasperate the negative impacts of traditional mining practices and the drilling associated with natural gas, coal and oil extraction, contributing to further anthropogenic climate change? Such questions, while vitally important, demonstrate not just the value in social science discussion and debate, but the importance of doing so before environmental harm is created. Therefore, although some may be sceptical of the value in discussing future environmental harms, it is arguably better to do so, for the sake of those humans, animals and ecologies that usually suffer from anthropogenic practices, prior to harm materialising. It is this solutions focussed approach to environmental harm that is often lacking within green criminological research and literature (Lampkin, 2020), but something that we advocate as important in future green criminological discussions about environmental harms.

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References

Aderin-Pocock, M., Bussey, B., Johnston, A. K., Couper, H., Dinwiddie, R., Farndon, J., Henbest, N., Hughes, D. W., Sparrow, G., Stott, C., & Stuart, C. (2014). *The planets: The definitive visual guide to our solar system*. Dorling Kindersley Limited.

Anderson, S. W., Christensen, K., & LaManna, J. (2018). The development of natural resources in outer space. *Journal of Energy & Natural Resources Law*, *37*(2), 227–258. https://doi.org/10.1080/02646811.2018.1507343.

Baiden, G., Grenier, L., & Blair, B. (2010). Lunar underground mining and construction: A terrestrial vision enabling space exploration and commerce. In: 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition. Resource document. Available at: http://ssi.org/2010/SM14-proceedings/Lunar-Underground-Mining-and-Construction-A-Terrestrial-Vision-Enabling-Space-Exploration-and-Commerce-Baiden-Grenier-Blair.pdf Accessed 8 September 2020.

Bowling, T. J., Ciesla, F. J., Davison, T. M., Scully, J. E., Castillo-Rogez, J. C., Marchi, S., & Johnson, B. C. (2019). Post-impact thermal structure and cooling timescales of Occator crater on asteroid 1 Ceres. *Icarus*, *320*, 110–118. https://doi.org/10.1016/j.icarus.2018.08.028.

Brisman, A. (2020). In N. South (Ed.), *Routledge international handbook of green criminology* (2nd Edition.). Routledge.

Bryant, R. (2013). Black ecology. In J. J. Cohen (Ed.), *Prismatic ecology: Ecotheory beyond green* (pp. 290–310). University of Minnesota Press.

Citron, R. I., Genda, H., & Ida, S. (2015). Formation of Phobos and Deimos via a giant impact. *Icarus*, *252*, 334–338. https://doi.org/10.1016/j.icarus.2015.02.011.

Cockell, C. S., Holt, J., Campbell, J., Groseman, H., Josset, J. L., Bontognali, T. R., Phelps, A., Hakobyan, L., Kuretn, L., Beattie, A., & Blank, J. (2019). Subsurface scientific exploration of extraterrestrial environments (MINAR 5): Analogue science, technology and education in the Boulby Mine, UK. *International Journal of Astrobiology*, *18*(2), 157–182. https://doi.org/10.1017/s1473550418000186.

De Lucia, V., & Iavicoli, V. (2018). From outer space to ocean depths: The spacecraft cemetery and the protection of the marine environment in areas beyond national jurisdiction. *California Western International Law Journal*, *49*(2), 345–389. https://doi.org/10.2139/ssrn.3153458.

Deutsch, A. N., Head, J. W., Ramsley, K. R., Pieters, C. M., Potter, R. W., Palumbo, A. M., Bramble, M. S., Cassanelli, J. P., Jawin, E. R., Jozwiak, L. M., & Kaplan, H. H. (2018). Science exploration architecture for Phobos and Deimos: The role of Phobos and Deimos in the future exploration of Mars. *Advances in Space Research*, *62*(8), 2174–2186. https://doi.org/10.1016/j.asr.2017.12.017.

Extreme Energy Initiative (no date) (July 2020). What is extreme energy? Resource document. Available at: https://extremeenergy.org/about/what-is-extreme-energy-2/ Accessed 3.

