Conceptualizing Space Environmental Sustainability

Weiwei Mo[1,*], Brad Kinsey[2], John Vickers[3], Henry Helvajian[4], Ioana Cozmuta[5], Marissa Herron[6], Ajay Malshe[7]

[1]Department of Civil and Environmental Engineering, University of New Hampshire

[2]Department of Mechanical Engineering, University of New Hampshire

[3]Marshall Space Flight Center, National Aeronautics and Space Administration

[4]Physical Sciences Laboratories, The Aerospace Corporation

[5]G-Space Inc; IAA Member Elect

[6]National Aeronautics and Space Administration

[7]Department of Mechanical Engineering, Purdue University

[*]Corresponding Author: 35 Colovos Road, 130B Gregg Hall, Durham, New Hampshire 03824, Ph: +1-603-862-2808, Email: weiwei.mo@unh.edu

Abstract - Recent advancements have significantly enhanced the capabilities for in-space servicing, assembly, and manufacturing (ISAM), to develop infrastructure in orbit and on the surface of celestial bodies. This progress is a departure from the traditional sustainability paradigm focused solely on Earth, highlighting the urgent need to define and operationalize the concept of "space sustainability" along with the development of an evaluation framework. The expansion of human activity into space, particularly in low-earth orbit, cis-lunar space, and beyond, underscores the critical importance of considering sustainability implications. Leveraging space resources offers economic growth and sustainable development opportunities, while reducing pressure on Earth's ecosystems. This paradigm shift requires responsible and ethical utilization of space resources. A space sustainability assessment framework is essential for guiding ISAM capabilities, operations, missions, standards, and policies. This paper introduces an initial framework encompassing 1) pollution, 2) resource depletion, 3) landscape alteration, and 4) space environmental justice, with potential metrics (resources use and emissions, midpoint, and endpoint indicators) to measure impacts in the four domains.

1. Introduction

Recently, significant strides have been taken to advance the capabilities for in-space servicing, assembly, and manufacturing (ISAM), with the goal of developing infrastructure on-orbit and on the surface of celestial bodies. “Servicing” in ISAM encompasses activities such as repair, refueling, relocation, and retrofitting of space assets (e.g., spacecraft and satellites), while “assembly and manufacturing” refers to the ability to produce and assemble components directly in space.[1] This progress has transcended the conventional sustainability paradigm focused on Earth and has underscored the imperative to conceptualize and articulate the notion of "space sustainability" as well as its assessment framework. In recent years, space sustainability has garnered growing public attention primarily driven by the heightened risks posed by space debris and the increasing number of launches enabled by reusable rocket technology. Several noteworthy recent initiatives include the United Nations adopting the Guidelines for the Long-term Sustainability of Outer Space Activities in 2019,[2] the ongoing signing of the Artemis Accords, emphasizing responsible space use since 2020,[3] and the establishment of the ISO 24113 standard in 2023, concentrating on space debris mitigation.[4] While the majority of the current discussions on space sustainability are centered around Earth orbit, which is the primary locus of space activities, a few recent efforts have sought to establish a more comprehensive and universally applicable definition of "space sustainability."[5], including the notable effort made by the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) which defined space sustainability similarly to the 1987 Brundtland definition of sustainable development in the Earth context.[6] The existing definitions of space sustainability lack a clear framework that would facilitate the assessment and comparison of ISAM technological or policy alternatives, as well as the identification of “hotspots” for improvement. In this paper, space sustainability is defined as responsibly managing space activities within the limits of the space environment to ensure long-term viability and benefit for present and future generations. Previous work that attempts to quantitatively assess space sustainability has been typically focused on the safety, longevity, or efficiency of space operations and/or the impact of space activities on the Earth environment, taking an Earth-centric view.[7,8] There is a pressing need to develop an assessment framework that can systematically evaluate ISAM initiatives, pinpoint areas for enhancement, and support informed decision-making in the realm of space sustainability. This framework should adopt a space-centric view, recognizing the space environment as an extension of Earth's boundaries while still treating space and all celestial bodies as individual planetary/environmental systems. It should address the best practices for stewarding the space environment in light of the rapid development of space accessibility and ISAM capabilities. Space infrastructure development and technological innovations in space must be approached with a deep understanding of their long-term impacts on the space and Earth environments, human societies, and ethical considerations.

