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Opinion/Position paper

Beyond planetary protection: What is planetary sustainability and what are its implications for space research?

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A R T I C L E I N F O

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A B S T R A C T

This paper presents recent developments in the interdisciplinary topic of “planetary sustainability” and discusses its potential implications for space research.

The current COSPAR Planetary Protection Policy address scientific space exploration only and is primarily concerned with the issue of contamination with micro-organisms. Other impacts of human space exploration that may be detrimental to space exploration itself are not covered. The best known example is the anthropogenic space debris orbiting Earth, but similar problems will occur in other places due to scientific and commercial space exploration in the near future.

One possible approach to discuss and mitigate the impact of space exploration on the environment is to consider the space environment as integral part of sustainable development. The resulting concept of “planetary sustainability” and its ethical, scientific, economic, and legal ramifications were discussed during a workshop co-sponsored by the International Space Science Institute in March 2018. In this paper, we first summarize the results of this workshop. Then we propose potential implications of this concept for space research and report reactions and suggestions by members of the space research community during the COSPAR assembly 2018.

1. Introduction

A sustainable development is a “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”, while these needs are “in particular the essential needs of the world’s poor” (World Commission on Environment and Development, 1987). Sustainability, as by this definition, includes an ecological, economical, and social component. This definition is the most widely accepted one, hence we use it as starting point for this paper.

To our knowledge, the term “planetary sustainability” was first coined by NASA in 2014 (NASA, 2014) as a vision with three main objectives:

1. A world in which all people have access to abundant water, food and energy, as well as protection from severe storms and climate change impacts;
2. Healthy and sustainable worldwide economic growth from renewable products and resources;
3. A multi-planetary society, where the resources of the Solar System are available to the people of Earth.

Throughout this paper, we will use the term “planetary sustainability” to denote an application of sustainability that explicitly considers the Earth as a planet in its space environment (Losch, 2018b). This concept of planetary sustainability combines the requirements for a sustainable development (World Commission on Environment and Development, 1987) with two recognitions:

- We must respect the boundaries of the Earth system (biodiversity, atmospheric composition, global fresh water etc.) outside of which safe operating space can no longer be guaranteed for humanity (Rockström, 2009).
- Without “expansion of our instruments and people into space, humanity could conceivably perish” (Pass et al., 2006).

The second aspect was elaborated by Losch (2018a): “Even in the very long run, later generations should be able to meet their own needs without perishing due to events in our Solar System. To enable us to last that long, all the developed dimensions of sustainability need to be upheld. Additionally, as noted, the technological imperative and the necessary acquisition of and intervention in extraterrestrial resources and therefore potential habitats need to be discussed, conscious of

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humankind's achievements and failures. Not all changes that are and that will be technically possible are good. The technological imperative [enabling us to explore outer space] therefore needs to be balanced by the imperative of responsibility (Jonas, 1985)."

The present paper approaches planetary sustainability from the perspective of space research and exploration: how can they be consistent with and supportive of sustainable development on Earth and how can they avoid irreversible damage to the very thing they want to study? For these questions, we concentrate here on the near-Earth environment less than 0.3 astronomical units from Earth, i.e., the space relatively easily accessible by present-day spacecraft.

This study continues previous efforts to understand how to limit unintended consequences of space exploration and exploitation of space resources (Williamson, 1998; Almár, 2002; Hofmann et al., 2010; Rummel et al., 2012). The economic analysis by Hofmann et al. (2010), e.g., concludes with: "The human nature to exploit, explore and develop can create problems for relevant future efforts. Taking such long-term concerns often requires an approach not in-line with the 'spirit' of pioneering and exploration. But as our capabilities increase so do our responsibilities. In this case, sustainability ensures future efforts are not handicapped by today's choices."

Fitting the space environment into the other aspects of sustainable development can be done in different ways. One option is to consider outer space as means to achieve the 17 Sustainable Development Goals on Earth set forth by the United Nations (2015). This was described by Di Pippo (2017), the director of the United Nations Office for Outer Space Affairs: "To build resilient and sustainable societies we have to pay more attention to the peaceful uses of outer space". On a similar note she explained at the UNISPACE + 50 conference in June 2018 that the Space2030 framework was intended "to make space a driver for equality and for the attainment of the Sustainable Development Goals" (Di Pippo, 2017). Alternatively, the space environment could be recognized as an 18th autonomous goal together with the existing 17 Sustainable Development Goals as defined by the UN. The pictograms of the 17 UN Sustainable Development goals plus a possible 18th goal for the space environment are shown in Fig. 1. We did not a priori decide how to weigh the outer space environment compared to other aspects of sustainability. The question whether outer space should be an autonomous goal for sustainable development or not was treated as a point of discussion at the interdisciplinary workshop (see Section 2) and at the COSPAR assembly 2018 (see Section 3).