Fraeman, A. A., Murchie, S. L., Arvidson, R. E., Clark, R. N., Morris, R. V., Rivkin, A. S., & Vilas, F. (2014). Spectral absorptions on Phobos and Deimos in the visible/near infrared wavelengths and their compositional constraints. *Icarus*, *229*, 196–205. https://doi.org/10.1016/j.icarus.2013.11.021.

Garber, S. (2015). A chronology of Mars exploration. Produced for: NASA. Resource document. Available at: https://history.nasa.gov/marschro.htm Accessed 28 July 2020.

Giraldo, W., & Tobón, J. I. (2013). Extraterrestrial minerals and future frontiers in mineral exploration. *Dyna*, *80*(182), 83–87.

Green, C. A., Styles, P., & Baptie, B. (2012). Preese Hall shale gas fracturing: review & recommendations for induced seismic mitigation. Resource document. Available at.

Halsey, M. (2004). Against 'green' criminology. *British Journal of Criminology, 44*(6), 833–853.

Hein, A. M., Saidani, M., & Tollu, H. (2018). Exploring potential environmental benefits of asteroid mining. arXiv:1810.04749: 1–7.

Hillyard, P., & Tombs, S. (2017). Social harm and zemiology. In: Liebling, A. Maruna, S. & McAra, L. (Eds.), The oxford handbook of criminology. Oxford: Oxford University Press. 6th Edition.

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/15745/5075-preese-hall-shale-gas-fracturing-review.pdf Accessed 6 (July 2020).

Iai, M., & Gertsch, L. (2013). Excavation of lunar regolith with large grains by rippers for improved excavation efficiency. *Journal of Aerospace Engineering*, *26*(1), 97–104. https://doi.org/10.1061/(asce)as.1943-5525.0000221.

Jackson, R. B., Vengosh, A., Carey, J. W., Davies, R. J., Darrah, T. H., O'Sullivan, F., & Pétron, G. (2014). The environmental costs and benefits of fracking. *Annual Review of Environment and Resources*, *39*, 327–362. https://doi.org/10.1146/annurev-environ-031113-144051.

Jopek, T. J., Valsecchi, G. B., & Froeschlé, C. (2002). Asteroid meteoroid streams. In W. F. Bottke Jr., A. Cellino, P. Paolicchi, & R. P. Binzel (Eds.), *Asteroids III* (pp. 645–652). University of Arizona Press.

Krinov, E. L. (1960). *Principles of meteoritics*. Pergamon Press Ltd.

Lampkin, J.A. (2018). *Will unconventional, horizontal, hydraulic fracturing for shale gas production purposes create environmental harm in the United Kingdom?* [PhD thesis, University of Lincoln]. https://eprints.lincoln.ac.uk/id/eprint/35711/1/Jack%20Lampkin%20PhD%20Thesis.pdf

Lampkin, J.A. (2020). *Uniting green criminology and Earth jurisprudence*. Routledge.

Lampkin, J.A. (2021). Mapping the terrain of an astro-green criminology: A case for extending the green criminological lens outside of planet earth. *Astropolitics: The International Journal of Space Politics and Policy, 18*(3), 238–259.

Long, M. A., Stretesky, P. B., Lynch, M. J., & Fenwick, E. (2012). Crime in the coal industry: Implications for green criminology and treadmill of production. *Organization & Environment*, *25*(3), 328–346. https://doi.org/10.1177/1086026612452266.

Lucas, M. T., & Hagan, P. C. (2014). Comparison of two excavations systems for the mining of lunar regolith. *Mining Education Australia: Journal of Research Projects Review*, *3*(1), 39–44.

Lynch, M. J. (1990). The greening of criminology: A perspective for the 1990's. *The Critical Criminologist*, *2*(3), 11–12.

Mallick, S., & Rajagopalan, R. P. (2019). If space is 'the province of mankind', who owns its resources? An examination of the potential of space mining and its legal implications. *ORF Occasional Paper*, *182*, 1–27.

