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# Ensuring the environmental sustainability of emerging space technologies

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# Introduction

As humanity's activities in space expand, their impacts on space and terrestrial environments should be scrutinised. A thorough understanding of those impacts is instrumental to informed decision-making, helping funders, developers and regulators take appropriate decisions to set space activities on a sustainable course. Space missions have very specific impacts as they involve the development and manufacturing of spacecraft on the ground, their launch through the different layers of the atmosphere, their operations in space or on other celestial bodies, and potentially their return to Earth. Space activities have long been the remit of governments focusing on national security and great-power influence. As they have only recently started to scale, notably due to the expansion of commercial ventures, the study of their potential negative impacts on the environment has been neglected. Important legislative and regulatory instruments pertaining to the environment often exclude space activities,[2] resulting in a lack of attention and the slow development of tools and methods to assess the space sector's impact on the environment.

The increase in space activities and concern about unsustainable practices have led the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) to elaborate 21 Guidelines for the Long-Term Sustainability of Outer Space Activities (hereafter LTS guidelines), which were adopted in 2019. These voluntary non-binding guidelines are the result of a decade-long effort. They focus on (1) the national policy and regulatory framework for space activities, (2) the safety of space operations with an emphasis on collision risk and space weather, (3) international cooperation, capacity-building and awareness, and (iv) scientific and technical research and development. These guidelines also provide a definition of the "long-term sustainability of outer space activities" as "the ability to maintain the conduct of space activities indefinitely into the future in a manner that realises the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations." While we follow this definition in this paper, we also extend it to consider the preservation of the Earth environment, including the atmosphere,[3] and do not focus on equitable access to the benefits of space exploration and use.[4]

At the heart of the concerns regarding the sustainable use of outer space is space debris. These non-functional human-made objects cause a collision risk for operational spacecraft threatening valuable assets. Congestion in near-Earth space is intensifying, especially in low Earth orbit (LEO),[5] increasing the cost of space operations and potentially limiting future benefits. Properly managing near-Earth orbital space is thus becoming ever more crucial to protect critical infrastructure and give access to new benefits from space activities.

This congestion issue is the result of the properties of near-Earth orbital space; it is both rivalrous and non-excludable. A space actor's use of a particular orbit prevents other space actors from using it, and it is difficult to exclude actors from enjoying the benefits of orbital space. Common-pool resources (CPR), which are defined by these two properties, face a management problem known as the tragedy of the commons (Hardin, 1968). The tragedy stems from space actors' failure to integrate the costs they impose on others when consuming the resource, leading to an overconsumption of the resource. Moreover, the benefits of the efforts from one space actor to maintain the resource accrue to all, which disincentivises resource preserving activities.

Near-Earth space is a finite resource whose value is increasing due to technological advances and demand for new services. As the value of orbits increases, many governmental and non-

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[2] For example, the Montreal Protocol on Substances that Deplete the Ozone Layer does not specifically address emission sources that emit directly into the stratosphere, such as launch vehicles, and the US National Environmental Policy Act (NEPA) only applies to the "human environment," which US Federal Agencies have interpreted (so far) as not encompassing the outer space environment.

[3] See, e.g., Yap & Truffer (2022), who advocate for a more holistic view on sustainability challenges by looking at "Earth-space sustainability."

[4] See also the definition elaborated as part of the space sustainability roadmap for Scotland (Space Scotland, 2022, p. 10) which extends the LTS guidelines definition to the preservation of "both the Earth and the outer space environment" and includes the "promotion of the use and environmental benefits of space data."

[5] Low Earth orbit (LEO) is the orbital region around the Earth ranging from the upper atmosphere to an altitude of 2,000 km.

governmental actors want to benefit from them. The space sector has steadily grown from about $176 billion in 2005 to about $360 billion in 2019, with the vast majority of the growth in commercial activities (Weinzierl, 2018), and investment bankers project a $0.9–1.5 trillion space economy in 2040 (McKinsey & Company, 2022). While there are, as of January 1st, 2022, more than 4,800 satellites in orbit from 73 countries (Union of Concerned Scientists, 2022), space analysts predict the launch of tens of thousands of satellites in the next decade (e.g., Gleason, 2021). However, the rush for this scarce resource raises a number of environmental concerns which are highlighted in this paper.

This paper presents how the sustainability concept is used in the space domain (section 1), key trends in the space ecosystem that can have a bearing on the sustainability of space activities (section 2), threats to environmental sustainability from space activities (section 3), and what is being done or could be done to ensure sustainable space activities (assessment in section 4 and management in section 5).