2. The intertwined nature of Earth and space sustainability

The advancement of ISAM is poised to transform human interaction with space, intensifying the interconnectedness of Earth and space sustainability. From a space exploration perspective, ISAM enables the equivalent of strategically positioned "supply stations" along the cosmic trail, enabling space explorers to replenish resources along their journey. Space-based infrastructure, such as satellites, space stations, and future colonization efforts, can have significant sustainability implications: space debris management, resource utilization, energy consumption, and the preservation of celestial bodies, to name a few. Although ongoing discussions regarding ISAM predominantly revolve around its immediate "in space, for space" applications, the overarching trajectory envisions a broader perspective - "in space, for Earth" - as its long-term objective. The resources available in space offer vast potential for economic growth and sustainable development by providing access to resources needed on Earth, including vacuum, space solar power, raw materials, such as helium and lunar regolith, and even meteorites made of ice and lithium, or asteroids with platinum. Most materials present on Earth can also be found, refined, or produced in space. By strategically and carefully accessing and leveraging these resources on Earth or in space, we can reduce the pressure on Earth's limited and delicate ecosystems while ultimately advancing technological innovation and economic prosperity.

The impact of ISAM on Earth and space sustainability varies depending on its developmental stage. In the initial stages, substantial Earth resources may be essential for the development and testing of ISAM technologies. With the advancement of ISAM capabilities, an increasing variety and volume of products can be directly manufactured in space, allowing for the gradual reduction of corresponding terrestrial production. The full realization of ISAM's potential to contribute to Earth sustainability is likely to be attained in the later stages of its development. In this progression, the impact of ISAM on the space environment is anticipated to intensify and broaden.

Safeguarding space sustainability along the trajectory of ISAM development is equally important in order to ensure Earth sustainability. Presently, human influence on the space environment is mainly confined to Earth's orbits. The neglect of space sustainability in Earth's orbits has led to the growth of a pressing problem exemplified by the hazardous accumulation of space debris. This problem, allowed to escalate unchecked, has now become a significant threat to present and future space activities. The mainstream approach to addressing this threat typically involves deorbiting and burning space debris to eliminate it. However, it is crucial to recognize that many objects labeled as space debris are valuable assets with a high price tag. Instead of viewing them solely as a threat, these objects represent an opportunity to be used as raw material feedstock in orbit. Had a space sustainability framework been in place earlier, these considerations would have been addressed in a more holistic and pragmatic manner, potentially mitigating the risks associated with space debris, while also maximizing the utilization of valuable resources already transported into space at a considerable cost. Such a framework would have enabled a proactive and sustainable approach to managing space resources and activities, ensuring the long-term viability and safety of space exploration and utilization.

Numerous instances highlight the interconnectedness between space and Earth sustainability. For instance, metal aerosols generated during the reentry of space debris have been detected in the Earth's stratosphere, prompting concerns about their potential impact on climate change and stratospheric ozone depletion.[9] Likewise, unsustainable practices in utilizing resources in-orbit or on the surface of celestial bodies could hinder future exploration efforts and necessitate the allocation of additional Earth resources for mitigation purposes. These examples underscore the symbiotic relationship between space and Earth sustainability. Safeguarding space sustainability is integral to ensuring Earth sustainability, emphasizing the need for responsible management of human activities to maintain a sustainable balance and maximize the utilization of space resources for the benefit of future generations.

3. Conceptualizing a space sustainability assessment framework

Three pillars underlie the traditional framework of sustainability on Earth: environmental, economic, and social sustainability.[10] In the context of space sustainability, our focus will primarily be on the environmental aspect, with no consideration for the potential impacts on extraterrestrial life due to our current lack of knowledge and uncertainty in this domain. To conceptualize the principles of "space environmental sustainability", it is beneficial to draw upon methodologies developed for terrestrial systems, like industrial ecology. Adopting a life cycle perspective to evaluate the impacts of space activities or systems from their inception to decommissioning becomes pivotal, enabling a comprehensive and equitable comparison of various alternatives.

