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Extraterrestrial environmental impact assessments — A foreseeable prerequisite for wise decisions regarding outer space exploration, research and development

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ABSTRACT

Although existing international instruments such as the Outer Space Treaty and Moon Agreement generally express sentiments for minimizing missions' extraterrestrial environmental impacts, they tend to be limited in scope, vague and generally unenforceable. There is no formal structure for assessing how and to what extent we affect those environments, no opportunity for public participation, no uniform protocol for documenting and registering the effects of our actions and no requirement to mitigate adverse impacts or take them into consideration in the decision-making process. Except for precautions limiting forward biological contamination and issues related to Earth satellites, environmental impact analysis, when done at all, remains focused on how missions affect the Earth and near-Earth environments, not how our actions affect the Moon, Mars, Europa, comets and other potential destinations. Extraterrestrial environmental impacts are potentially counterproductive to future space exploration, exploitation and scientific investigations. Clear, consistent and effective international protocols guiding a process for assessing such impacts are warranted. While instruments such as the US National Environmental Policy Act provide legally tested and efficient regulatory models that can guide impact assessment here on Earth, statutory legal frameworks may not work as well in the international environment of outer space. A proposal for industry-driven standards and an environmental code of conduct based, in part, on best management practices are offered for consideration.

1. The need for an environmental review process for actions in outer space

In the US, the two decades following World War II witnessed significant increases in industrial, transportation and agricultural infrastructure development. These supported an expanding industrial society that helped to sustain the increasing population of the nation and world. The associated externalities of wasteful resource depletion, pollution and adverse landscape and ecosystem alteration, however, were often either largely unrecognized or ignored by related industries, the general public and federal and state governments. Public and government awareness of the adverse environmental effects of largely unregulated actions began to change significantly in the 1960s and early 1970s [[1] p. 120]. Rachel Carson's 1962 *Silent Spring* was a significant marker in a process of public recognition of the cumulative adverse impacts of pesticide pollution and the potential for unanticipated, synergistic effects [2]. In 1968, Paul Ehrlich's *Population Bomb* and Garrett Hardin's landmark paper in *Science*, "The Tragedy of the Commons," warned of the dangers of overpopulation and related exploitation of commons' resources without mitigating or otherwise compensating for pollution and physical and biological degradation of the environment [3,4]. The 1969 oil spill in Santa Barbara, California, the largest such spill to that date in the US, coupled with nationwide press reporting of Ohio's Cuyahoga River catching on fire due to petroleum pollution that same year, brought additional attention. The American public was learning of the potential environmental harm that human actions could cause; environmental degradation was becoming a significant social and political issue that affected not only then-current activities but long-range health, agricultural, industrial and infrastructure planning. The US National Environmental Policy Act of 1969 (NEPA) helped to address those concerns and many other nations have enacted similar regulations [5].

We are now rapidly entering an entirely new phase of human environmental impact that likely was not imagined when NEPA was signed into law — the exploration and exploitation of

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environments beyond Earth's atmosphere. As nations and private enterprises increasingly describe their intentions to undertake major actions on planets, moons, asteroids and even comets, it is sobering to consider that there is no comprehensive process required by the US, other states or groups of states, or the UN for assessing human impacts on those extraterrestrial environments. Rather, the focus has been on reducing forward biological contamination and the dangers and liabilities inherent in objects launched with the intent that they will return to Earth or orbit Earth, not for missions that land on other celestial bodies, such as Mars. Belgium's Law on the Activities of Launching, Flight Operation or Guidance of Space Objects is an exception that anticipates the need for consideration of extraterrestrial impacts [6]. It states at Article 2 §1, "This law covers the activities of launching, flight operations and guidance of space objects carried out by natural or legal persons in the zones placed under the jurisdiction or control of the Belgian State or using installations, personal or real property, owned by the Belgian State or which are under its jurisdiction or its control." Article 3(1) defines "space object" as "any object launched or intended to be launched, on an orbital trajectory around the Earth or to a destination beyond the earth orbit." The law requires that an environmental impact assessment be submitted prior to the launch, assessing the effects of the action on both the Earth and any celestial body affected. It is attached to the application for authorization by the Belgian Minister for Space Policy, who may add special conditions regarding extraterrestrial environments. Additional assessments may be required during and after the mission. These requirements reflect the sentiments of the Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (Moon Agreement), to which Belgium is an official party [7]. However, Belgian space law's authorization and supervision regime only applies to non-governmental entities launching from areas under the jurisdiction or control of the Belgian state, not to actions of the Belgian government itself or to launches from areas outside of Belgian jurisdiction. To date, actions approved under the law have been confined to near-Earth launch and return and satellite missions, not to any actions affecting celestial bodies or other environments beyond Earth orbit.