## 1.

## Space sustainability: A broad concept

The term “space sustainability” is commonly used in the space community but can be understood differently depending on the forum for discussion. Its primary meaning refers to the concerns addressed in the LTS guidelines, that is, to ensure that space activities can be performed safely and without interference, such that the benefits they provide on Earth are sustained, and that the outer space environment is preserved for current and future generations (Martinez, 2021). This meaning leans more towards the ability to sustain activities in space rather than considering outer space as an environment worthy of protection. However, space sustainability can have a broader meaning by taking a holistic view on the supply chain of space missions, thus encompassing environmental impacts from the design phase to the decommissioning of space assets, both on Earth and in space. Space sustainability can also expand more explicitly to the other two dimensions of sustainable development: the social and economic dimensions. Sustainable development is generally defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987) and is embodied in the UN Sustainable Development Goals (SDGs; Transforming Our World: The 2030 Agenda for Sustainable Development, 2015). It requires a delicate equilibrium between competing environmental, social and economic interests.

In her exploration of the space sustainability concept, Aganaba-Jeanty (2016) argues that its current conception “ties more clearly to global security than to sustainable development” with a focus on the needs of the present space actors. She also notes that space sustainability is sometimes “conceptualised as defining good behavior, its boundaries, and disincentives for negative behavior in space” thus limiting its reach.

Two adjacent and sometimes overlapping concepts are often used in the space community: space safety and space security. Space safety refers to “space mission hazards and relevant risk avoidance and mitigation measures” and “encompasses the safeguard of critical and/or high-value space systems and infrastructures, as well as the protection of orbital and planetary environments” (Pelton et al., 2020). It is often perceived as minimising hazards for space assets and humans in the short-term and is seen as a prerequisite for space sustainability. Space security is traditionally associated with the military security of states and encompasses the maintenance of peace and stability. This concept can include “the security of satellites and spacecraft in orbit, the security of access to space, and also the contribution to the security of people on Earth made by various types of satellites” (Sheehan, 2014). However, its meaning has broadened to include the freedom of access to and utilisation of space, blurring the distinction with space sustainability.

The space sustainability concept needs to be contrasted with the concept of space for sustainability which refers to space activities’ contributions towards the UN SDGs. Indeed, the growing space infrastructure is increasingly important for monitoring and improving the sustainability of many Earth activities. Satellite-based services can enhance the monitoring, assessment and management of environmental risks, such as fires or floods, and are thus key enablers of progress towards the SDGs (e.g., Anderson et al., 2017; Ferreira et al., 2020; Kavvada et al., 2020; Song & Wu, 2021; UNOOSA, 2018). The space infrastructure is also key in our response to climate change as many essential climate variables can only be measured from space.

This paper focuses on environmental sustainability and only touches upon the social and economic dimensions. It takes a holistic view on space activities and looks at their environmental impacts on Earth and in space. Currently, the most valuable region of space to humankind is near-Earth orbits as only limited activities happen beyond this region. Therefore, the environmental risks associated with the exploration and use of space beyond Earth orbits are only briefly addressed.

In many respects, the concept of environmental sustainability, as used in the Earth context, can be extended to space. In this regard, the concept of ecosystem services is particularly useful. Ecosystem services can be defined as “the benefits human populations derive, directly or indirectly, from ecosystem functions” (Costanza et al., 1997). The Millennium Ecosystem Assessment (2005) groups services into four categories: provisioning services (e.g., food, water, timber), regulating services (e.g., bees pollinating flowers, tree roots holding soil in place), cultural services (e.g., recreational, aesthetic, spiritual benefits) and supporting services (e.g., photosynthesis, nutrient cycling). Near-Earth orbital space is an ecosystem providing services. The vantage point above Earth’s surface enables services such as Earth monitoring and communications, which support human activities on Earth. The proliferation of debris can alter the ability of the ecosystem to provide those services. Similarly, the night sky provides cultural services that can be degraded by light reflected from human-made objects in outer space.

## 2.

## Space industry trends affecting the environmental sustainability of space activities

The environmental impacts of space activities are more linked to the scale of those activities than to their characteristics. Emerging technologies are a driver of the growth in space activities and are thus indirectly affecting their sustainability. Some space applications are not intrinsically new but can now scale due to external factors, such as reduced launch cost or increased demand for space-based services. A bundle of new technologies is often required to make a new application emerge. For example, the combined emergence of partially reusable launchers, new constellation architectures, and smaller and cheaper user terminals is enabling large constellations of satellites for broadband internet, resulting in fundamental changes in the space economy.

