IAC-18

Planetary Protection Issues of Private Endeavours in Research, Exploration, and Human Access to Space: an Environmental Economics Approach to Forward Contamination

George Profitiliotis[a]*

[a] *Unit of Environmental Science and Technology, School of Chemical Engineering, National Technical University of Athens, 9, Iroon Polytechneiou St., Zographou Campus, 15773, Athens, Greece,* gprofitiliotis@hotmail.com
* Corresponding Author

Abstract

In light of the rapidly growing New Space Economy, the landscape of space exploration and development activities will certainly become much more complicated year by year. Relevant commercial space actors have already emerged, pushing the boundaries of entrepreneurial space ventures beyond the Earth-oriented upstream and downstream market segments and opening up the path towards the novel segments of space exploration, space resources utilization, and space research. Planetary protection is usually defined as a set of guidelines concerning the avoidance of bidirectional biological material exchange between the Earth and other celestial bodies. Recent success stories of established and new-entrant NewSpace actors, although posing no realistic planetary protection threat, clearly indicate that serious work needs to be done in order for the relevant guidelines to keep up with the rapid advances of the technology development cycles that occur within NewSpace companies. This need may become even more urgent, as space entrepreneurs acquire and develop the resources and competencies to target the currently underserved market segments of space research, exploration, and utilization. As of now, these capabilities were maintained solely by public space agencies; thus, all planetary protection priorities, strategies, and responsibilities were discussed, agreed-upon, and delegated for implementation among national and international working groups of public stakeholders. Although top-down regulations can be effective in controlling the quality and conformity of the deliverables of private subcontractors to public contractors, international planetary protection frameworks might need to evolve even beyond such unmet public-private interaction and partnership models. For this reason, this study did not focus on the legal and political issues of mandating NewSpace actors to adhere to planetary protection guidelines; rather, drawing from the field of sustainable development on Earth, an environmental economics approach was followed, with the goal of viewing the relationship between planetary protection and private space exploration and development as another "tragedy of the commons" problem that must be settled accordingly. After the problem's framing, i.e. the conceptual presentation and synthesis of four extraterrestrial non-excludable goods, the initial approach of their total economic value, and the negative externalities of their exploitation, a discussion of the forward contamination mitigation costs was conducted. Drawing from the literature and using examples from both the terrestrial and aerospace sectors, a pre-emptive move was suggested: the establishment of a global industry consortium for the pre-competitive collaboration in forward contamination mitigation technologies, centered on an international planetary protection analogue program and its respective testbed facility.

Keywords: Planetary Protection, Forward Contamination, NewSpace, Environmental Economics, Pre-Competitive Collaboration

1. Introduction

In light of the rapidly growing New Space Economy, the landscape of space exploration and development activities will certainly become much more complicated year by year. Relevant commercial space actors have already emerged, pushing the boundaries of entrepreneurial space ventures beyond the Earth-oriented upstream and downstream market segments and opening up the path towards the novel segments of space exploration, space resources utilization, and space research. In the past, the space industry was almost exclusively dominated by public actors, e.g. space agencies, and their prime business contractors. Being both cost-intensive and top-down regulated, space activities mainly focused on scientific, political, and strategic goals which rendered the relevant market unsuitable for private endeavors. However, after decades of uninterrupted public investment and governmental support, the space sector grew to a point where the relevant technologies became enablers of growth for other more commercially-focused sectors. This novel view of space technology as an enabler has started to facilitate a growing wave of new business actors that wish to capture the value of various established and emergent market segments, either on Earth or in space. The term "NewSpace" reflects this rising trend of innovative private space endeavors that seek business opportunities autonomously and without being constrained exclusively by governmental pursuits [1].

Some of these new market segments that are being actively considered for commercialization are the activities concerning research, science [2], exploration, and human access to space [1]. The privatization of in-space research and science has already commenced aboard the ISS: the ScienceBox [3] and the ICE Cubes Service [4] are examples of platforms that have been recently added and are currently available on Europe's Columbus module as an end-to-end service for commercial microgravity scientific projects and experiments – similar opportunities for commercial research exist on the USA National Laboratory module as well [5]. Mainly ignited by the Google Lunar X Prize competition, four private actors are still following through their plans of commercializing the on-surface exploration of the Moon [6], while the first successful deployment of two deep-space cubesats by NASA [7] has now extended the private unmanned exploration horizon with an even farther goal: Mars. The market segment of human access to space is, perhaps, the most widely known in popular culture, thanks to a series of recent breakthroughs in reusable launchers that can enable such plans in a relatively affordable manner; these plans, apart from commercial transportation services of professional astronaut crews, include manned suborbital flights [8], tourism in low-Earth orbit [9], lunar tourism and Martian colonization [10].