Article IV of the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies (the Outer Space Treaty) places limitations on the testing and use of weapons on extraterrestrial landscapes [7]. This has indirect environmental protection value in that if there are no explosions due to nuclear weaponry there will be no resulting environmental damage. But adverse impacts due to other foreseeable human actions are generally not addressed by any state or by international agreement or treaty except for Belgium as noted above [[8] p. 58]. Except for impacts in the immediate vicinity of assembly and launch facilities, downrange areas where hardware may fall and various re-entry scenarios, space activities are often falsely assumed to be benign with respect to environmental impacts [[9] p. 238]. But this conclusion has been reached only because the focus has been on Earth, not on extraterrestrial sites. For example, the US National Aeronautics and Space Administration's (NASA) 2005 *Final Programmatic Environmental Impact Statement for the Mars Exploration Program* contains detailed discussions and analyses of the Program's environmental and other effects on Earth (such as air quality near the launch pad and impact on the economies of nearby communities), but there is no mention of potential impacts to Mars [10]. Likewise, the 2006 *Final Environmental Impact Statement for the Mars Science Laboratory Mission* includes Cape Canaveral, Florida, and other locations on Earth including the troposphere and stratosphere in its consideration of impacts, but does not address the impact of the Mars rover Curiosity on Mars itself [11].

As expressed by NASA and the European Space Agency (ESA), the search for existing or extinct extraterrestrial life is a priority among their programs [12–14]. The identification of a sea of oxygen-rich water under the ice of Jupiter's moon Europa and oxygen and water ice on Saturn's Enceladus have heightened interest in exploration and exploitation there [15]. The probability of discovering past or present extraterrestrial life in our Solar System is no longer remote, and if the area is expanded to include our galaxy, it may be more a matter of when rather than if [16,17]. Forward biological contamination, defined as the intentional or unintentional introduction of Earth-origin life (mostly microorganisms and similar forms such as bacteria and spores) to any extraterrestrial venue, is of special concern. Precautions are clearly expressed in the Preamble to the Planetary Protection Policy of the Committee on Space Research [18,19]. Any such contamination may confound our search for extraterrestrial life as well as potentially disrupt the alien living systems we may be attempting to document and research. Yet standards and protocols may not be uniform and enforcement can be lax, as evidenced in the pre-launch contamination of the Mars Science Laboratory [20].

Similar to the emergence of American environmental awareness in the early 1960s, some are beginning to recognize the potential for human actions to adversely affect extraterrestrial environments. However, others either do not foresee adverse impacts as being problematic or maintain that environmental regulation would be overly restrictive and counter to the spirit and purposes of space exploitation. As the resources of the New World likely first appeared limitless to European explorers, so bountiful that the traditions of conservation and husbandry practiced at "home" seemed irrelevant, so might our Solar System seem so vast that our impacts would appear inconsequential. But we must guard against repeating in outer space our past mistakes of underestimating the cumulative, enduring and potentially synergistic environmental effects of our actions here on Earth.

2. The increasing scope of extraterrestrial actions

The crewed US Apollo 11 Mission in 1969 and the five subsequent Apollo missions that landed on the Moon through 1972 left little more than an iconic footprint, golf ball and flag in addition to several tons of miscellaneous hardware on the surface. There was no intrusive mining, surface alteration or other landscape-altering action other than the collection of surface rocks. The Moon's surface has not likely been significantly affected; debris is confined to the surface layer and locations of larger pieces have been cataloged and mapped. On Mars, as with the Moon, disturbances have been relatively minor. Missions with greater physical impact have included Deep Impact, which fired a projectile into comet Tempel 1 in 2005, blasting a crater and causing the ejection of a plume of comet components into space that provided data on its composition. But the number of such missions and the impacts they may impart to the Moon, Mars and elsewhere are increasing. If the current paucity of assessment and reporting continues, it may become unmanageable to catalog debris, landscape alteration, the location, nature and concentration of pollutants (such as lubricants, hydraulic fluids, metals and other materials with the potential to enter the environment) and other environmental impacts.