Following this, we explore the aspects related to four specific dimensions of space environmental sustainability, alongside the potential assessment indicators that can guide data collection and analyses within these areas: 1) pollution, 2) resource depletion, 3) landscape alteration, and 4) space environmental justice. Apart from space environmental justice, these domains were identified and synthesized based on a comprehensive review of existing life cycle impact assessment methods designed for terrestrial systems (e.g., ReCiPe, TRACI, IMPACT World, CML-IA, EPD, EPS, and Ecological Scarcity). On Earth, impacts are typically first quantified through raw resource uses and emissions, which are then aggregated into midpoint and endpoint indicators. Midpoint indicators focus on specific environmental issues, such as climate change or ozone depletion, while endpoint indicators reveal the broader environmental impact on human health, biodiversity, and resource scarcity. Given the currently limited knowledge of specific space environmental concerns and damage pathways, this paper primarily focuses on raw consumptions/emissions and midpoint indicators. Space environmental justice, on the other hand, is often placed within the social domain, despite its close connection to environmental sustainability. We regard space environmental justice as a vital dimension of space environmental sustainability, as it serves as one of the guiding principles in humanity's interactions with the space environment to ensure fairness and equity in space activities. Figure 1 below illustrates the four discussed space sustainability domains in relation to the Earth sustainability assessment framework. Sections 3.1 to 3.4 delve into a thorough examination of the four domains, adopting a framework that extends Earth-defined domains to space. This includes determining what definitions from Earth's context are applicable to space sustainability given the stark differences in environment and ecosystem support services, identifying existing examination methods, and proposing indicators for assessment.

3.1 Pollution.

Pollution on Earth is broadly defined as the introduction of harmful materials into the environment.[11] Two question arise: (1) Should this definition be adopted as is for the space sustainability framework and (2) Is it acceptable to pollute the space environment? Some may contend that if no life exists on a celestial body, it is permissible to pollute. Contrary to this perspective, we argue that it is imperative to protect the space environment from pollution for future exploration, utilization, and habitation by humans, regardless of the existence of celestial life. Space debris serves as a compelling example, illustrating that actions taken without due consideration and proactive management of consequences can result in significant challenges for future space use and exploration. Similarly, dust generated during moon landings or launches can suspend in the air for an extended period without settling, creating obstacles for future landings and launches, as well as the increased damage potential on electronic devices exposed to the dust. During the Apollo missions, lunar dust disturbed during surface operations challenged the lifetime of hardware.[12,13] Hazardous materials or wastes left in space (e.g., ignitable, corrosive, toxic, reactive, or radioactive substances) may come into contact with humans in exposed celestial environments or within manmade celestial facilities, and harm other operations in the vicinity. A more futuristic concern lies in the possibility of introducing life forms from Earth to a specific celestial body, leading to potential ecological challenges in space.

Pollution in space can be evaluated by examining emissions or waste generated throughout the life cycle of a space activity or system. Specific indicators may include a pollutant's mass, volume, size, shape, concentration, and duration of presence, among others. It is important to note that each parameter's significance depends on its impact on space activities and assets. For instance, there are far more debris particles between one and ten centimeters in size currently, posing a far greater risk of collisions that may lead to damages in working satellites and the creation of new debris particles.[14] Emissions on Earth are typically categorized into air, water, and soil emissions based on the receiving medium of pollutants. Each type of emissions also signifies specific exposure pathways for humans and other life forms, such as inhalation, ingestion, and skin contact. The classification framework may still apply on celestial bodies, albeit with variations due to the unique characteristics of each celestial body. For instance, water may not exist on the majority of the lunar surface, and lunar air and soil can differ significantly from their Earth counterparts. It should also be noted that due to the drastic environmental changes on many celestial bodies, it is likely a pollutant can quickly switch between phases (e.g., a contaminant may switch back and forth across gas, liquid, and solid states under dramatic temperature changes) and pose unexpected threats beyond our current understanding of the same contaminant’s fate and transport on Earth. Orbital debris, on the other hand, may not easily fit into any of these categories. Debris is typically solid, but their suspended nature mimics air pollution on Earth. Given the uniqueness of the orbital environment, it is worthwhile to consider adopting a four-category system, where anthropogenic air, water, solid, and orbital emissions are studied in parallel.