The aforementioned facts mean that as space entrepreneurs acquire and develop the resources and competencies to target currently underserved market segments related to the Moon and Mars, the need to harmonize Planetary Protection guidelines with NewSpace technology development cycles may become even more urgent. Planetary Protection is defined as a set of guidelines concerning the avoidance of bidirectional biological material exchange between the Earth and other celestial bodies; the protection of the terrestrial biosphere from extraterrestrial biological material is called "backward contamination" mitigation, while the protection of extraterrestrial environments from terrestrial biological material is called "forward contamination" mitigation [11]. As of now, these capabilities were maintained solely by public space agencies; thus, all planetary protection issues were settled among national and international working groups of public stakeholders. Although top-down regulations can be effective in controlling the quality and conformity of the deliverables of private subcontractors to public contractors, international planetary protection frameworks might need to evolve even beyond such unmet public-private interaction and partnership models. This paper focuses solely on the issue of forward contamination of future private space endeavors, while the issue of backward contamination is left for an upcoming work.

2. An environmental economics approach to forward contamination

In the First Article of the "Outer Space Treaty", a treaty supported by 105 States Parties of the United Nations, the exploration and development of the Moon and other celestial bodies is considered "the province of all mankind" [12]. This almost unanimous declaration seems to link the celestial bodies with the concept of "commons", a key element of the environmental economics discipline.

The analytical scientific field of environmental economics is mainly concerned with the interplay between the human economic behavior and the quality of the natural environment [13]. In this framework, an environmental good, such as a forest or a lake, can be assigned a total economic value that includes both use values and non-use values. The use values of an environmental good can be further decomposed into: its direct use value, i.e. the value it acquires through its economic exploitation in the market; its ecological or functional value, i.e. the value it acquires through its importance as a functional element of the economy via its ecosystem services; and its option value, i.e. the value it acquires through its conservation for a possible future exploitation. On the other hand, the non-use values can be decomposed into: the existence value, i.e. the value that an environmental good acquires from an individual simply by offering them the satisfaction that it is being preserved, either per se or for the enjoyment of other individuals, regardless of any present or future personal exploitation; and the bequest value, i.e. the value that an environmental good acquires from an individual, by offering them the satisfaction that it is being preserved for the wellbeing of future generations [14].

According to the environmental economics framework [13], the quality of the natural environment is essentially a public good or common-property resource, since it is difficult to exclude an individual from enjoying its value, while the natural environment itself can be considered a "commons", i.e. a domain where a non-excludable good can be found. Specifically, according to their subtractability, i.e. the degree to which the utilization of an environmental good by an individual diminishes its availability for exploitation by others, environmental goods can be further categorized into common pool goods, with high subtractability, such as the number of harvestable fish in a fishery, and public goods, with low subtractability, such as the amount of air in a city center [15].

By adopting a system's perspective, the analytical framework of environmental economics proposes that the effects of the utilization of a non-excludable environmental good can extend beyond the individual that captures its value. This notion is described as a set of externalities; positive externalities are external benefits that extend beyond the formal market of an environmental good and its exploiter agent to other individuals, while negative externalities are the external costs, respectively. Pollution and other forms of degradation are an example of negative externalities that occur during the exploitation of an environmental good [16].

Upon close inspection, the issues of planetary protection seem to bear strong similarities to the problems that concern the field of environmental economics. Joshua Lederberg, as cited in [17], realized early on that a failure to adhere to forward contamination mitigation requirements by one nation could have deleterious impacts to the present and future astrobiological research of every other nation. The aforementioned statement clearly frames the forward contamination of celestial bodies as a negative externality of irresponsible human activity that can irreversibly pollute and contaminate their pristine state – in environmental economics this is known as a "tragedy of the commons" or "free-riders" type of problem [18]. Although this perspective captures the primary aspect of forward contamination as a negative externality exerted upon the scientific knowledge non-excludable good, by severely confounding astrobiological research with false positives [19], the scope can be expanded to include other possible human activities, in addition to in-situ science. Another perspective that is currently the object of ongoing debate in the academic circles of environmental ethics and bioethics is that of the negative externality exerted upon the extraterrestrial biodiversity non-excludable good, by endangering and disrupting possible pristine niches of microbial ecology [20]. A third aspect of this issue that has been reported in the literature and seems of critical importance to a number of NewSpace activities is that of the negative externality exerted upon the planetary resources non-excludable good, by inserting hardy terrestrial microorganisms to in-situ resources deposits, e.g. aquifers, that may hinder their future utilization through bio-fouling [21]. Finally, a fourth viewpoint to the forward contamination hazard is that of the negative externality exerted upon the future ecopoiesis non-excludable good, by inadvertently introducing terrestrial microorganisms that may interfere with future attempts of terraforming through ecological competition with other, deliberately introduced and useful, terrestrial life-forms [22].