During the latter decades of the 20th century, the US and the USSR/Russia were the only entities sponsoring ambitious space programs, but the field has now grown to include other nations and private commercial enterprises. For example, the Indian Space Research Organization (ISRO) has launched 71 satellites, including high altitude geosynchronous Earth satellites and the Mars Orbiter Mission, a Mars satellite that will remotely survey the planet's surface and atmosphere, as well as test engineering systems for

future flights. ISRO is planning crewed flights within the decade and has negotiated a contract with Russia for acquiring a Soyuz spacecraft for space tourism [21,22]. A 2014 United Kingdom Ministry of Defense analysis of significant future trends reported:

> Several companies are already proposing to extract water and minerals from asteroids that travel near Earth. One of these companies, Planetary Resources, is hoping to launch its first spacecraft in 2014, with prospecting platforms operating in the next decade. By 2045, companies pursuing off-Earth resources are likely to have extensive operations, particularly if the potential revenues are as significant as suggested by some analysts [[23] p. 166].

The European Space Agency is planning to land on a comet. The People's Republic of China has already launched terrestrial and lunar satellites, placed humans in space, landed the Chang'e 3 rover on the Moon in 2013 and plans to retrieve lunar samples in 2017. They have announced their intention of placing humans on the Moon in 2024 [24]. Even if schedules for these projected missions are overly optimistic, they demonstrate a high degree of resolve. Should progress in space exploration continue, such endeavors will become routine.

To date, only launches funded by national governments have attempted to land on extraterrestrial bodies. That is changing. For example, Google, Inc. is sponsoring the Google Lunar XPRIZE, a $40-million cash award to the first predominantly private venture to place a vehicle on the Moon, travel 500 m (1640 feet) and send photographs back to Earth. To win the prize, the first of the 22 private entrants currently active in the competition must accomplish the feat by the end of 2015 [25]. SpaceX, founded in 2002, is the first private venture to both take and return supplies from the orbiting International Space Station. Space tourism is a goal for some private enterprises, such as Virgin Galactic, and many have expressed interest in exploiting the mineral resources of the Solar System, establishing extraterrestrial robotic or human presence and sponsoring data gathering, communications and other missions. Both private and state-sponsored ventures are increasingly engaged in extraterrestrial projects with potential adverse environmental impacts.

3. Foreseeable problems

Article VI of the Outer Space Treaty states that States Parties to the Treaty bear international responsibility for national activities in outer space, whether they are carried out directly by that state or by non-governmental entities associated with that state. Article VI also provides that states are responsible for assuring that the outer space activities of any non-governmental entity adhere to the provisions of the Treaty through "authorization and continuing supervision." However, the scope of such oversight and how that is to be accomplished are not detailed. To what degree are states responsible? How long does "continuing supervision" last and how is supervision to be accomplished in foreseeable futures where multinational non-governmental entities collaborate on projects that may span decades?

Article IX of the Outer Space Treaty encourages states to pursue studies of outer space, but cautions that they must avoid "the harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose." It continues that should a State have "reason to believe that an activity or experiment planned by it or its nationals in outer space… would cause potentially harmful interference with activities of other States Parties in the peaceful exploration and use of outer space, it shall undertake appropriate international consultations before proceeding with any such activity or experiment." As assessed by Sands and Peel in *Principles of International Environmental Law*, "It is evident that the approach of Article IX is directed towards the protection of human beings, rather than the protection of the environment as an end in itself" [[26] p. 300].

The Moon Agreement is more aggressive regarding provisions for extraterrestrial environmental consideration. Article 7(1) stipulates that "In exploring and using the Moon (defined within the Agreement to include other celestial bodies in the Solar System, excluding Earth), States Parties shall take measures to prevent the disruption of its environment, whether by introducing adverse changes in that environment, by its harmful contamination through the introduction of extra-environmental matter or otherwise." Article 11(5) continues by requiring that "States Parties to this Agreement hereby undertake to establish an international regime, including appropriate procedures, to govern the exploitation of the natural resources of the Moon as such exploitation is about to become feasible." More specifically, Article 11(7) states:

> The main purposes of the international regime shall include:
>
> (a) The orderly and safe development of the natural resources of the Moon;
>
> (b) The rational management of those resources;
>
> (c) The expansion of opportunities in the use of those resources;
>
> (d) An equitable sharing by all States Parties in the benefits derived from those resources, whereby the interests and needs of the developing countries, as well as the efforts of those countries which have contributed either directly or indirectly to the exploration of the Moon, shall be given special consideration.