3.2 Resource depletion

Earth's resources are finite, with many metals and minerals anticipated to be depleted within the next 150 years. Space offers a promising reservoir to replenish or supplement Earth's dwindling nonrenewable resources. The question under consideration pertains to whether it is appropriate to regard space as an "unlimited" reservoir of materials and energy. We posit that adopting a perspective that views space as a limited resource is a more prudent approach than considering it without bounds. Firstly, our current capability to access remote celestial bodies is constrained. The distances involved necessitate advanced propulsion systems, precise navigation, and durable life support systems. The financial, technological, and logistical challenges for space travel are still substantial, limiting the frequency and scope of human missions beyond Earth's immediate vicinity. Secondly, although the current number of celestial bodies appears limitless, this perception may evolve with economic development and technological progress, much like the paradigm shift witnessed during the Earth’s industrial revolution. Earth's resources were once deemed inexhaustible until human development and demand proved otherwise. Hence, adopting a perspective that views space resources as finite and exercising prudent stewardship is advisable when utilizing these resources for human development. For instance, water is exceedingly scarce in the space environment. Initial indications suggest the possible presence of limited water at the lunar pole.[15] Recognizing the critical role of water in enabling ISAM, careful consideration becomes crucial when determining the utilization of lunar water for these activities and the extent of such usage. Lunar regolith is another resource considered for ISAM. Though seemingly abundant, it is important to apply a limited resource framework in its exploitation, as well as to identify and respect limits to its usage, especially with the growing interests on lunar mining (e.g., mining helium-3 as fusion reactor feedstock).[16,17] Last but not least, it is essential to give careful consideration to the potential constraints of Earth's capacity to accommodate extraterrestrial materials, ensuring that their introduction does not adversely impact Earth environment.

Resource depletion can be assessed using indicators such as raw material and energy used from various celestial sources. Furthermore, the resource criticality concept can be employed, which assesses the importance of a particular resource concerning its demand/use and its availability to humans, as well as the potential impact a particular resource may have on various societal functions.

3.3 Landscape alteration

Human exploration and settlement in space are likely to result in some degree of landscape alteration on celestial bodies. We contend that it is crucial to exercise careful consideration and planning to minimize the potential impacts associated with such alterations. Early societies could not have foreseen that landscape alteration on Earth would evolve into an environmental issue, particularly with the explosive development of infrastructure systems. For instance, pavements change land permeability, contributing to significant challenges in stormwater management.

Roads can disrupt the connectivity of natural habitats and rivers, resulting in biodiversity losses. While the extent of current anthropogenic landscape alteration in space is relatively minimal, it is acknowledged that Apollo missions have left waste on the lunar surface. We argue that preserving the celestial body's landscape aligns with the principles of responsible space exploration and sustainability, regardless of the presence of identified living organisms. It also enables future studies of a celestial body's geological history, impact events, and other processes without human interference. While a certain degree of celestial landscape alteration might be inevitable due to the necessity of surface exploration and resource extraction, striking a balance between exploration objectives, economic development, scientific goals, and environmental protection becomes crucial.[18]

Landscape alteration can be measured based on the footprint of human facilities, infrastructure, or other land use changes on a celestial body. Beyond the footprint, the shape and the extent of the alterations may also influence the level of space environmental impact.