A synthesis of these extraterrestrial non-excludable goods, which can be found in the commons of celestial bodies, from the perspective of forward contamination may offer an expanded view to the problem and may strengthen the argument that environmental economics can and should inform planetary protection policy research with additional methods and tools. All the four aforementioned aspects could, in principle, be supported quantitatively through the concept of total economic value of the environmental economics framework that was previously discussed. Specifically, the aspect of the "astrobiological scientific knowledge" non-excludable good can be approached as a subcategory of the scientific knowledge public good [23]; as such, its total economic value comprises of both its use value -in the form of positive outputs in research, innovation, and technology, such as products or services, as well as in the form of the development of human capital, and of the cultural impact of science outreach and communication- and its non-use value -in the form of basic research- [24]. The aspect of the "extraterrestrial biodiversity" non-excludable good can be approached as an approximation of the terrestrial biodiversity public good [25]; as such, its total economic value is the sum of its non-use value -both bequest and existence value- and its use value [26], especially the direct use and option value of commercially valuable genetic and biological resources, which is also the case of terrestrial biodiversity in Antarctica [27]. Furthermore, the aspect of the "planetary resources" non-excludable good could be approached as an analogy of the global resources common pool good [28]; as such, its total economic value can be captured through its use value and its non-use value; a terrestrial example of such a case are high-seas fisheries and deep sea resources, which deliver benefits to human well-being both through their utilization in the market and through their protection and preservation [29]. Finally, the aspect of the "future ecopoiesis" non-excludable good could be approached as a parallel case to the climate change mitigation for future generations public good [30]; as such, its total economic value can be disaggregated into its non-use value, primarily the bequest value of delivering a viable global climate to future generations, and its use value to a lesser extent, specifically its functional value as an enabler of other economic activities [31].

A more thorough quantitative examination of this line of thought is currently underway in an upcoming work and may prove useful to the growing body of scholarly research that systematically tries to set the foundations for a sustainable development paradigm of outer space through the utilization of terrestrial sustainability tools, such as life-cycle analysis [32] and environmental impact assessment [33].

3. The costs of forward contamination mitigation measures

In the previous section, the issue of forward contamination was framed as an environmental economics problem via a conceptual presentation and synthesis of four extraterrestrial non-excludable goods, the approach of their total economic value, and the negative externalities of their exploitation. As with terrestrial environmental issues, the mitigation of forward contamination incurs costs. On Earth, the analogy of environmental pollution abatement and control policies causes both public expenditures, e.g. via municipal waste management, and private expenditures, e.g. via adherence to best available technology-based standards, although there seems to be a growing wish to shift the share of the public/private mix of environmental expenditure towards the private sector [34]. One proposed core mechanism for this shift is the internalization of the negative externalities by the industry, which drives the demand for the quantification of the relevant external environmental costs [35]. The objective measurement of such costs on Earth is a complex issue and a very active research field in environmental economics; the quantification of the negative externalities upon other celestial bodies is not expected to be simpler either. The reason for the economic valuation of the various negative externalities is to assist in policy-making, together with the total economic value of the environmental goods that are at risk of degradation, through a cost-benefit analysis approach of multiple policy alternatives [36]. In the case of the non-excludable goods on celestial objects, especially through the prism of forward contamination, such an in-depth valuation has not been attempted in the literature yet, to the best of the author's knowledge.

As mentioned in a previous section, the rapidly expanding NewSpace economy gives rise to private actors that seek to target some market segments that were traditionally served by public space agencies. This fact, combined with the absence of a mandatory framework that can impose planetary protection requirements to private actors [37], calls for novel regulatory actions by the legal authorities of space-faring nations. Until now, these private actors were bound by technical requirements that were flowing down to them from upper-level planetary protection guidelines which were set in place by public space agencies. Although this method successfully controlled the quality and conformity of the deliverables of private subcontractors to public contractors, as space entrepreneurs acquire and develop the resources and competencies to operate autonomously, the need for planetary protection harmonization with NewSpace technology development cycles may become even more urgent. This business entry of a growing number or private actors in the research, science, exploration, and human access to space market segments is expected to showcase the relevance of the environmental economics framework that is being proposed in this work to the issues of planetary protection.