Although several of the fifteen states that have ratified the Agreement actively participate in outer space activities, including Australia, Belgium and Mexico, the Agreement has not been ratified by any spacefaring nation [27]. But other than the clear prohibitions against claiming territory as sovereign or issues regarding nuclear weapons and militarization, there is much that remains unresolved regarding how states or private entities might relate to extraterrestrial environments.

Every problem we face today at one time did not exist, and potential problems can often be avoided entirely through early recognition. When problems do arise, they are most often efficiently mitigated early on, when more options for resolution are available and the negative effects of corrective actions are relatively small. When allowed to evolve, problems may become pervasive and intractable. Except for the relatively few locations where probes and satellites have landed or crashed on the surface of extraterrestrial bodies in our Solar System, we are entering virtually pristine natural environments unaffected by human activities. But problems associated with environmental alteration of extraterrestrial bodies and landscapes are foreseeable.

3.1. Forward biological, chemical and radioactive contamination

Any action with the potential to introduce biological, chemical or radioactive contaminants could alter pre-contact conditions. Without strict requirements for documenting incidents of such contamination, the nature of the contaminant, volume, location and other pertinent information, it will be increasingly difficult to distinguish indigenous processes and background conditions from those of Earth origin. Might some future detection of radiation indicate that the extraterrestrial body contains naturally-occurring

radioactivity, or is the signal generated by a previous experiment's radio-tagged compounds or pollution from a reactor leak? Would the discovery of an organic compound associated with living systems or processes provide evidence of extraterrestrial life, or might it be the product of bacterial contamination from a human habitat module? It may be difficult in future decades to determine the origin of such life (especially should Earth organisms mutate there) or compounds, and the validity of conclusions regarding the past or present existence of extraterrestrial life may be compromised. NASA's Dr. Christopher McKay has argued that forward biological contamination "will remain local and static and can be removed without requiring an effort vastly larger than the missions that carried the contamination. Even at the crash sites, debris from Earth extends no more than a few meters into the surface" [28]. But as the pace of space exploration quickens, the locations and nature of such sites may no longer be documented, especially should humans be present. As McKay continues, "With human exploration, sterilization is not an option. Nor is it realistic to imagine that a human base could be so carefully engineered that it would release no microorganisms into the environment." For the foreseeable future, wherever humans go, biological as well as chemical contamination will likely follow.

Contamination also has the potential to affect indigenous extraterrestrial life. The search for life is a prominent rationale for space exploration, and to alter that life, perhaps even in advance of our discovery of it, would have profound scientific as well as philosophical and ethical implications [[29] p. 291]. Potentials for all forms of contamination must be uniformly assessed, considered as part of project planning and decision-making and documented.

3.2. Altered topography and geology

Should state and private ventures establish permanent extraterrestrial habitations, it is likely that natural terrains would ultimately be modified by a range of actions similar to what we have experienced on Earth. Projects might include excavations and deep drilling, road building, installation of communication and energy-generating facilities and waste disposal. Other infrastructure, such as habitats and related structures, launch pads, observatories, storage structures and scientific and administrative facilities would be expected both on the surface as well as under. Without an environmental assessment and vetting process, it may be increasingly difficult to differentiate human from natural features. Does the presence of a ridge of rocks at the mouth of a valley indicate some ancient moraine or other geologic process, or is it the result of a mineral prospecting mission? Were rocks fractured due to geologic factors, or were they shattered as part of a research project decades earlier?

3.3. Conflicting actions

By the end of this century there may be multiple and simultaneous national and private missions working on the same extraterrestrial body. How will the actions of one affect those of another? Article IX of the Outer Space Treaty requires that where such conflicts are expected, a State Party to the Treaty shall undertake appropriate international consultations before proceeding with the activity. Should there only be two or three missions established on, for example, Mars, such coordination may be easily facilitated. However, if there are many different groups working on Mars on a variety of scientific, exploration, exploitation, tourism and other projects, the complexity of coordination of all of their actions may rapidly become problematic. For example, how might human-generated detonations affect a distant, unrelated seismic study, or how might dust created by the explosion affect machinery or an optical telescope's ability to operate with minimal atmospheric interference? Some method to ensure coordination of actions must be implemented, and a formal environmental assessment process would aid in reaching that goal. Without an assessment of expected environmental impacts, it would be impossible to accurately predict how an action may affect other state's or private venture's activities.