Martínez-Jiménez, M., Moyano-Cambero, C. E., Trigo-Rodríguez, J. M., Alonso-Azcárate, J., & Llorca, J. (2017). Asteroid mining: mineral resources in undifferentiated bodies from the chemical composition of carbonaceous chondrites. In: Trigo-Rodríguez, J.M. Gritsevich, M. & Palme, H. (Eds.), Assessment and mitigation of asteroid impact hazards: proceedings of the 2015 Barcelona asteroid day. Cham: Springer. Pp 73–101.

McKay, D. S., Heiken, G., Basu, A., Blanford, G., Simon, S., Reedy, R., French, B. M., & Papike, J. (1991). The lunar regolith. In G. H. Heiken, D. T. Vaniman, & B. M. French (Eds.), *Lunar sourcebook: A user's guide to the Moon* (pp. 285–356). Cambridge University Press.

Migaud, M. R. (2020). Protecting Earth's orbital environment: Policy tools for combating space debris. *Space Policy*, *52*(101361), 1–9. https://doi.org/10.1016/j.spacepol.2020.101361.

Milligan, T. (2016). Asteroid mining, integrity and containment. In J. Galliott (Ed.), *Commercial space exploration: Ethics, policy and governance* (pp. 123–134). Routledge.

Mueller, R. P., & Van Susante, P. J. (2011). A review of lunar regolith excavation robotic device prototypes. In: American Institute of Aeronautics and Astronautics Space 2011 Conference, Long Beach, California, Paper no.1073752. Resource document. Available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110016233.pdf Accessed 8 September 2020.

Nakamura, E., Makishima, A., Moriguti, T., Kobayashi, K., Tanaka, R., Kunihiro, T., Tsujimori, T., Sakaguchi, C., Kitagawa, H., Ota, T., & Yachi, Y. (2012). Space environment of an asteroid preserved on micrograins returned by the Hayabusa spacecraft. Proceedings of the National Academy of Sciences, 109(11), E624-E629. https://doi.org/10.1073/pnas.1116236109.

NASA (2019). Meteors & meteorites. Resource document. Available at: https://solarsystem.nasa.gov/asteroids-comets-and-meteors/meteors-and-meteorites/overview/?page=0&per_page=40&order=id+asc&search=&condition_1=meteor_shower%3Abody_type Accessed 16 July 2020.

NASA (2020a). NASA science Mars 2020 mission perseverance rover. Resource document. Available at: https://mars.nasa.gov/mars2020/ Accessed 31 July 2020.

NASA (2020b). OSIRIS-Rex. Resource document. Available at: https://www.nasa.gov/osiris-rex Accessed 21 July 2020.

Naser, M. Z. (2019). Extraterrestrial construction materials. *Progress in Materials Science*, *105*, 100577. https://doi.org/10.1016/j.pmatsci.2019.100577.

Pajola, M., Lazzarin, M., Dalle Ore, C. M., Cruikshank, D. P., Roush, T. L., Magrin, S., Bertini, I., La Forgia, F., & Barbieri, C. (2013). Phobos as a D-Type captured asteroid, spectral modeling from 0.25 to 4.0 μm. *The Astrophysical Journal*, *777*(2), 127–132. https://doi.org/10.1088/0004-637x/777/2/127.

Peacock, D. A. (2017). Mining on the moon. Mining Engineering, 2017, 23–31.

Prud'homme, A. (2014). *Hydrofracking: What everyone needs to know*. Oxford University Press.

Race, M., & Kramer, W. (2018). The need for a rational framework for coordinated management of future exploration, uses and exploitation of outer space environments and resources. In: Conference presentation: 42nd COSPAR scientific assembly held 14–22 July 2018 in Pasadena, California: USA. Abstract id: PEX.2-33-18. Resource document. Available at: https://ui.adsabs.harvard.edu/abs/2018cosp… E2763R/abstract Accessed 8 September 2020.