There are no planetary sustainability guidelines for space research yet. Setting up such guidelines is beyond the scope of this paper; it merely wants to draw the attention of the space science community to the subject and to a few cases where consequences of a non-sustainable usage of outer space and its resources are already observable or are predicted for the near future. The present paper can hopefully initiate the process of discussing the issue of planetary sustainability among the space science community. This process may ultimately lead to guidelines, if people and institutions involved in space research and exploration reach a consensus that such guidelines are indeed useful.

A template, albeit a very ambitious one, for such guidelines could be the existing Planetary Protection Policy maintained by the Committee on Space Research (COSPAR). Planetary protection covers all space exploration processes that are necessary to prevent biological cross-contamination between the Earth and other celestial bodies. Having a more limited scope, this policy is respected by all national space agencies and by individual scientists: "COSPAR maintains and promulgates this planetary protection policy for the reference of spacefaring nations, both as an international standard on procedures to avoid organic-constituent and biological contamination in space exploration, and to provide accepted guidelines in this area to guide compliance with the wording of this UN Space Treaty and other relevant international agreements." (part of the preamble of "COSPAR's Planetary Protection Policy", COSPAR (2002)).

In parallel to this study, several other initiatives and studies are addressing this demand for more general guidelines or agreements to avoid degradation of space environments that goes beyond biological contamination. Newman and Williamson (2018) put more emphasis on the legal and policy aspects about "space sustainability" (mainly in the context of human-made space debris) than we do, but they reach similar conclusions: "if space activity is to be sustainable for future generations, the different values that underpin state activity and commercial activity will need to be reconciled with the need for respect for the fragile space environment." On a similar note, Race and Kramer (2018) state that "standards or approaches to avoid harmful contamination or irreversible damage to extraterrestrial environments are warranted. Yet the path forward to achieving such policies is uncertain at best. What project planners and proponents need are clear guidelines and policies that include more than vague notions of responsible activities." Recently, The Hague Space Resources Governance Working Group (2017) has gathered draft building blocks for an international framework on space resource activities. The Building Block 9 in that framework ("Avoidance of harmful impacts resulting from

Fig. 1. The 17 goals for Sustainable Development as defined by the UN, plus the space environment as a potential 18th goal (design by Karl Herweg).

space resource activities") should be of interest to COSPAR (Rummel, 2018). Some of the impacts mentioned (i.e., forward and backward contamination) are addressed by the COSPAR Panel on Planetary Protection (COSPAR, 2002), whereas others (e.g., man-made space debris) rather relate to the topics of the COSPAR Panel on Exploration (Rummel, 2018). The objective of the Panel on Exploration is to provide independent scientific advice to support the development of exploration programs and to safeguard the potential scientific assets of solar system objects (Rummel, 2018). This panel therefore has "(…) begun to consider issues of space environmental management beyond planetary protection concerns, but it will undoubtedly take many more years to provide necessary details. In addition, while other groups are focusing on regulatory approaches and policies for exploration and uses of beyond Earth orbit, they are a long way from dealing with the implementation details needed to guide space activities for different bodies." (Race and Kramer, 2018).

In this paper, we first summarize the different aspects of planetary sustainability discussed during an interdisciplinary workshop supported by the International Space Science Institute (ISSI) in Bern in March 2018 (Section 2). We then study the implications of the concept of planetary sustainability on space research (Section 3.1), and summarize the reactions of the scientific community during the COSPAR assembly (Section 3.2). Section 4 concludes the paper.

2. Summary of the interdisciplinary workshop on planetary sustainability

The potential meanings of planetary sustainability and its ethical, scientific, economic, and legal ramifications were discussed during a workshop co-sponsored by the ISSI in March 2018. A forthcoming special issue in the "Global Sustainability" journal will include several presentations from this workshop and other contributions related to planetary sustainability.

Herweg, University of Bern, set the scene with the introductory talk "Sustainability as a Mediating Concept", interpreting the topic as question: Will activities in the orbit and outer space lead towards "building better lives on Earth"? The subsequent talks belonged to one of four general categories: legal aspects, economic aspects, philosophical and theological aspects, and implications for space research.