Let us take a look at some important trends in the space ecosystem that can have a bearing on the sustainability of space activities, impacting the space debris issue but also other environmental aspects discussed in the next section:

- **Low-cost access to space** — The development of partially reusable launch systems by commercial companies has drastically reduced the cost of launching spacecraft. Whereas the Space Shuttle cost about $54,000 per kg launched in LEO, SpaceX’s Falcon 9 costs about $2,700 per kg, a twenty-fold reduction (Jones, 2018). Dropping launch costs is an enabler of new space activities.
- **Miniaturisation of satellites** — The use of smaller and lighter components, as well as commercial off-the-shelf (COTS) components, enables the production of smaller and cheaper satellites, such as CubeSats.

These two background trends have led to a 17-fold increase in the annual number of satellites launched in LEO over the last ten years and are fueling the following foreground trends:

- **Large LEO constellations for broadband internet** — Although satellite constellations for communications in LEO are not intrinsically new, more favorable market conditions are resulting in a proliferation of large systems (Portillo et al., 2019). SpaceX is leading the race with more than 3,000 satellites already launched, followed by OneWeb with 428 satellites.[6] Several other companies also intend to launch large constellations consisting of thousands of satellites. Not only has demand for high bandwidth low latency communication increased, but several technology developments, such as advances in antennas, inter-satellite links and artificial intelligence, have reduced the cost of LEO constellations (Daehnick et al., 2020).

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[6] As of August 2022.

- **Introduction of new actors** — The lower barriers to entry lead to a plethora of new operators, including academic institutions and startup companies. Operators are also more diverse geographically, with more than 73 countries owning or operating at least one satellite (Union of Concerned Scientists, 2022).
- **Emergence of in-orbit services** — The space industry operates under the launch, use and discard paradigm. Maintenance services in orbit, e.g., to deorbit, refuel or repair a satellite, are emerging and are likely to change this paradigm (ESPI, 2020).
- **Space tourism** — Suborbital and orbital spaceflight are democratising with the availability of various services (FutureLearn, 2022). Commercial destinations in the form of private space stations are also developing. Space tourism is bound to become a significant part of the space economy.
- **Resources exploitation** — The moon, asteroids and other celestial bodies are sources for natural materials that can be extracted for use in outer space (e.g., for refueling) and on Earth. There is growing interest and investment for mining in space (Gilbert, 2021).

## 3.

## Risks to environmental sustainability from space activities

Throughout their life cycle, space missions have environmental impacts on the ground, in the atmosphere, in space and potentially on other celestial bodies (see Figure 1). The development and production of spacecraft have impacts similar to other manufacturing activities on Earth. However, compared to other products, space technologies are often custom-made, need long development cycles, use specialised materials and industrial processes, and require thorough testing.

The unique nature of space missions starts with the launch. This paper thus focuses on the environmental impacts that are particular to space technologies, and are the result of the launch of spacecraft into space, their operations and decommissioning in space or on other celestial bodies, and their return to Earth (see, e.g., Boley & Byers, 2021, for a study of the potential impact of large LEO constellations throughout these phases).[7]

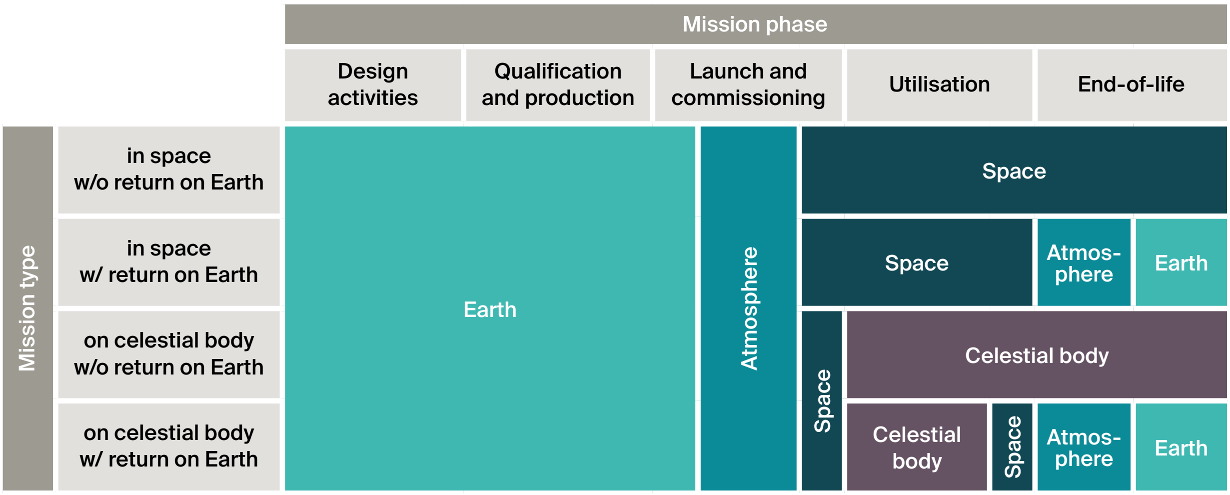

Figure 1 | Basic life cycle stages of a space mission and locations of impacts

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[7] For life cycle assessment of the Earth-based impacts (ecospheric) of space missions, see Wilson et al. (2022). They estimate that the global contribution from space missions to climate change is only 0.01% of total greenhouse gases emissions.