Before considering the valuation of extraterrestrial environmental goods and negative externalities and the possible mechanisms for the internalization of the latter, it should be noted here that private actors who act as subcontractors of public space agencies currently handle the costs of planetary protection as internal to their core business. It is because of the total amount of investment in planetary protection measures by public agencies to their operations and their subcontractors for the whole lifecycle of certain missions that some researchers support the idea of relaxing the requirements to cut down the stemming costs [38]. On the other hand, although calculations of planetary protection costs can vary greatly -up to one order of magnitude- and have a non-linear relationship with the total mission costs [39], some case studies have shown that these expenditures are not prohibitive and can be estimated to be around 10% of total mission cost for the Viking lander and 14% above the cost of the non-sterilized alternative option of a hypothetical Viking-level sterilized rover [40]. Because of the structured space systems engineering process, planetary protection requirements and their associated costs get split among the different subcontractors of public space agencies, while the overall expenditure is supported by public funding.

This will not hold true in the case of a commercial NewSpace mission: a private space actor would have to face the whole budget overhead. Although in the case of unmanned spacecrafts this overhead may be a small percentage of the total mission cost, the sterilization of commercial manned systems is expected to require novel methods [41] that may lead to sharp expenditure increases. Consequently, the minimization of the planetary protection costs of space missions which are internal to the core business of private space actors is expected to be a firm goal in the commercial space sector [42]. This means that a possible mechanism for the internalization of negative externalities should take into consideration both the current status of planetary protection cost structure for publicly-funded space missions -which are bound by space agencies' planetary protection policies- and the expected expenditure for commercial missions -which are not bound yet-. A useful insight to this end from terrestrial sustainability is that the prevention of environmental degradation is far more cost-efficient than its remediation [43]. A thorough examination of the current internal costs of planetary protection mitigation measures, combined with an assessment of the total economic value of extraterrestrial environmental goods and of the associated negative externalities, may offer quantitative insights on the costs and benefits of whether it is better, in financial terms, to protect celestial bodies or not, as well as on whether we should focus on prevention rather than remediation. These insights may guide the decision-making regarding the relevant policies, especially with respect to a possible internalization of the expected negative externalities.

4. Pre-competitive collaboration: a possible solution for pre-emptive cost reduction

Despite the heavy regulation of knowledge regarding space technology by some space-faring nations, planetary protection is the subject of international law and is governed by global instruments [44]. This fact proves useful to framing a possible solution for the cost reduction of forward contamination mitigation technologies. Although future government regulations and national legislation may set the upper level goals of planetary protection measures that will bind NewSpace actors, a gap still exists with respect to how these goals will be met in the most cost-efficient manner. In the previous sections, the forward contamination of celestial bodies was framed as a “tragedy of the commons” type of problem, where the inappropriate exploitation of extraterrestrial non-excludable goods by individual actors may have detrimental negative externalities to their utilization by every other actor. On Earth, one of the proposed answers to such an environmental economics problem is the self-regulation of the communities of stakeholders with the goal of the sustainable management of non-excludable resources – the other answers being formal top-down enforcement schemes and privatization plans [45]. Moreover, it has been stated in the space sustainability literature that globally agreed-upon norms of behavior [46] and international technological standardization [47] may form the basis of a possible solution. Consequently, drawing from the analogy of sharing eco-design knowledge and other good environmental practices to promote terrestrial sustainability [48], pre-competitive collaboration emerges as a promising approach that may pre-emptively protect NewSpace actors from top-down regulations that could prove more severe than necessary.