Rothe, D. L., & Collins, V. E. (2023). Planetary geopolitics, space weaponization and environmental harms. *The British Journal of Criminology*, azad003. https://doi.org/10.1093/bjc/azad003.

Ruggiero, V., & South, N. (2013). Green criminology and crimes of the economy: Theory, research and praxis. *Critical Criminology*, *21*(3), 359–373. https://doi.org/10.1007/s10612-013-9191-6.

Sachdeva, G. S. (2018). Commercial mining of celestial resources: Case study of U.S. space laws. *Astropolitics: The International Journal of Space Politics and Policy*, *16*(3), 200–215. https://doi.org/10.1080/14777622.2018.1534312.

Schmitt, H. H. (2004). Mining the moon. Produced for: Popular Mechanics. Resource Document. Available at: http://www.searchanddiscovery.com/documents/2004/schmitt/ Accessed 9 July 2020.

Shackleton Energy (no date). Overview. Resource document. Available at: http://www.shackletonenergy.com/overview#goingbacktothemoon Accessed 9 July 2020.

Shaw, L. E. (2013). Asteroids, the new western frontier: Applying principles of the general mining law of 1872 to incentive asteroid mining. *Journal of Air Law & Commerce*, *78*(1), 121–168.

Short, D., Elliot, J., Norder, K., Lloyd-Davies, E., & Morley, J. (2015). Extreme energy, 'fracking' and human rights: A new field for human rights impact assessments? *The International Journal of Human Rights*, *19*(6), 697–736. https://doi.org/10.1080/13642987.2015.1019219.

Sivolella, D. (2019). *Space mining and manufacturing: Off-world resources and Revolutionary engineering techniques*. Springer Praxis Publishing.
South, N. (1998). A green field for criminology? A proposal for a perspective. *Theoretical Criminology*, *2*(2), 211–233.
Stretesky, P. B., Long, M. A., & Lynch, M. J. (2014). *The treadmill of crime: Political economy and green criminology*. Routledge.
Summerhayes, C. P., & Zalasiewicz, J. (2018). Global warming and the anthropocene. *Geology Today*, *34*(5), 194–200. https://doi.org/10.1111/gto.12247.
Tabas, B. (2020). Hatred of the Earth, climate change, and the dreams of post-planetary culture. *Ecozon@ European Journal of Literature Culture and Environment*, *11*(1), 63.
Takemura, N. (2019). Astro-green criminology: A new perspective against space Capitalism. *Toin University of Yokohama Research Bulletin*, *40*, 7–17.
White, R. (2016). The foundations of eco-global criminology. In R. Ellefsen, R. Sollund, & G. Larsen (Eds.), *Eco-global crimes* (pp. 15–32). Routledge.
White, R. (2020). *Climate change criminology*. Bristol University Press.
White, R., & Heckenberg, D. (2011). Environmental horizon scanning and criminological theory and practice. *European Journal on Criminal Policy and Research*, *17*(2), 87–100.
Wilson, S. (2014). *Melancology: Black metal theory and ecology*. John Hunt Publishing.
Wolf, S., & Stanley, N. (2014). *Wolf and Stanley on environmental law* (6th ed.). Routledge.
Wyatt, T. (2013). *Wildlife trafficking: A deconstruction of the crime, the victims, and the offenders*. Springer.
Yano, H., Kubota, T., Miyamoto, H., Okada, T., Scheeres, D., Takagi, Y., Yoshida, K., Abe, M., Abe, S., Barnouin-Jha, O., & Fujiwara, A. (2006). Touchdown of the Hayabusa spacecraft at the muses sea on Itokawa. *Science*, *312*(5778), 1350–1353. https://doi.org/10.1126/science.1126164.

Authors and Affiliations

Jack Adam Lampkin[1] · Bill W. McClanahan[2]

✉ Jack Adam Lampkin
j.lampkin@yorksj.ac.uk

Bill W. McClanahan
billmcc@utk.edu

1 York Business School, York St John University, York, England

2 Department of Sociology, University of Tennessee, Knoxville, United States of America