## 3.1 Collisions with space debris

The most unusual, probably most concerning, and thus most studied risk to environmental sustainability associated with space activities is space debris (see, e.g., Bonnal & McKnight, 2017; Buchs, 2021, for a general review). As a by-product of space activities, non-functional human-made objects, or space debris, are generated. Space debris ranges from sub-millimeter paint flakes to 9-ton rocket bodies.

With the current monitoring infrastructure, only space debris larger than 5–10 cm in LEO can reliably be tracked and catalogued. The population of more than 30,000 trackable debris pieces is dominated by fragments resulting from explosions and collisions, but there are about 3,000 derelict intact objects in orbit.

Operational spacecraft face a collision risk from the space debris population. A low-intensity collision can affect the performance of a spacecraft or disable some subsystems. If the collision intensity is higher, it can result in the disabling of the spacecraft or its complete fragmentation. As objects travel at 7–8 km/s in LEO, even a collision with a centimeter-sized object can have devastating consequences.

When equipped with manoeuvring capabilities, spacecraft can potentially avoid catalogued objects. However, not all spacecraft can manoeuvre, and the ability to accurately determine the position of space debris is limited. Objects with sizes below the tracking threshold are much more numerous and can disable or even fragment a spacecraft. Statistical modelling estimates a population of a million pieces of debris in the 1 to 10 cm size range (ESA Space Debris Office, 2021). Thus, these lethal non-trackable objects dominate the risk profile of operational spacecraft (Maclay & McKnight, 2021).

The large number of derelict objects abandoned in LEO have a significant risk-generating potential as they could create tens of thousands of lethal non-trackable debris if they were to collide or explode (Rossi et al., 2020). In 2009, the collision between the active commercial satellite Iridium 33 and a derelict Russian military satellite Cosmos-2251 generated about 3,000 trackable fragments and many more non-trackable ones. Collisions involving more massive objects would create much more debris. Military activities are also a major source of debris and an increasing cause for concern. In 2007, China deliberately destroyed one of its derelict weather satellites to test an anti-satellite (ASAT) weapon, generating more than 3,400 trackable fragments, and in 2021, Russia conducted a similar test generating about 1,500 pieces of trackable debris.

The evolution of the space debris population is a balance of sources and sinks. The sources are satellites that have reached their end-of-life and cannot be deorbited, satellites of which the operator has lost control, mission-related objects, such as rocket upper stages, and fragmentation debris resulting from on-orbit break-ups. Only two sinks are available to clear space debris from orbits: atmospheric drag and direct retrieval. The lifetime of a piece of debris increases with its altitude; while at 500 km objects take between a few years to a few decades to reenter the atmosphere, at 800 km the reentry can take centuries. Direct retrieval of large pieces of debris from orbit is in its infancy, with demonstration missions coming up in the next years.

The population of space debris has steadily increased over time. The sharp growth in space activities combined with poor compliance with commonly agreed-upon debris mitigation guidelines is a cause for concern (ESA Space Debris Office, 2022). Modelling of the space debris environment has shown that the environment has probably already reached the tipping point where even without new launches the population would keep growing as a result of collisions.

The loss of spacecraft due to collision with debris pieces can result in large disruptions on Earth as a result of the unavailability of critical satellite services. Space debris is also a threat to human spaceflight as a collision with a non-trackable piece of debris can result in the loss of human lives. Space debris uses some of the space environment capacity, augmenting the costs of conducting space activities and limiting the benefits we can extract from this resource.

## 3.2 Optical and radio interferences

Human-made objects in Earth orbit produce passive and active electromagnetic emissions (Dark and Quiet Skies II for Science and Society, 2022). All space objects passively reflect the sunlight and operational spacecraft actively communicate with stations on the ground using radio frequencies. Both types of emissions affect astronomical observations, but only the former impacts stargazing. They likely also have an impact on the wildlife, but very little about this topic is known.

These electromagnetic emissions scale up as the number of objects in Earth orbit grows. The plans to launch numerous large constellations consisting of thousands of spacecraft is thus a cause for concern given their impact on the appearance of the night sky and on astronomical observations (e.g., Hainaut & Williams, 2020; Massey et al., 2020; McDowell, 2020).