Pre-competitive collaboration refers to cooperative early-stage research and development (R&D) which, instead of focusing on the creation of marketable goods, produces data or tools, not for the sake of a single organization but for the benefit of a whole industrial sector. This model of collaboration allows competitors to share and better utilize their financial and knowledge resources, in order to overcome common problems, support enabling technologies, and set standards [49]. For this reason, pre-competitive collaboration has become a significant paradigm in various knowledge-intensive industries, such as the biotechnological and pharmaceutical [50] and the sustainable agriculture [51] industries. According to the literature [52], there are eight models of pre-competitive collaboration: open-source initiatives, with the goal of creating open-source innovation networks; industry consortia for process innovation, with the goal of developing novel technologies to improve industrial R&D workflows; discovery-enabling consortia, with the goal of discovering and disseminating novel scientific knowledge; public-private consortia for knowledge creation, with the goal of consolidating university research and preparing it to enter a future commercialization pipeline; prizes, with the goal of outsourcing solutions for internal R&D problems in exchange for cash awards; innovation incubators, with the goal of attracting external R&D talent and combining them with internal resources to develop research studies in a company; industry complementary relationships, with the goal of combining complementary existing knowledge between organizations and producing a superior synergistic product; and, finally, virtual entities, in the form of foundations established together with advocacy groups and other interested stakeholders, with the goal of streamlining complex applied research processes and supporting them across the R&D value chain, from policy formulation to product creation.

In the case of forward contamination mitigation technologies, the “industry consortium for process innovation” model seems to be the most appropriate; this type of pre-competitive collaboration has already proven useful in other sectors of the aerospace industry as well [53], especially when combined with the “public-private consortium” model, which can integrate both business organizations and academic institutions within an industry consortium [54]. It should be noted here that a similar pre-competitive collaboration model has been proposed in the past -ahead of its time- with the goal of reducing the technical and economic risks of space resources utilization through the formulation of a consortium centered on a flagship project [55]. Regarding the hereby proposed global industry consortium for forward contamination mitigation technologies, such a flagship project might take the form of an international planetary protection analogue program and its respective testbed facility, as suggested initially by Conley and Rummel [56]; the proposed flagship project could also benefit from the “International field research program in analog environments on Earth preparing for planetary exploration” program, proposed by the COSPAR Panel on Exploration [57].

A rigorous systems engineering approach should be followed for the overall design, implementation, and management of this flagship project. Although a relevant feasibility study shall be discussed in an upcoming work, some of the core elements that might assist in the minimization of the technology development costs for the mitigation of forward contamination by unmanned space systems have already been reported in the literature [47]: the harmonization of sterilization methods across the various equipment parts; the usage of a set of validated spacecraft integration procedures; the construction of a database for all the validated and qualified sterilization methods that are compatible with the various materials and equipment parts; the availability of planetary protection standards that can provide specifications and requirements early on a new system's lifecycle; the characterization and the consideration of the sterilization effects of various mission events, such as the heat during atmospheric entry; the usage of quarantine requirements -not sterilization- for orbiters; the establishment of a specialized product assurance process specifically focused on the control of organic and biological cleanliness; and, lastly, the early estimation and assessment of the total cost of a new space program, taking into account the costs of planetary protection. Thus, a future systems engineering approach to the proposed flagship project should explore the relevance and possible incorporation of the aforementioned cost minimization elements within its pre-competitive R&D strategic plan, in conjunction with the investigation of those elements that are unique to manned missions as well.

Finally, as far as the financial aspect of the proposed forward contamination mitigation analogue program is concerned, it should be noted here that this is a prevention measure. As mentioned in a previous section, the prevention of environmental degradation is usually more cost-efficient than its remediation, though this remains to be quantitatively assessed for the case of forward contamination. Following the paradigm of funding environmental pollution abatement and control, this flagship project could be financed via a public/private expenditures scheme as well. To gauge the contribution of public funding to this mix, a valuation of the total economic value of the aforementioned extraterrestrial non-excludable goods may be utilized. Respectively, to gauge the contribution of private capital, a valuation of the negative externalities upon celestial bodies, in light of forward contamination, may be used, in conjunction with an internalization mechanism of these costs, since this trend of privatization of environmental expenditures is also growing in the field of terrestrial sustainability policies. However, although private space actors already handle some of the planetary protection costs as internal to their core business, an internalization of the negative externalities through a pre-competitive collaborative funding of a shared forward contamination mitigation analogue program may assist in a reduction of the internalized costs, by splitting them across a global industry consortium. Setting aside functional business strategies, such as corporate social responsibility and sustainability, that may use such a flagship project for positive branding purposes, it seems that NewSpace companies could be significantly benefitted from such an initiative even from a strictly financial point of view.