3.4. Data management

The nature of atmospheric, surface and subsurface temperatures, the chemical composition of atmospheres, rocks and other natural features and processes at extraterrestrial sites may all potentially be altered by our actions. If human activities proceed without first establishing environmental baselines by measuring pre-action environments, it may be extremely difficult to determine original conditions decades or centuries from now. Data would be especially critical from remote surface areas, microclimates and unique subsurface environments such as lava tubes, ice layers or pockets of liquid water.

While the environmental effects of our extraterrestrial actions may still be relatively insignificant, their cumulative impact will predictably increase with the number and scope of future missions. Current reporting protocols will likely become inefficient and accountability will predictably be harder to assign. Will data be accurate, verified and registered in a manner that allows easy access by future researchers? Would, for example, a contaminant spill be fully disclosed and duly reported if it demonstrated a technological failure that might diminish a nation's spacefaring image or disappoint stockholders in a private space venture? Would such an occurrence be publicly announced if it documented the violation of a regulation or international protocol? As Val Plumwood states in *Environmental Culture – The Ecological Crisis of Reason*, "Remoteness negates responsibility, for consumers, workers and shareholders. In rationalist commodity culture, we are actively prevented from exercising care and living in ecologically-embedded and responsible ways" [[30] p. 16]. There are certainly abundant examples here on Earth of both intentional and unintended adverse environmental effects of government and private actions being misrepresented or not reported at all. In space, where remoteness is extreme, human behavior may be no better and, perhaps, worse.

4. NEPA and Executive Order 12114

While the Outer Space Treaty disallows militarization of space, promotes cooperation among spacefaring states and discusses the hazards and liabilities of space debris, it only indirectly addresses extraterrestrial environmental impacts. During that portion of the Cold War when no human had yet stepped onto an extraterrestrial body and the only spacefaring states were the US and the USSR, environmental effects on the Moon and beyond were not the predominant concern. Accordingly, Article IX of the Treaty urges parties to avoid overt contamination and minimize effects on other states' endeavors, not to minimize environmental impacts to the planet or moon itself:

> States Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in *the environment of the Earth* resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose. If a State Party to the Treaty has reason to believe that an activity or experiment planned by it or its nationals in outer space, including the Moon and other celestial bodies, would

> cause potentially harmful interference with activities of other States Parties in the peaceful exploration and use of outer space, including the Moon and other celestial bodies, it shall undertake appropriate international consultations before proceeding with any such activity or experiment [31].

While confined to US federal actions within the nation's borders, NEPA, signed into law two years after the Outer Space Treaty, provides a more aggressive approach for addressing the issue of environmental impacts [32]. It establishes (§4321) that its purpose is to:

> Declare a national policy which will encourage productive and enjoyable harmony between man and his environment; to promote efforts which will prevent or eliminate damage to the environment and biosphere and stimulate the health and welfare of man; to enrich the understanding of the ecological systems and natural resources important to the Nation; and to establish a Council on Environmental Quality.

At §4331(a), it recognizes the "profound impact of man's activity on the interrelations of all components of the natural environment, particularly the profound influences of … industrial expansion, resource exploitation and new and expanding technological advances."

Recognizing that US federal actions beyond the domestic geographic limits of NEPA may also result in adverse environmental consequences, President Jimmy Carter signed Executive Order (EO) 12114, Environmental Effects Abroad of Major Federal Actions, in 1979 [33]. Section 1.1, Purpose and Scope, states, "This Order furthers the purpose of the National Environmental Policy Act… with respect to the environment outside the United States, its territories and possessions." Section 2.2 states as a purpose, "to provide information for use by decisionmakers, to heighten awareness of and interest in environmental concerns and, as appropriate, to facilitate environmental cooperation with foreign nations." The geographic reach of the EO is stated, in part, in Section 2.3 to include "major Federal actions significantly affecting the environment of the global commons outside the jurisdiction of any nation (e.g., the oceans or Antarctica)." Executive Orders, however, lack Legislative Branch blessing and may be ignored or reversed by succeeding Presidential administrations. Nevertheless, the fact that the various Executive Branch agencies have generally complied with EO 12114 since 1979 is a testament to its usefulness.