The visibility from the ground and the brightness of satellites depend on their altitude, surface reflectivity and attitude with respect to the observer. Only a fraction of the planned satellites will be visible by the naked eye, but all of them are potentially detectable by highly sensitive telescopes.

While research has recently focused on the discrete streaks produced by artificial objects on astronomical images, little information is known about the contribution of these objects to the diffuse brightness of the night sky. The cloud of artificial objects orbiting the Earth, comprised of both space debris and operational spacecraft, reflects and scatters the sunlight towards ground-based observers. Their combined effect is a diffuse night sky brightness component similar to that of the starlight background of the Milky Way. According to preliminary estimations, the contribution of space objects to the skyglow has already reached 10% of the luminance of a typical natural night sky (Kocifaj et al., 2021). The launch of large constellations of satellites is bound to exacerbate this light pollution.

The lack of a multistakeholder appraisal of the impact of large constellations is a concern. Venkatesan et al. (2020) argue that space is an ancestral global commons, and that the impact of humanity's expansion of activities in space on the essential human right to dark skies and on cultural sky traditions across all peoples needs to be properly evaluated.

## 3.3 Marine pollution

Two phases of space missions can result in pollution in the marine environment: the launch and the reentry of objects into the atmosphere. Expendable launch vehicles can only be used once. The stages of a rocket and its fairings are jettisoned at different altitudes. Some objects are discarded at sea before reaching space while others reenter the atmosphere in a short amount of time without fully burning. The development of reusable launch systems will reduce the amount of debris ditched at sea. For now, only partially reusable orbital launch systems have flown, but the first fully reusable orbital launch vehicles should be ready during the 2020s.

The development of the launch industry, with the emergence of small launchers in countries that were not used to launch rockets (e.g., the UK, New Zealand) has led to renewed scrutiny regarding this activity. Debris jettisoned during launch can have the following impacts on the marine ecosystem: direct strikes on the fauna, underwater noise and disturbance on impact, toxic contaminants (e.g., fuel, batteries), ingestion of debris, smothering of seafloor and provision of hard substrate (Lonsdale & Phillips, 2021). A report prepared for the New Zealand Ministry for the Environment regarding Electron Rocket launches from New Zealand assessed that for up to 100 launches the ecological risk is low for all ecological impacts identified (NIWA, 2016), and only flagged a high risk to the air breathing fauna with 10,000 launches. As highlighted by the case of the now-retired Russian Rockot launch vehicle which was powered by unsymmetrical dimethylhydrazine (UDMH), a highly toxic chemical creating potential environmental risks (Byers & Byers, 2017), new propellants require detailed assessment before authorising their use to avoid releasing toxic material in the natural environment.

Objects in Earth orbit are dragged down by the residual atmosphere. When reentering the atmosphere, objects do not always fully disintegrate — depending on their size, shape and materials — and can hit the ground. Objects which are likely to survive the reentry and cause a significant risk of damage or casualty on the ground require a controlled reentry. In such a case, Point Nemo, the farthest point from any land on Earth, in the South Pacific ocean is targeted (Lucia & Iavicoli, 2019). While this practice has raised concerns, as oceans should not be seen as a dumping ground, compared to the 11 million tons of plastic that end up in the ocean, the space debris contribution is negligible (David, 2022).

## 3.4 Atmospheric pollution

Like the marine environment, the atmosphere can be impacted by the launch of space vehicles and the reentry of objects into the atmosphere. Rocket engines emit different gases and particles into the atmosphere with potential local and global consequences (e.g., Dallas et al., 2020; Ross & Sheaffer, 2014; Ross & Vedda, 2018; Ryan et al., 2022; The Aerospace Corporation, 2022). Rockets are the only direct anthropogenic emission sources in the upper atmosphere. Although these emissions can affect Earth's climate and the ozone layer, limited scientific research has been conducted on them, as the space industry has for a long time been assumed to be too small to have a significant effect. Moreover, the number of launches had been declining from 157 in 1967 to only 42 in 2005, leading to a disinterest on the impact of rocket emissions. However, this trend is reversing, with an annual growth of about 6% in the past ten years leading to 135 successful launches in 2021. Given the plans to launch large satellite constellations and the emergence of space tourism, the number of orbital launches could reach 400 per year by 2030.