2.1. Legal aspects

A thorough treatise on space law was beyond the focus of this workshop and of this paper, but the interested reader may refer, e.g., to Hobe et al. (2015). Space law pertains to the wider field of extraterritorial[1] jurisdiction but some basic definitions, such as the legal delimitation between airspace and outer space, are not unified yet in international law.

At the workshop, Bohlmann, ESA Strategy Department, discussed the legal challenges of space activities. The existing international space law in the narrow sense can be summarized as the series of international treaties and agreements shown in Fig. 2. The most fundamental treaty, the Outer Space Treaty (United Nations, 1967), has been ratified by more than 100 nations and is legally binding on them. It provides the fundamental principles of space law that are accepted by most countries. Most of these principles are considered to have crystallized into customary international law as they have been universally and uniformly applied consistently over time. The other treaties and conventions on outer space affairs mainly build on the principles of this Outer Space Treaty. The more recent attempt to agree on more specific terms of exploration, usage, and settlements for the case of celestial bodies (the Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, United Nations (1979)) was only ratified by a minority of States (18 States are treaty parties as of 2018). That agreement is therefore not considered legally binding for States non-party.

Beyond space law in this narrow sense, Bohlmann reminded the public that there are more general legal bodies and international agreements that need to be considered international law. The general principles of international law including the charter of the United Nations apply in addition to the legal regime of outer space per se. According to the Principle 21 of the Stockholm declaration, e.g., "States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction."(United Nations, 1972) The Report of the International Law Commission (United Nations, 2006) therefore summarizes: "the various existing models of liability and compensation have confirmed that State liability is accepted essentially in the case of outer space activities." Moreover, non-governmental entities are explicitly included under the responsibility of States for their "national space activities" according to article VI of the Outer Space Treaty.[2] This contradicts a common misconception that there are no rules in outer space for private enterprises.

Archinard, Swiss Federal Department of Foreign Affairs, followed this up by presenting the preparations for the UNISPACE + 50 conference (United Nations, 2018) celebrating the 50th anniversary of the first United Nations Conference on the exploration and the peaceful uses of outer space: The overarching goal of that conference was to take stock of the accomplishments in space in the last 50 years and to look toward the future of space activities, with an emphasis on improving international cooperation in the peaceful uses of outer space in support of the 2030 Agenda for Sustainable Development while ensuring the safety and the long-term sustainability of outer space activities.

Archinard explained that, given the lack of political will, the existing international space treaties were not likely to be revised in a foreseeable future. Instead, States were working on non-legally binding "soft law" instruments, like guidelines and recommendations. The development of any new legally binding treaty would be very difficult given the actual trends in multilateralism and international politics. For the subsequent discussion and conclusions (Sections 3 and 4) we therefore will take the existing space law as given, without investing thoughts how to change or renegotiate it.

2.2. Economic aspects

Matuleviciute from the Ministry of Economy, Luxembourg, presented the Luxembourg Space Policy and SpaceResources.lu initiative. According to the government web site (SpaceResources.lu, 2018), "Luxembourg provides a unique legal, regulatory and business environment enabling private investors and companies to explore and use space resources. (…) [Luxembourg's] goal is to ensure that space resources explored under its jurisdiction serve a peaceful purpose, are gathered and used in a sustainable manner compatible with international law and for the benefit of humankind." When it comes to mining space resources, the initiative mainly considers the Moon and Near-Earth Objects (NEOs). The latter are defined as asteroids and comets (less common than asteroids near Earth) that have perihelion distances ≤ 1.3 astronomical units and aphelion distances ≥ 0.983 astronomical

[1] The term "extraterritorial" in this context refers to an area "outside the territorial jurisdiction of any State, namely the high seas and adjacent airspace as well as outer space." (United Nations, 2006).

[2] "States Parties to the Treaty shall bear international responsibility for national activities in outer space, including the Moon and other celestial bodies, whether such activities are carried on by governmental or by non-governmental entities (…)" (United Nations, 1967).