5. Conclusions

As space entrepreneurs acquire and develop the resources and competencies to target the currently underserved market segments of space research, exploration, and utilization, the need to harmonize planetary protection policies with the rapid technology development cycles will become even more urgent. In this work, the issue of forward contamination that may occur through the exploration, utilization, and human access to space was framed as an environmental economics problem, via a conceptual presentation and synthesis of four extraterrestrial non-excludable goods, the initial approach of their total economic value, and the negative externalities of their exploitation. Since the mitigation of forward contamination incurs costs, a possibly cost-efficient solution to this problem was proposed, taking into account the rising trend of shifting the public/private terrestrial environmental protection expenditures scheme towards the privatization end. Drawing from the literature and using examples from both the terrestrial and aerospace sectors, a pre-emptive move was suggested: the establishment of a global industry consortium for the pre-competitive collaboration in forward contamination mitigation technologies, centered on an international planetary protection analogue program and its respective testbed facility. With the use of environmental economics tools for the valuation of extraterrestrial non-excludable goods and the negative externalities of their exploitation, the probable financial contribution of both the public and the private sectors to this end could be gauged, in order to inform an upcoming feasibility study. Fortunately, planetary protection is already a subject of international law. The first steps towards the sustainable expansion of the human civilization have been taken; only international cooperation among public and private actors will ensure a gentle passage into the realm of the final frontier.

References

[1] A. Vernile, The Rise of Private Actors in the Space Sector, Vienna, Austria: European Space Policy Institute, 2018.

[2] A. González, "A Snapshot of Commercial Space: an EU Fellowship Report," Center for Science and Technology Policy Research, Boulder, CO, USA, 2017.

[3] Airbus Defence and Space GmbH, "MY EXPERIMENT IN SPACE," [Online]. Available: http://www.my-experiment-in.space/#platform. [Accessed 20 / 5 / 2018].

[4] Space Applications Services NV/SA, "ICE CUBES," [Online]. Available: http://www.icecubesservice.com/#whats-is. [Accessed 20 / 5 / 2018].

[5] ISS U.S. National Laboratory, "SPACE STATION RESEARCH," [Online]. Available: http://www.spacestationresearch.com/. [Accessed 20 / 5 / 2018].

[6] Space.com, "Moon Rush: These Companies Have Big Plans for Lunar Exploration," [Online]. Available: https://www.space.com/39398-moon-rush-private-lunar-landings-future.html. [Accessed 20 / 5 / 2018].

[7] NASA/JPL, "JPL | CubeSat: Mars Cube One (MarCO)," [Online]. Available: https://www.jpl.nasa.gov/cubesat/missions/marco.php. [Accessed 20 / 5 / 2018].

[8] Space.com, "Blue Origin Launches New Shepard Space Capsule on Highest Test Flight Yet," [Online]. Available: https://www.space.com/40439-blue-origin-launches-new-shepard-2018-test-flight.html. [Accessed 20 / 5 / 2018].

[9] Forbes.com, "Mankind's First Space Hotel Is Coming In 2021 - Probably," [Online]. Available: https://www.forbes.com/sites/duncanmadden/2018/03/09/mankinds-first-space-hotel-is-coming-in-2021-probably/. [Accessed 20 / 5 / 2018].

[10] TheGuardian.com, "SpaceX to send two people around the moon who paid for a 2018 private mission," [Online]. Available: https://www.theguardian.com/science/2017/feb/27/spacex-moon-private-mission-2018-elon-musk. [Accessed 20 / 5 / 2018].

[11] A. Frick, R. Mogul, P. Stabekis, C. A. Conley and P. Ehrenfreund, "Overview of current capabilities and research and technology developments for planetary protection," Advances in Space Research, vol. 54, no. 2, pp. 221-240, 2014.

[12] UNODA - United Nations Office for Disarmament Affairs, "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies," [Online]. Available: http://disarmament.un.org/treaties/t/outer_space. [Accessed 21 / 5 / 2018].

[13] B. C. Field and M. K. Field, Environmental Economics: an Introduction, 7th ed., Dubuque, IA, USA: McGraw-Hill Education, 2017.

[14] E. Plottu and B. Plottu, "The concept of Total Economic Value of environment: A reconsideration within a hierarchical rationality," Ecological Economics, vol. 61, pp. 52-61, 2007.

[15] S. J. Buck, The Global Commons: an Introduction, 1st ed., Washington, DC, USA: Island Press, 1998.

[16] J. van den Bergh, "Externality or sustainability economics?," Ecological Economics, vol. 69, pp. 2047-2052, 2010.

[17] M. Meltzer, When biospheres collide: a history of NASA's planetary protection programs, Washington, DC, USA: NASA, 2011.