Emissions include gases such as water vapor and carbon dioxide ($CO_2$), but the quantities emitted by rockets are significantly smaller than those from other human sources. The emergence of space tourism has drawn public attention to the carbon emission of launches. However, $CO_2$ emissions from rockets are insignificant in the global picture, as rockets emit less than 0.01% of the $CO_2$ emitted by aviation (The Aerospace Corporation, 2022). More concerning are the emissions of small particles of soot (or black carbon) and alumina (aluminium oxide) directly into the stratosphere (Ross & Toohey, 2019). For comparison, in 2018, the amount of black carbon emitted in the stratosphere by rocket engines was similar to the amount released by global aviation. Black carbon and alumina particles reduce the intensity of solar flux entering the troposphere, and thus contribute to cooling the Earth's lower atmosphere and surface. Ross & Toohey (2019) estimate that "the magnitude of present-day cooling from rocket particles is about the same as the magnitude of warming from aviation carbon dioxide." However, the physics at play is different and Earth responds to stratospheric particle injections in complex ways which are not yet fully understood. More research is needed to unravel these complex effects and the potential impacts of an increase in launches. The effects of 400 launches per year could be unsettling.

Human-made objects reentering the atmosphere mostly burn up: about 60% of rocket bodies and 60 to 90% of satellite mass disintegrate during atmospheric reentry (Werner, 2020). While there are currently about 100 tons of hardware reentering the atmosphere per year, if the planned constellations materialise, the annual mass reentering Earth's atmosphere could eventually rise to between 800 and 3,200 tons. Historically, the concerns have been on the potential hazard to aircraft and people of objects surviving reentry. To comply with space debris mitigation guidelines requiring a probability of less than 1 in 10,000 that someone gets hit by a part of a space object reentering the atmosphere, manufacturers are pushed to implement design for demise practices. However, the disintegrated spacecraft deposit fine aluminum particulates which can damage the ozone layer and change the Earth's albedo, and thus change the radiative balance of the Earth.

The combined effects of rocket emissions and space objects' reentries is akin to uncontrolled geoengineering experiments, which are much debated (Pultarova, 2021). This raises more questions regarding the interplay of these effects and geoengineering, at both the research and governance levels, if geoengineering were to be deployed.

## 3.5 Interplanetary contamination

The exploration and exploitation of other celestial bodies and the return of spacecraft to Earth comes with the risk of biological contamination. "Forward" contamination, that is the transfer of life and other forms of contamination from Earth to another celestial body, could potentially harm extraterrestrial ecosystems and mislead scientific efforts to detect extraterrestrial life. "Backward" contamination, that is the introduction of extraterrestrial organisms and other forms of contamination into Earth's biosphere, might harm terrestrial ecosystems. Limiting the risk of these harmful contaminations is called planetary protection.

Recognising these risks, the Committee on Space Research (COSPAR) has been responsible for setting the international standards for planetary protection since the early 1960s. Following the launch of several Mars missions in 2020 and the progress of the Artemis programme which intends to return humans to the Moon during the 2020s, NASA and COSPAR have updated their planetary protection policy (COSPAR, 2021; NASA, 2020a, 2021). As the number and diversity of actors, especially private companies, involved in space activities on other celestial bodies expand, planetary protection is growing in importance (Cheney et al., 2020).

## 3.6 Cross-cutting aspects

Space actors tend to have a retroactive approach towards the sustainability risks discussed above. A reaction is often triggered by affected stakeholders, as was the case with the astronomy community for optical interference caused by satellites. Experts researching the environmental impacts of space activities often highlight that “sustainability has not been much of a concern for space systems development” (The Aerospace Corporation, 2022). Attention has been on national pride and security, rather than sustainability. While the approach is evolving, space endeavours remain closely linked to defence and national security interests, with sustainability hanging in the background.

While the different risks mentioned above were treated in silos, there is growing interest in considering them simultaneously, with the development of all-encompassing guidelines or best practices. The recognition of space as an environment worthy of protection will help extend approaches developed to address sustainability on Earth and produce a coherent approach to space sustainability.

The different risks discussed have interactions and trade-offs which will need to be addressed. For example, design for demise results in less marine pollution but more material deposited in the atmosphere. There might also be tensions in the measures needed to limit collision risk and to limit optical interference from satellites. Tools and agreements on how to quantify and balance those risks are far from being settled.

# 4.

# Assessing the environmental impacts of space activities

As discussed in section 3, space activities have a large diversity of environmental impacts. As a result, the tools to assess them can be very specific to the impacts considered. In this section, we first briefly present two methods which are increasingly used in the space domain to assess environmental impacts: life cycle assessment (LCA) and environmental impact assessment (EIA). The space sector is only starting to use these tools which are commonly used in other sectors, highlighting the sector’s lateness in its consideration of the environment. Addressing uncertain impacts of emerging technologies will require other tools, more capable of coping with uncertainty and a long-term perspective. We then discuss approaches developed to assess environmental impacts that are specific to space activities such as space debris. In particular, we look at the space environment capacity, an approach currently gaining traction to measure orbital use by active spacecraft and space debris.