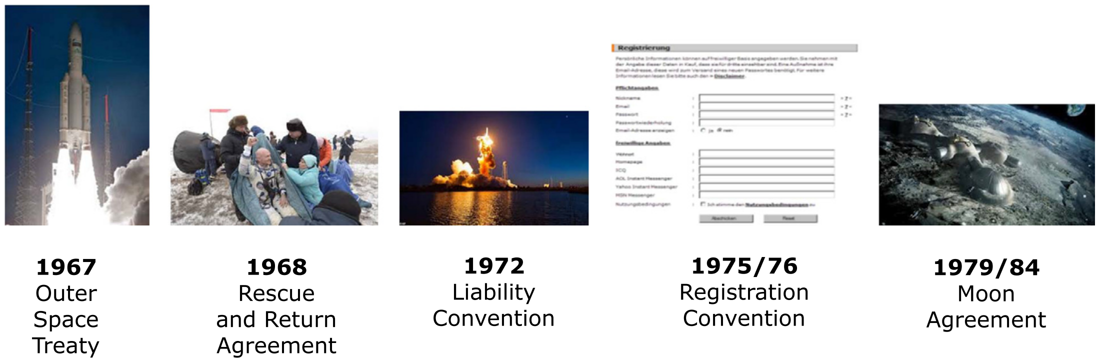

Fig. 2. Existing space law in the narrow sense (slide presented by Bohlmann during the ISSI workshop in March 2018).

units (NASA, 2017). SpaceResources.lu (2018) state with respect to the legal challenges (see Section 2.1): The Outer Space Treaty from 1967 "bans countries from appropriating celestial, outer space bodies, including the Moon. However, no international legislation so far has set rules about ownership of metals, minerals and other resources that may be found there. This legal uncertainty now needs clarification. Investors, companies and their customers rightfully expect certainty if they are to commit significant resources – human, material and financial – to long-term projects. (...) As more countries develop their own legal framework, Luxembourg is ready to join international efforts to harmonize global rules for the peaceful exploration and utilization of space resources."

In a response, Rowan, University of Zurich, voiced opposition to space mining. Space mining will, by definition, take place at the frontier or beyond state control. Judging from historical precedents, this implies little regulation and large potential for abuse. Moreover, it may distract Earth's societies from the necessary economic transformation to achieve a sustainable usage of natural resources.

2.3. Philosophical and theological aspects

The project "Ethics of Planetary Sustainability" (Losch, 2018a) is based on the philosophical and theological concept of constructive-critical realism. During the workshop, two presentations discussed this concept: C. Beisbart, University of Bern, examined the paper of Losch (2018a) by formulating a philosophical critique of the underlying concept. D. Barr, University of Chicago, presented the concept of "Realist Theological Ethics". One of the insights relevant to the space environment can be formulated as follows: If our emotional bonds to people or entities affected are weak, we tend to act less heroically and are rather driven by self-interest. As a consequence, we need legal regulation concerning space exploration because our emotional bonds to outer space are weak.

Weber, LMU Munich, presented recent challenges of the sustainability concept. In his opinion, "the model of sustainability is a clearly defined objective" is a fallacy for policy making. He pointed out that sustainability goes beyond the principle of passive limitation (i.e., preserving everything what exists at a given moment in time) and argued that also religions play a role in the concept of sustainability.

2.4. The perspective from space research

Persson, Lund University, discussed the meaning of sustainable development for astrobiology: "How do we ascertain that our project does not destroy or deplete any resources or biological systems necessary for improving our understanding of life, its origin, distribution and future on Earth and in the universe or for human survival and well-being (and the survival and well-being of other life-forms)? (...) Should we apply sustainable development on astrobiology?"

To Altwegg, University of Bern, sustainable behavior (from the point of view of a space scientist) in space starts with the planetary protection guidelines (COSPAR, 2002) but does not end there. One area where ethical questions will become relevant soon is asteroid mining.

We dedicate the rest of this paper to this question: What does planetary sustainability imply for space research and exploration?

3. Implications of planetary sustainability for space research

As the second stage of our study we submitted the topic of planetary sustainability to the COSPAR assembly in July 2018 in form of an interactive poster to engage the space science community. We asked the attendees for feedback about the topics discussed at the workshop and about implications of planetary sustainability on space research in general.