While those who drafted NEPA and the EO may have contemplated potential environmental effects of federal actions in space, both directives are clear in their intent that US federal decision-making must consider the environmental effects of proposed federal actions here on Earth. Given the accelerating tempo of extraterrestrial actions, recognition of the potential of our extraterrestrial activities to do lasting environmental harm to those destinations is warranted. Although the administrative processes of NEPA and the EO may not be practical in an international extraterrestrial context, the environmental spirit of both in recognizing the consequences of un-assessed adverse actions is clear. As with NEPA and the EO, proponents for extraterrestrial actions should, at a minimum, be encouraged to identify and describe anticipated environmental impacts as part of their planning process. Assessments could be considered by any licensing or permitting agency within appropriate state governments or non-governmental organizations as part of the decision-making process. The intent would not be to block or even slow the pace of space exploration and exploitation, but to acknowledge impacts, facilitate informed decision-making and, perhaps most importantly, contribute to documenting baseline natural conditions on other worlds prior to human alteration and subsequently tracking how natural systems are affected over time. Such data would become increasingly valuable in future decades and centuries.

5. Advantages of extraterrestrial impact assessments

5.1. Broader data dissemination and public participation

Proprietary data serve a purpose where patents, publications, industrial advantage and other issues related to competitive profits are significant. But at this early stage of space exploration, extraterrestrial environmental data should be available to all. Under NEPA, environmental assessments and impact statements are typically public documents, freely accessible and open to public review and comment. Russell Train, the first Chair of the President's Council on Environmental Quality created to administer NEPA, wrote:

> It is fair to say that NEPA brought the environment front and center to federal agencies…. It also opened up the federal decision making process. No longer could federal agencies say 'we know best' and make decisions without taking environmental consequences into account. Nor could they simply pick an outcome or project and deem all others unworthy of consideration. NEPA democratized decision-making. It recognized that citizens, local and state governments, Indian tribes, corporations, and other federal agencies have a stake in government actions – and often unique knowledge of hazards, consequences, and alternatives that can produce better decisions [[34] p. 3].

Similar sentiments would likely apply to formal reviews of the potential impacts of extraterrestrial actions. It would "open the decision making process" and challenge statements such as "we know best" from action proponents having vested interests in controlling decision outcomes. As Train stated, it would democratize decision-making. At present, in the US and likely elsewhere, space policy regarding exploration is dominated by those with vested financial interests [35]. This seems counter to Article I of the Outer Space Treaty, which pledges that "the exploration and use of outer space, including the Moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind."

If a review process could be crafted to require that assessments be digitally posted to an internationally accessible site (such as a web page), the condition where space exploration and exploitation are predominantly guided by Western values and philosophies would be tempered. Where the integrity of landscapes and life, whether of Earth or elsewhere, may be dramatically affected by the actions of a few, other perspectives, including indigenous belief systems, should be encouraged and considered [36].

5.2. Potential extraterrestrial life

In *The Evolution of National Wildlife Law*, Michael Bean writes, "[NEPA] may also be among the most important federal statutes for the protection of wildlife, yet it never so much as mentions the word 'wildlife'" [[37] p. 195]. The same may be true regarding impact analyses for actions on Mars, Europa or other locations holding a potential for indigenous life. Formal assessments of our actions and their impacts on extraterrestrial environments now presumed sterile will be crucial should life subsequently be discovered there. Given the predictably immense scientific and

potentially significant economic value of such a discovery, international agreement on standards for how that life might be procedurally addressed may be especially challenging. It would be far more productive to establish procedures regarding extraterrestrial environments now, prior to any discovery of life, and then amend those protocols to fit specific scientific data and economic interests at some future time should life be discovered [[29] p. 11–12].

5.3. Fostering best management practices

Best management practices (BMP) are usually industry-developed standards that help guide (in this case) construction and other activities that may adversely affect the environment. A simple example here on Earth would be to initiate effective erosion control measures, such as settlement ponds or silt curtains, when grading on a slope until natural ground cover capable of holding the soil has become reestablished. BMPs evolve to become better with each use, but that is most often best achieved when involved industries freely trade information on the efficacy of the practice, determining what techniques are most effective under local conditions. While generally encouraged by governments, BMPs are not necessarily required by governments, but are adopted by the various industries because they provide effective solutions to common environmental problems.

An extraterrestrial environmental assessment process would assist both governments and the industries involved in outer space in developing BMPs to reduce adverse impacts. Documentation of effective and ineffective practices would be shared, adding to overall efficiency.