3.4 Space environmental justice

Space environmental justice has become and will continue to be a critical issue in the realm of ISAM. On Earth, environmental justice typically revolves around the fair distribution of environmental benefits and burdens across society, with a particular consideration of traditionally marginalized and vulnerable groups. Similar to environmental justice issues on Earth, the most developed and affluent groups often gain early access to and ownership of space resources. The prevailing "first come, first served" approach, already adopted in various cases, such as the use of Earth orbits and the allocation of radio frequency for space communication, may disadvantage less developed nations and widen the gap between developed and developing countries. This approach could also lead to hasty exploitation of space resources without adequate consideration for broader environmental consequences. Additionally, the environmental burdens resulting from space activities may disproportionately affect disadvantaged groups, e.g., based on the location of launch sites, or less developed countries. Therefore, it is crucial to develop approaches that promote fair access to space resources while minimizing both space and Earth environmental burdens on marginalized or less developed groups. This will contribute to a more equitable and sustainable approach to space exploration and utilization. Furthermore, the use and ethics of technology in space raises complex questions. Technologies developed for space exploration and utilization, such as artificial intelligence (AI) and robotics, and advanced materials, not only offer tremendous opportunities but also pose ethical challenges. Issues such as data privacy, autonomy of AI systems, robots replacing human workers, and the potential militarization of space need careful consideration and regulation.

Space environmental justice can be measured from two main perspectives: distributive and procedural. Distributive justice refers to the fair and equitable distribution of space resources, opportunities, rights, and benefits in a global context, while procedural justice focuses on the fairness and impartiality of the processes and procedures used to make decisions and allocate space resources or benefits. Due to the inherently human-centric nature of this field, the assessment of distributive and procedural justice should initially adopt an Earth-centric perspective. Delving into the discourse on justice for potential future human “inhabitants” of celestial bodies is beyond the scope of this paper. Distributive justice can be quantified based on how diverse populations benefit from the progress of ISAM and how environmental burdens created by ISAM are distributed across populations. Quantifying distributive justice may entail measuring the extent of jobs, income, and educational opportunities generated by ISAM for various populations on Earth. Additionally, it involves evaluating how ISAM's environmental impacts on Earth (and space, depending on the group's accessibility to space environments) are distributed among different countries and social groups. The procedural justice, on the other hand, can be measured based on indicators, such as 1) the representation and participation of diverse groups in ISAM development and implementation, 2) the presence of guidelines, policies, and initiatives that promote ethical space exploration and commercial activities, 3) diversity and inclusivity in space endeavors, 4) the level of exchange of scientific knowledge and technological advancements, and 5) the commitment of space organizations to socially responsible practices, among others.

4. Towards space environmental sustainability

Planning ahead and being pragmatic in achieving the goals of the space-Earth synergy in a sustainable manner is essential. We must learn valuable lessons from our stewardship efforts on Earth to avoid repeating past mistakes. This underscores the need to avoid replicating the "pollute and treat" mindset or adopting a pure capitalism or profit-driven approach in our ventures into space.

A comprehensive understanding of space environmental sustainability should be developed in tandem with, if not before the ongoing efforts to develop and advance ISAM. This includes an enhanced understanding of the various aspects of space sustainability and a tangible methodological framework to assess the potential short and long-term benefits and threats for forward planning.

Anticipating future limitations posed by space resources underscores the importance of striving for efficiency and conservation of both space and terrestrial resources within ISAM endeavors. A guiding framework for this approach lies in the principles of Rethink, Refuse, Reduce, Reuse, Recycle, and Repair (6Rs) and a circular economy. These principles should inform the design and implementation of ISAM technologies, ensuring a comprehensive life cycle perspective is applied. Furthermore, it is critical to apply system thinking to ensure benefits obtained through ISAM do not create undesired side-effects as well as to understand critical feedback loops and tipping points along the trajectory of ISAM endeavors. New research is underway which seeks to harness space debris as potential raw materials for ISAM. Substantial technological barriers still exist with the collection, transportation, disassembly, and reuse/remanufacturing of space debris.

To break free from the detrimental "pollute and treat" cycle observed on Earth, preventive measures are paramount. This includes adopting green chemistry principles for the creation and utilization of new chemicals in space, as well as implementing materials that align with the inherent nature of celestial bodies. This mimics the terrestrial concept of “nature-based solutions”, which promotes the use of nature or natural processes to provide solutions to terrestrial issues. It is also important for governments to incentivize and support sustainable exploration and commercial space activities, along with establishing international cooperation and regulations to prevent irresponsible use of the space environment. Much like the terrestrial context where polluters bear the responsibility of environmental restoration, it is crucial for space laws to explicitly define the liability framework for issues related to space sustainability. By adhering to these principles, we can proactively shape the trajectory of ISAM, fostering responsible and sustainable practices for the benefit of both Earth and the broader space environment.