[18] L. Viikari, "Environmental Impact Assessment and space activities," Advances in Space Research, vol. 34, pp. 2363-2367, 2004.

[19] D. P. Glavin, J. P. Dworkin, M. Lupisella, G. Kminek and J. D. Rummel, "Biological contamination studies of lunar landing sites: implications for future planetary protection and life detection on the Moon and Mars," International Journal of Astrobiology, vol. 3, no. 3, pp. 265-271, 2004.

[20] W. R. Kramer, "Colonizing mars—An opportunity for reconsidering bioethical standards and obligations to future generations," Futures, vol. 43, no. 5, pp. 545-551, 2011.

[21] J. D. Rummel, "Planetary protection for human missions: Options and implications," in Aerospace Conference, 2016 IEEE. 5-12 March 2016 , Big Sky, MT, USA, 2016 .

[22] C. P. McKay, "The search on Mars for a second genesis of life in the solar system and the need for biologically reversible exploration," Biological Theory, vol. 13, no. 2, pp. 103-110, 2018.

[23] D. Dalrymple, "Scientific knowledge as a global public good: Contributions to innovation and the economy," in The role of scientific and technical data and information in the public domain: proceedings of a symposium, J. M. Esanu and P. F. Uhlir, Eds., Washington DC, USA, National Academies Press, 2003, pp. 35-49.

[24] M. Florio and F. Giffoni, "Willingness-to-Pay for Science as a Public Good: A Contingent Valuation Experiment," Departmental Working Papers, Department of Economics, Management and Quantitative Methods at Università degli Studi di Milano, Milano, 2017.

[25] H. Doremus, "A policy portfolio approach to biodiversity protection on private lands," Environmental Science & Policy, vol. 6, pp. 217-232, 2003.

[26] N. Beaumont, M. Austen, S. Mangi and M. Townsend, "Economic valuation for the conservation of marine biodiversity," Marine Pollution Bulletin, vol. 56, no. 3, pp. 386-396, 2008.

[27] B. P. Herber, "Bioprospecting in Antarctica: The search for a policy regime," Polar Record, vol. 42, no. 2, pp. 139-146, 2006.

[28] E. Louka, "Chapter 2. Foundations of International Environmental Law," in International Environmental Law: fairness, effectiveness, and world order, New York, NY, USA, Cambridge University Press, 2006, pp. 59-113.

[29] M. V. Folkersen, C. M. Fleming and S. Hasan, "The economic value of the deep sea: A systematic review and meta-analysis," Marine Policy, vol. 94, pp. 71-80, 2018.

[30] R. Uehleke and B. Sturm, "The Influence of Collective Action on the Demand for Voluntary Climate Change Mitigation in Hypothetical and Real Situations," Environmental and Resource Economics, vol. 67, no. 3, pp. 429-454, 2017.

[31] R. Brouwe, L. Brander and P. Van Beukering, "“A convenient truth”: air travel passengers’ willingness to pay to offset their CO2 emissions," Climatic Change, vol. 90, no. 3, pp. 299-313, 2008.

[32] M. De Santis, G. Urbano, G. A. Blengini, R. Zah, S. Gmuender and A. Ciroth, "Environmental impact assessment of space sector: LCA results and applied methodology," in Proceedings of 4th CEAS conference in Linköping, 16-19 September 2013 , Linköping, Sweden, 2013.

[33] W. R. Kramer, "In dreams begin responsibilities – environmental impact assessment and outer space development," Environmental Practice , vol. 19, no. 3, pp. 128-138 , 2017.

[34] D. Pearce and C. Palmer, "Public and private spending for environmental protection: a cross-country policy analysis," Fiscal studies, vol. 22, no. 4, pp. 403-456, 2001.

[35] G. Long, W. Lei, C. Sijie and W. Bo, "Research on Internalization of environmental costs of Economics," IERI Procedia, vol. 2, pp. 460-466, 2012.

[36] T. Eshet, O. Ayalon and M. Shechter, "An inclusive comparative review of valuation methods for assessing environmental goods and externalities," Int. J. Business Environment, vol. 1, no. 2, pp. 190-210, 2006.

[37] D. A. Porras, "Astro-propriation: Investment Protections for and from Space Mining Operations," in Space India 2.0: Commerce, Policy, Security and Governance Perspectives, R. P. Rajagopalan and N. Prasad, Eds., New Delhi, India, Observer Research Foundation, 2017, pp. 311-334.

[38] A. G. Fairén and D. Schulze-Makuch, "The overprotection of Mars," Nature Geoscience, vol. 6, no. 7, p. 510, 2013.