3.1. Our questions to the space research community at the COSPAR assembly

The basic dilemma we wanted to discuss was the meaning of the precautionary approach for space exploration. The Principle 15 of the Rio Declaration of Environment and Development (United Nations, 1992) describes the precautionary approach as follows: "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." The precautionary approach is fundamental to sustainability, as irreversible damages would undermine the ability of future generations to meet their own needs. The precautionary approach implies that humanity should limit consumption of non-renewable resources and that humanity should not introduce irreversible changes to an environment. This may pose a dilemma for space research and exploration: Space resources, such as water in asteroids, are vast, but they are not renewable in the sense of regenerating (in contrast to fish or forests, for which the original concept of sustainable management was developed). Moreover, the celestial bodies of imminent economic interest, the Moon and water rich near-Earth asteroids, would be quickly and irreversibly altered by the continuous presence of humans or by robotic mining (see Section 3.2). On the other hand, we would limit future generations now by not exploring space and thus not advancing scientific knowledge and technology levels that might become necessary in the near future.

This dilemma is linked with a seemingly technical question we asked: Should the space environment be considered in its potential for the 17 UN Sustainable Development Goals, and/or should the space environment be considered an autonomous 18th goal of sustainable development? If the space environment is an autonomous aspect of sustainable development and we take the precautionary approach, human space exploration might have to be restricted or re-assessed to reduce irreversible changes (with unforeseeable consequences) to the space environment. Less stringent restrictions to space exploration apply if we consider the space environment primarily an enabler for sustainable development on Earth.

We asked an even more fundamental question linked to the implications of planetary sustainability: What are the purposes of space research and exploration? This question did not prove useful for discussions during the conference. None of the proposed purposes of space research (e.g., improve human life on Earth, advance scientific knowledge, advance technology) was disputed by the audience. But we found that this question was too vague or broad to initiate a fruitful dialogue with people involved in space exploration. The following approach turned out to be more useful during the conference: let us consider a well-defined area, such as the Moon or NEOs, and ask what planetary sustainability (or other ethical considerations) implies for the exploration of these objects.

3.2. Outcome of discussions during the COSPAR assembly

On two points all visitors of our poster did agree: First, the question about the role of outer space in a sustainable development is important both for the general public and for space researchers. None of the attendees disputed that space research and exploration should conform with planetary sustainability as part of a general sustainable development on Earth and in Earth's space environment. If the outer space environment, due to human action, is deteriorated beyond a threshold level, it cannot fulfill its role in enabling sustainable development on Earth or might even be detrimental to it. One example is the increasing amount of man-made space debris orbiting Earth (orbital debris) that may render some orbits unusable for satellites in the future. For many conference attendees this is the most obvious case of a situation that is not sustainable and has been known to be problematic already decades ago (Kessler and Cour-Palais, 1978). Second, a purely prohibitive approach of shutting down space research and exploration entirely in order to avoid any potentially irreversible changes to the outer space environment is neither realistic nor would it benefit sustainable development on Earth. Outer space affects human and non-human life on Earth in many ways, so we cannot afford not to explore outer space if life on Earth is to thrive.

The majority of the COSPAR assembly attendees visiting our poster were in favor of adding 'Outer Space' as an autonomous 18th goal to the 17 Sustainable Development Goals (United Nations, 2015) in contrast to just consider outer space as an enabler to a sustainable development on Earth. To set up wider guidelines on space research and exploration, the environment of interest obviously must have been explored to some extent.

The areas most often mentioned for which guidelines of exploration are needed were the Moon, the NEOs, and the space from low Earth orbits to geostationary orbits at roughly 36000 km away from Earth. These areas are closest to Earth, they are considered the most obvious commercial targets (for space mining or for tourism), and they are probably sterile, therefore underlying fewer restrictions from planetary protection.[3]

Setting up guidelines is most straightforward in the case of orbital debris: Because no spacefaring party has a competing interest in having more instead of less orbital debris and because the problem is identified, guidelines and standards for the reduction of orbital debris have already been formulated (United Nations, 2010; NASA, 2012; ESA, 2012; The Hague Space Resources Governance Working Group, 2017). The guidelines by ESA (2012) also foresee the active removal of existing orbital debris, but the envisioned solutions are not ready to use yet. Apart from the technical challenge of active debris removal, the most pressing question is how to ensure that all spacefaring parties implement the existing guidelines.