5.4. Supporting the precautionary principle

Principle 15 of the Rio Declaration on Environment and Development (drafted in 1992 at the United Nations Conference on Environment and Development in Rio de Janeiro, Brazil, also known as the "Earth Summit") states: "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" [38]. This has come to be known as the precautionary principle. It seeks to "provide guidance in the development and application of international environmental law where there is scientific uncertainty" [[26] p. 218]. While the scope of its application in international law is debated, it is frequently referenced in the decision-making process for a range of environmental issues where scientific knowledge is limited [[39] p. 171]. It acknowledges that is what is known at the time of the decision may be limited. Pertinent to application to outer space impacts, "Briefly stated, the precautionary principle ensures that a substance or activity posing a threat to the environment is prevented from adversely affecting the environment, even if there is no conclusive scientific proof linking that particular substance or activity to environmental damage. …Its purpose is to encourage -perhaps even oblige- decisionmakers to consider the likely harmful effects of their activities on the environment before they pursue those activities" [[40] p. 2].

For impact assessments on Earth, we have centuries of experience and libraries of data to reference that would not be available when assessing the need for avoiding or mitigating environmental degradation on Mars or elsewhere in the Solar System. That would be expected to improve as our knowledge improves, as we have time to consider the efficacy of preventive and mitigating actions. Impact assessments trigger anticipatory preventive action, the core of the precautionary principle.

Deep seabed mining provides a comparable scenario to space. Relatively little is known about the environment of this international commons and its potential for exploitation. In 1982, the United Nations Convention on the Law of the Sea (UNCLOS) declared the resources of the deep ocean floor to be the "common heritage of mankind" (Article 136), comparable to the "province of all mankind" in the Outer Space Treaty (Article I) and the "heritage of all mankind" in the Moon Agreement (Article 11) [41]. While the precautionary principle is not mentioned in UNCLOS (Principle 15 was not written until 1992), it has been incorporated into subsequent deep seabed regulations. As referenced by Viikari, "pursuant to the Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area (also called the 'Mining Code'), which was adopted in 2000, 'in order to ensure effective protection for the marine environment from harmful effects which may arise from activities (on the deep seabed)', the Authority and sponsoring States shall apply a precautionary approach, as reflected in principle 15 of the Rio Declaration to such activities" [[39] p. 174].

5.5. Establishing international standards for environmental impact assessment

To be most effective, all spacefaring nations and enterprises would voluntarily participate in assessing their extraterrestrial environmental impacts prior to undertaking actions in space. A hypothetical chronology of such a process might include: (1) Impact assessments are prepared by the action proponent and submitted to an impartial international panel or board; (2) The panel determines the assessment's sufficiency; (3) The assessment is published in an electronic or other format accessible to the public followed by a comment period; (4) The action proponent addresses comments and submits responses to the panel; (5) The panel publishes its approval or concerns; (6) The action proceeds, is modified or is abandoned; and (7) should the action proceed, periodic reports of the action's progress and impacts are filed for future reference in a digital format to allow broad access. The process would support the spirit of both NEPA to "fulfill the responsibilities of each generation as trustee of the environment for succeeding generations" (42 USC §4331(b)(1)) and Article 4(1) of the Moon Agreement's directive that "due regard shall be paid to the interests of present and future generations." Given the likelihood that all states would appreciate the need for maintaining extraterrestrial environments and landscapes for both future research and exploitation, pressure from peer states and space industries may be sufficient to encourage a trend of compliance.

Such a review and approval system (perhaps similar to NEPA's relationship with the Council on Environmental Quality and its oversight function) could be attempted within the structure of the UN, such as within the UN Office of Outer Space Affairs. The spirit of an extraterrestrial environmental assessment program would be likely to fit within the mandate of the organization. However, amending the Outer Space Treaty or otherwise developing an administrative UN capacity to achieve the goals proposed in this paper would require a level of international commitment and cooperation that may be both lengthy and difficult to achieve. Spacefaring nations and international organizations are already invited to submit annual reports on their space activities and research to the UN Committee on the Peaceful Uses of Space, so a precedent for reporting exists. Presently, however, reports tend to document positive actions and research, not details of extraterrestrial environmental impacts.