[39] C. A. Conley and J. D. Rummel, "Appropriate protection of Mars," Nature Geoscience, vol. 6, no. 8, pp. 587-588, 2013.

[40] J. D. Rummel and C. A. Conley, "Four fallacies and an oversight: searching for martian life," Astrobiology, vol. 17, no. 10, pp. 971-974, 2017.

[41] C. A. Conley and J. D. Rummel, "Planetary protection for human exploration of Mars," Acta Astronautica, vol. 66, pp. 792-797, 2010.

[42] C. J. Newman, "The new space ethics: COSPAR, Planetary Protection and beyond," [Online]. Available: https://room.eu.com/article/The_new_space_ethics_COSPAR_Planetary_Protection_and_beyond_. [Accessed 2 / 6 / 2018].

[43] J. Rabinovitch, "Global, regional and local perspectives towards sustainable urban and rural development," in Environmental Strategies for Sustainable development in Urban Areas: Lessons from Africa and Latin America, Aldershot, England, Ashgate, 1998, pp. 16-44.

[44] R. S. Jakhu and J. N. Pelton, "Space Environmental Issues," in Global Space Governance: An International Study, 1st ed., Cham, Switzerland, Springer, 2017, pp. 435-477.

[45] S. F. Pires and W. D. Moreto, "Preventing wildlife crimes: Solutions that can overcome the ‘Tragedy of the Commons’," European Journal on Criminal Policy and Research, vol. 17, no. 2, pp. 101-123, 2011.

[46] L. Delgado-Lopez, "Beyond the Moon Agreement: Norms of responsible behavior for private sector activities on the Moon and celestial bodies," Space Policy, vol. 33, pp. 1-3, 2015.

[47] A. Debus, "Planetary protection: Elements for cost minimization," Acta Astronautica, vol. 59, pp. 1093-1100, 2006.

[48] H. Griese, L. Stobbe, H. Reichl and A. Stevels, "Eco-design and beyond - key requirements for a global sustainable development," in International Conference on Asian Green Electronics, 15-18 March 2005, Shanghai, China, China, 2005.

[49] J. L. Contreras and L. S. Vertinsky, "Pre-Competition," North Carolina Law Review, vol. 95, no. 1, pp. 67-132, 2016.

[50] J. Altshuler, E. Balogh, A. Barker, S. Eck, S. Friend, G. Ginsburg, R. Herbst, S. Nass, C. Streeter and J. Wagner, "Opening up to precompetitive collaboration," Science Translational Medicine, vol. 2, no. 52, pp. 1-4, 2010.

[51] V. Nelson and D. Phillips, "Sector, Landscape or Rural Transformations? Exploring the Limits and Potential of Agricultural Sustainability Initiatives through a Cocoa Case Study," Business Strategy and the Environment, vol. 27, no. 2, pp. 252-262, 2018.

[52] F. Fernandez, E. Vasconcellos, L. Guedes, R. Carlana and V. Da Matta, "Long-Term R&D-Based Consortia: Paths to Integrate Basic Research with Company Strategy," in 25th International Association for Management of Technology Conference, 15-19 May 2016, Orlando, Florida, 2016.

[53] L. T. Seng, R. Thampuran and Y. K. Chuan, "Partnering Multinational Corporations in R&D," in The Singapore Research Story, C. C. Hang, R. Thampuran and L. T. Seng, Eds., Singapore, World Scientific Publishing, 2016, pp. 165-187.

[54] F. Armellini, P. C. Kaminski and C. Beaudry, "Consortium for research and innovation in aerospace in Quebec, Canada–a reference model for the Brazilian aerospace industry," Product:

Management & Development, vol. 9, no. 2, pp. 101-109, 2011.
[55] W. W. Mendell, "A strategy for investment in space resource utilization," Acta Astronautica, vol. 26, no. 1, pp. 3-10, 1992.
[56] C. A. Conley and J. D. Rummel, "Planetary protection for humans in space: Mars and the Moon," Acta Astronautica, vol. 63, pp. 1025-1030, 2008.
[57] P. Ehrenfreund and C. P. McKay, "Activities of the COSPAR Panel on Exploration supporting the Global Exploration Roadmap," Space Policy, vol. 30, no. 3, pp. 170-173, 2014. [1] J. van der Geer, J.A.J. Hanraads, R.A. Lupton, The art of writing a scientific article, J. Sci. Commun. 163 (2010) 51–59.