Regarding the Moon, our knowledge of the surface, the tenuous atmosphere, and its interaction with the plasma environment is advanced enough to aim at exploration guidelines. The conference attendees were unsure whether the Moon Agreement (see Section 2.1) is the best basis for such guidelines. One point of concern regarding the lunar environment is the tenuous atmosphere. It consists mostly of He, Ne, Ar, CH_4, and other, less abundant, species such as CO, CO_2, N_2, Rn, Na, and K (Stern, 1999; Benna et al., 2015). These atmospheric species originate from surface release processes, i.e., thermal desorption, meteoritic impacts, and photons and solar wind particles sputtering the surface (Stern, 1999; Wurz et al., 2007). The total mass of the lunar atmosphere is estimated to be only 10t approximately (Benna et al., 2015). If we compare this mass to the air mass required per person per day for respiration (15 kg of N_2, O_2, CO_2), we notice that this corresponds to 0.1% of the total lunar atmosphere in terms of mass. Thus, without careful recycling of resources and waste management, human presence on the Moon will rapidly and irreversibly alter the atmosphere and surface. This might compromise the Moon's scientific and cultural value for future generations (Bochsler, 1994; Fernandes, 2019).

Our knowledge is more limited when it comes to NEOs (NASA, 2017). Most near-Earth asteroids with diameters of 1 km or larger have been identified, but only a small fraction of the much more frequent smaller asteroids has been detected so far (Harris and D'Abramo, 2015). Identifying NEOs is important because they pose an impact hazard to Earth (Stuart and Binzel, 2004), they offer insight into the early evolution of the solar system, and some of them are abundant in water ice and other volatiles that may be used for radiation shielding, propellant, and life support consumables for space exploration (Lewis et al., 1993; Sercel, 2018). The reason for the commercial interest in asteroid water is its utility for space exploration combined with the high transportation cost of water from Earth: once asteroid mining technology has matured, extracting and transporting water from a near-Earth asteroid to a spacecraft in Earth orbit or to a space station on the Moon, e.g., will be cheaper than lifting the same amount of water from Earth to outer space (Lewis et al., 1993; Sonter, 1997; Sercel, 2018). Likewise, Hein et al. (2018) conclude that bringing back rare minerals (platinum in their example) to Earth may fail to turn out economically profitable, whereas "mining volatiles and supplying them to cis-lunar orbit seems to be economically viable without the development of mining and refining processes with very high throughput rates." Building on recent approaches to better characterize NEOs (Heinze et al., 2015; Granvik et al., 2016; NASA, 2017; Elvis et al., 2011; Sercel, 2018; Jedicke et al., 2018) therefore propose to study the size, composition, and spatial distribution of NEOs more thoroughly with dedicated telescopes. Sercel (2018) argue that their intended "Sutter survey" will "allow for identification and characterization of the most accessible and useful NEOs. At this point the use of the Sutter name becomes clear as it is anticipated that these resources will enable the

[3] The precautionary approach, which is fundamental to the concept of sustainability itself, rules out some possible actions on potentially habitable worlds when it is combined with the existing planetary protection guidelines (COSPAR, 2002). The most severe limitations apply to so-called category IV missions: landing on Mars, Europa, or Enceladus. COSPAR (2002) lists these objects as target bodies "of chemical evolution and/or origin of life interest and for which scientific opinion provides a significant chance of contamination which could compromise future investigations." As a hypothetical example, releasing terrestrial microbes into the subsurface ocean of Enceladus (for scientific reasons or to ensure life exists beyond Earth) would violate the planetary protection guidelines and the precautionary approach: Excluding the presence of endemic life in Enceladus' oceans is impossible in the foreseeable future, thus the mere possibility of contaminating an alien habitat and compromising future

(*footnote continued*)
investigations must be ruled out. In contrast, landing on the Moon or asteroids (categories I or II) underlies fewer (category II) or no (category I) restrictions from the viewpoint of planetary protection because of the "remote" chance of contamination.

equivalent of the California Gold Rush (triggered by the discovery of gold at Sutter's Mill) in space." Given the commercial interest, implications of sustainability for asteroid mining must be investigated as soon as possible. Guiding questions to tackle this problem might be: How does the consumption rate of NEOs due to asteroid mining compare to natural source and loss rates of NEOs and for how long can the proposed asteroid mining be kept up before the target population of water-rich NEOs is exhausted?[4] Might a long-term depletion of NEOs be considered acceptable or even beneficial if this demonstrably lowers the hazard of asteroid impacts on Earth? How do we ensure that the increasing satellite traffic volume, resulting from and enabled by asteroid mining, does not aggravate the orbital debris situation near Earth?