Acknowledgement

We acknowledge the National Science Foundation's support via an FMRG award (#2328383). The views, findings, and conclusions expressed in this study are those of the authors and do not necessarily reflect the views of the funding agencies.

Competing interests

The authors declare no competing interests.

Author contributions

W.M. wrote the main manuscript text and prepared Figure 1. All authors reviewed the manuscript.

References

1. NASA. NASA Creates In-Space Servicing, Assembly, Manufacturing Consortium - NASA. https://www.nasa.gov/news-release/nasa-creates-in-space-servicing-assembly-manufacturing-consortium/ (2023).
2. United Nations Office of Outer Space Affairs. Long-term sustainability of outer space activities. https://www.unoosa.org/oosa/en/ourwork/topics/long-term-sustainability-of-outer-space-activities.html (2024).
3. NASA. Artemis Accords. https://www.nasa.gov/artemis-accords/ (2024).
4. International Organization for Standardization. ISO 24113:2023 - Space systems — Space debris mitigation requirements. https://www.iso.org/standard/83494.html (2023).
5. Wilson, A. R. & Vasile, M. The space sustainability paradox. *J. Clean. Prod.* **423**, 138869 (2023).
6. United Nations Office for Outer Space Affairs. *Guidelines for the long-term sustainability of outer space activities of the committee on the peaceful uses of outer space*. https://www.unoosa.org/documents/pdf/PromotingSpaceSustainability/Publication_Final_English_June2021.pdf (2021).
7. Maury, T., Loubet, P., Serrano, S. M., Gallice, A. & Sonnemann, G. Application of environmental life cycle assessment (LCA) within the space sector: A state of the art. *Acta Astronaut.* **170**, 122–135 (2020).
8. Wilson, A. R., Vasile, M., Maddock, C. A. & Baker, K. J. Ecospheric life cycle impacts of annual global space activities. *Sci. Total Environ.* **834**, (2022).
9. Murphy, D. M. *et al.* Metals from spacecraft reentry in stratospheric aerosol particles. *Proc. Natl. Acad. Sci. U. S. A.* **120**, e2313374120 (2023).

10. Purvis, B., Mao, Y. & Robinson, D. Three pillars of sustainability: in search of conceptual origins. *Sustain. Sci.* **14**, 681–695 (2019).
11. USGS. Pollution. https://education.nationalgeographic.org/resource/pollution/ (2023).
12. Stubbs, T. J., Vondrak, R. R. & Farrell, W. M. Impact of Lunar Dust on the Exploration Initiative. *Lunar Planet. Sci. XXXVI, Part 18* (2005).
13. Pohlen, M., Carroll, D., Prisk, G. K. & Sawyer, A. J. Overview of lunar dust toxicity risk. *npj Microgravity 2022 81* **8**, 1–9 (2022).
14. David, L. Space Junk Removal Is Not Going Smoothly | Scientific American. https://www.scientificamerican.com/article/space-junk-removal-is-not-going-smoothly/ (2021).
15. NASA. NASA's SOFIA Discovers Water on Sunlit Surface of Moon - NASA. https://www.nasa.gov/news-release/nasas-sofia-discovers-water-on-sunlit-surface-of-moon/ (2020).
16. The Washington Post. NASA names companies that will mine moon - The Washington Post. https://www.washingtonpost.com/technology/2020/12/03/moon-mining-contracts-named/ (2020).
17. Popular Science. The elements we might mine on the moon | Popular Science. https://www.popsci.com/elements-mine-on-the-moon/ (2019).
18. Lawrence, S. LEAG update. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.lpi.usra.edu/pac/presentations/1219/Lawrence.pdf (2019).

Figure legend:

Figure 1. Proposed framework for space sustainability evaluation in reference to the traditional Earth sustainability assessment framework across four domains: 1) pollution, 2) resource depletion, 3) landscape alteration, and 4) space environmental justice, as well as the example indicators under each of these domains in relation to three assessment levels: 1) resource uses and emissions, 2) mid-point, and 3) end-point.