## 4.1 Life cycle assessment

LCA has been identified as a practical tool to monitor and reduce the environmental impact of space activities, particularly in Europe (see Maury et al., 2020, for a review). However, only a limited number of studies are publicly available and even fewer have been published in peer-reviewed journals. The application and formalisation of LCA of space missions have been pioneered by the European Space Agency (ESA), which has developed a set of guidelines (handbook), a specific database and an eco-design tool.

The space sector has very unique impacts which are not captured in conventional life cycle models, making the application of LCA challenging. In their current form, traditional LCA models can only provide results with significant uncertainties and are often unable to come up with actionable results (Wilson et al., 2022). Furthermore, LCA typically requires benchmarking to compare technologies, which is often difficult in the case of space technologies. Efforts aimed at developing standardised approaches for declaring environmental impacts of space systems over their entire life cycle, thus ensuring accurate and verifiable impact quantification for regulatory and economic purposes are ongoing (Wilson et al., 2021).

ESA’s efforts have been geared towards adapting current ISO standards on LCA to space specificities, as methodological rules were missing. The agency has also championed the development of methods to include impacts related to space debris within the LCA of space missions (Maury et al., 2019). Work conducted at the University of Strathclyde has attempted to not only take into account the environmental dimension of sustainable development, but also to include the social and economic dimensions (Wilson, 2019). The resulting integrated framework is aimed at improving concurrent engineering activities to help develop cost-efficient, eco-efficient and socially responsible technologies.

Sustainability requires looking into the long term, and assessing the environmental sustainability of emerging space activities or technologies will require tools that have the capacity to help anticipate future impacts (see Miraux et al., 2022, for an application of a streamlined LCA to future space activities over the period 2022-2050 under two scenarios). Not only do the outcomes of the technology need to be anticipated, but also the future system in which it will be deployed.

## 4.2 Environmental impact assessment

EIA is a tool used to assess the potential environmental consequences of a particular project or action. EIAs are currently performed to evaluate the impact of space activities on the terrestrial environment, in particular for the development of new spaceports (e.g., Lonsdale & Phillips, 2021; NIWA, 2016). However, in its current implementation in laws and regulations, as a requirement before undertaking major infrastructure projects, EIA is not meant to assess impacts in outer space.[8]

As humanity's horizon expands beyond Earth's orbit, and major actions, such as resource extraction, are undertaken on other celestial bodies, there is a need for the development of a comprehensive process to assess human impacts on extraterrestrial environments (Kramer, 2014). Different frameworks for extraterrestrial EIA have been proposed (e.g., Dallas et al., 2021; Kramer, 2020; Mustow, 2018) but their application in practice remains distant.

## 4.3 Special approaches in the space domain

To address the specific aspects of space activities, dedicated approaches are under development (see, e.g., Maury et al., 2020; Wilson, 2019, in the context of LCA). In particular, several metrics have been proposed to improve the management of near-Earth space, where most space activities currently happen (e.g., Letizia et al., 2018; Rossi et al., 2015). Of notable interest is the concept of space environment capacity (ESPI, 2022). It assumes that near-Earth orbital space is a limited shared resource and aims to provide an indication of how much of this resource is used by space missions and objects in a defined orbital region (see Figure 2).

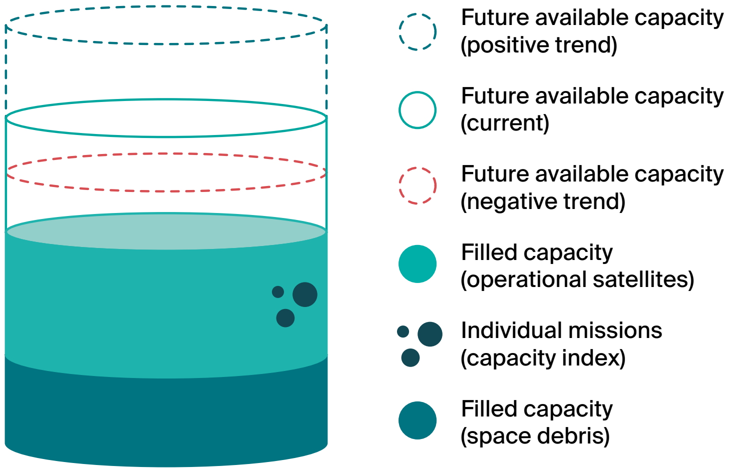

**Figure 2** | Schematic depiction of the space environment capacity concept (reprinted from ESPI, 2022)

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[8] Reasons for not applying EIA to outer space infrastructure development include the perception that space is not part of the environment and the fact that space is not under the jurisdiction of any state.