Single noteworthy statements voiced by attendees of the COSPAR assembly that may not necessarily reflect the opinion of the majority of space researchers:

a) Use Antarctica and the international waters on Earth as templates to come up with a legally binding framework on exploration and usage of the Moon and near-Earth asteroids.
b) Mining near-Earth asteroids is unlikely to substitute consumption of terrestrial resources (and thus to reduce negative ecological and social impacts of mining on Earth).
c) People need natural resources to make a living and in the long run this will include natural resources from outer space. Humanity also needs new goals, new frontiers, and most important the hope that the future will be better than the present.
d) Looking at globalization and other instances when humanity's consumption of natural resources increased, how plausible is it that adding more natural resources (from outer space) to the global economy will lead to a more sustainable development?
e) The possibility of taking action unilaterally means actions will be taken before their consequences are fully understood.
f) Outer space is not beyond the law, but it may be beyond state control. In that regard, the comparison of outer space with the Wild West is appropriate: In both cases, laws exist(ed), but they were/are difficult to enforce.
g) We (as space researchers) need guidelines to decide how to conduct research benefiting sustainable development.
h) If there are rules or guidelines or laws, they must be enforced.
i) In addition to spacefaring nations, also non-governmental organizations including scientific bodies such as COSPAR are required to identify potential problems and solutions and share this discussion with policy-makers and the wider public.
j) Irreversible changes to the outer space environment are acceptable and even ethically compulsory if they are necessary for the survival of humanity.
k) A specific rule for the Moon (potentially applies to other celestial bodies with solid surface) about acceptable changes introduced by humans: So long as we do not change the general aspect of the Moon, anthropogenic changes are acceptable. Thus, excavating some material would be acceptable because there already are many craters in the Moon, whereas painting the entire Moon pink would be unacceptable.
l) A human colony on the Moon might be an exercise in sustainability with benefits beyond the Moon: The sparseness of available resources would force the inhabitants to be very thrifty and considerate with resources and ingenious about closing the life cycles of material used.

[4] We did not discuss predictions with the attendees in detail, but we add the following estimate for the benefit of the reader: Harris and D'Abramo (2015) and Sercel (2018) estimate that there are roughly 5000 NEOs with 5–20 m diameter and a relative velocity < 3 km/s, which makes them attractive as mining targets. Assuming 20% of these NEOs to be water-rich with a water content of 10% each, Sercel (2018) then conclude: "Assuming 50% of identified water-rich targets turn out to be useful, 2500 tonnes of water could be extracted annually for at least 20 years based on the detections expected up through the end of the Sutter Extreme missions." This seems like a plausible conservative order of magnitude estimate for the supply. The demand of water in space exploration over the same 20 years is much harder to predict. For the sake of an example, 2500 tons of water per year would be sufficient for a Moon village of 70 people if their per capita water consumption were equal to the one on Earth and if the water were not used for other purposes, such as rocket propellant.

4. Conclusions and next steps

As space researchers, we need a framework to help us guide research and exploration of outer space (whether it be conducted by space agencies/nations, or companies, or individuals) in a wider scope than the very specific planetary protection guidelines. Planetary sustainability is a useful general concept but its implications on space research and exploration must be elaborated. The questions guiding this process were found from our work and the input by conference attendees: Which irreversible changes to the outer space environment are acceptable under which circumstances? Can a consensus between interested parties – researchers, governments, companies, and the wider public – be reached? And how can any guidelines or laws emerging from that consensus be implemented?

The space research community obviously must be and wants to be included in this discussion from the very beginning. To make better use of the available expert knowledge and to reach specific guidelines, we recommend to separate the outer space environment for such discussions into the three areas that are of imminent interest to space exploration: the space most relevant for satellites (low Earth orbits to geostationary orbits), the Moon, and near-Earth asteroids. These three areas are also important because, being probably sterile, their exploration does not underly strict regulation from planetary protection.

Within the scientific community, COSPAR is the obvious environment to initiate the discussion about the role of space researchers and about potential guidelines how to bring space research and exploration in agreement with planetary sustainability. COSPAR and its executive bodies have proven successful with the similar task of formulating and maintaining universally accepted guidelines for planetary protection. For aspects about planetary sustainability pertaining to policy-making and space law, an interdisciplinary dialogue with other expert bodies and interested parties (e.g., the International Institute of Space Law, the National Space Society, the Secure World Foundation, and others) is needed.

Conflicts of interest

The authors consider sustainability relevant and therefore presume that planetary sustainability is a topic worthy of investigation. No financial conflicts of interest apply.

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