Laws and treaties tend to be (1) authoritative and prescriptive, (2) binding and inflexible, (3) slow to adapt to changing conditions, (4) challenging to enforce, and (5) difficult to judge and punish when violated. Mechanisms other than regulations promulgated by

states or the UN may provide a preferable alternative. When compared with laws, self-generated industry standards and guidelines similar to those found in trade organizations and other non-governmental organizations, an international code of conduct and other forms of "soft law" have several significant advantages:

- They are relatively quick to approve. They may be drafted entirely by a single government or industry group or a consortium of interested parties with or without government oversight, intervention or approval. This helps to ensure that the standards support the overall objectives of the group and that they are practical within the economic and physical capacities of the industries themselves. They may be drafted and implemented by only one party, followed by an open invitation for others to join in adopting them. Although there is a demonstration of commitment when a government or private entity agrees to standards or a code of conduct, they are non-binding, making them far less onerous and politically threatening. Those who may not wish to commit to the standards or code of conduct are under no legal obligation to do so.
- They are highly adaptive. Work in extraterrestrial environments is characterized by novel and evolving challenges. Whereas legislative or regulatory actions are generally required to modify laws, standards can be altered quickly to address unique problems.
- They are generally enforceable through peer pressure. In those cases where a government or private group carries out actions that violate the standards and adversely affect an extraterrestrial environment to a significant degree, they could be ostracized from the spacefaring community. Where mutual support is as critical as it is in outer space, this may provide an effective deterrent. In addition, those with a history of disregarding environmental standards may be denied a state's authorization to launch, or the state may make the standards binding on the applicant prior to authorization.

Why might a for-profit venture, industry group or government agree to standards, a code of conduct or similar statement committing them to consider the environmental impact of their extraterrestrial actions? First, it is likely that most would agree that such analyses will eventually be required. It is to their advantage to participate in drafting the standards and securing a degree of control now rather than facing the uncertainty of having standards imposed without their consultation at some indefinite point in the future. Second, while there is likely a financial cost for adherence to environmental standards, many kinds of planning (e.g., engineering) are already critical to meeting mission objectives, including financial objectives. An environmental assessment is a planning document that aids in identifying potential obstacles and developing practical alternatives. It contributes to informed decision making, which ultimately serves to reduce costs and increase the potential for mission success. Third, pledging to an international code of conduct or abiding by a recognized set of environmental standards provides evidence that the action proponent intends to behave in an environmentally responsible manner. Such evidence may prove crucial in securing financial backing or receiving government or scientific assistance.

6. Conclusion

We are in the infancy of space exploration and exploitation, and missions to the Moon and beyond are still relatively few in number. Now is the time to devise and initiate mechanisms for extraterrestrial environmental assessment and monitoring. If a legislative remedy is sought, urgency is heightened due to the substantial lag between drafting regulations, especially international regulations of the type envisioned here, and their implementation through an organization such as the UN [39,42]. But as with NEPA and EO 12114, once assessments become routine, they will likely be more easily accepted and assimilated into project budgeting, planning and scheduling. One option would be for the US to lead by modifying NEPA and EO 12114 to explicitly include outer space within its regulatory jurisdiction. NEPA has been honed throughout its four decades of practice and has been applied to many types of human actions affecting the environment of the US. It has been legally tested in hundreds of court cases.

But a preferable alternative is for space industry groups themselves to take the initiative to draft standards or a code of conduct reflecting the spirit of NEPA and EO 12114, the Outer Space Treaty and the Moon Agreement. These would encourage consideration of extraterrestrial environmental impacts, monitoring and, where such impacts cannot be avoided, mitigation.

It may be claimed that the spirit of NEPA provides an inappropriate model for addressing outer space actions in that it is specific to Earth and is limited to US federal actions "significantly affecting the human environment." It is true that NEPA does not require consideration of extraterrestrial actions; it was signed only six months after the first human stepped onto the Moon. But the Solar System is now very much a part of our environment and becomes more so with each mission to Mars or other space destination. The same concerns we had in 1969, the realization that human actions can cause significant environmental degradation that limits future options, will be raised on our Moon, Mars and beyond in coming years.

Mars One is a not-for-profit, non-governmental organization that is proposing to launch a crew of humans to that planet in 2024 [43]. If they keep to their ambitious schedule, what kinds of construction are they anticipating to undertake in the years that will follow their landing? Where and how will they build? How will they handle their waste? Will they have any impact on subsurface water ice? If they travel outside of their immediate surroundings, where will they go, how will they get there and what will they do when they arrive? Will they drill wells or explore deep lava tubes? Will their community release volatiles or other compounds that have a potential to harm the environment? If there is any life on Mars, will human presence affect it? These and the many other questions that easily come to mind may have simple and straightforward answers; there may cause no significant environmental impact. But that conclusion should be based on critical analysis and should not be left to those with a vested interest in the outcome.

We should not be initiating actions that may adversely affect any environment without considering environmental impacts, their cumulative and synergistic effects and their potential to significantly constrain options for future generations. We should not wait until we are committed to living on other planets before we assess and document how we affect them.

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