Another effort worth mentioning is the development of the Space Sustainability Rating (SSR). This voluntary rating system for space missions relies on a composite indicator of a mission's footprint on the space environment which incorporates the space environment capacity (Letizia et al., 2021; Rathnasababapathy et al., 2020). The SSR was launched in June 2022 and is aimed at offering a transparent and data-based assessment of the level of sustainability of space missions. For now, the different modules forming the indicator are focused on the space debris issue, and do not address the other risks mentioned in this paper.

## 5.

## Managing the environmental impacts of space activities

As some of the risks associated with space activities have only recently been identified and their quantification is insufficient, the response strategies are in most cases only emerging. Collision with space debris was one of the earliest risks identified and has benefited from some, albeit limited, policy and regulatory attention since the 1990s. The other risks discussed have been mostly left out of legislative and regulatory instruments.

### 5.1 Technical approaches

Identification and characterization of most of the risks described in section 3 are at a preliminary stage. As highlighted for a number of them, more research is needed to understand the significance of their impacts on environmental sustainability and to develop appropriate response strategies. Space debris has been identified early and thus has more mature technical approaches.

Collision risk from space debris is addressed through four sets of technical activities: impact tolerance, collision avoidance, debris mitigation and debris remediation (see, e.g., Buchs, 2021). The first two consist of minimising risk in the existing environment while the latter two involve changing the environment. Impact tolerance is reducing the probability of losing a spacecraft when it is hit by a piece of debris through, for example, shielding or redundancy (S. Ryan, 2022). Collision avoidance consists of manoeuvring spacecraft in the case of an approaching trackable piece of debris to avoid being hit (NASA, 2020b). Debris mitigation involves different activities, such as post-mission disposal or passivation, to reduce the likelihood that a spacecraft becomes or generates debris (ISO, 2019). Finally, debris remediation consists of minimising the chances that existing debris creates further debris, for example, by actively removing derelict objects (Bonnal et al., 2013) or upgrading them with manoeuvring capabilities (Marchionne et al., 2021).

### 5.2 Governance approaches

The only internationally binding instruments of public international space law are five UN treaties on outer space adopted in the 1960s and 1970s. Although they are legally binding on the states who have signed and ratified them, enforcement mechanisms are weak. Moreover, these treaties do not directly address the sustainable use of space. They have been complemented by non-binding guidelines on space debris mitigation (UNCOPUOS, 2007) and on the long-term sustainability of outer space activities (UNCOPUOS, 2019; see introduction).

The UN treaties render states internationally responsible for national activities in outer space whether such activities are carried on by governmental agencies or by non-governmental entities (Outer Space Treaty, 1966, Article VI). Thus, licensing for space launches and operations at the national level has a major role to play in ensuring the sustainability of space activities. International guidelines (e.g., IADC, 2021; ISO, 2019) are often integrated as part of the requirements in licensing procedures. However, so far the only risk mentioned in section 3 that is commonly assessed in the licensing process is collision risk from space debris, albeit only before launch, without mechanisms to address what actually happens once in space.

## 6.

## Way forward

Apart from space debris, the space industry's contribution to adverse environmental sustainability impacts appears minimal at present. However, "these impacts may become more meaningful with the scaling up of space activities in the near-to-medium term future" (Wilson et al., 2022). In the case of space debris, most experts agree that tipping points have already been reached and that congestion in LEO is alarming, threatening the long-term use of these orbits.

There is a need for more in-depth research on all the risks discussed in this paper. Crafting effective response strategies requires more scientific evidence, technology developments and harmonised international governance. Some of the risks, such as atmospheric pollution, require more investigation into the impacts of space activities on the environment, while others, such as collision risk from space debris, would benefit from a better understanding of the cost-benefits of approaches to address it. In comparison to other sectors, research efforts to analyse the environmental impacts of space activities and potential response strategies are not commensurate with the size of the sector, even less so with the predicted growth of the sector in the coming decade.

Instruments developed so far to assess the sustainability of space activities are not comprehensive and are not routinely implemented. Efforts are needed to expand and operationalise them. Effective tools to anticipate future risks and address large uncertainty are typically absent. The space sector could benefit from findings in other sectors regarding foresight and long-term sustainability.

For spacefaring nations, national interests and security are the primary drivers of space policy, outweighing concerns regarding the environmental impacts of space activities. For now, sustainability is only an after-thought and is not prioritised. However, the growing share of commercial applications and greater environmental consciousness can help move space sustainability higher on the political agenda. The UK's recent announcement of a package of new measures to drive space sustainability goes in this direction (BEIS, 2022).

Major threats to environmental sustainability from space activities have global consequences, requiring a global response. However, due to the nature of international space law, national contexts and sovereignty must be recognised. Unilateral but coordinated action (e.g., by like-minded states) can be the way forward. Despite divergences among stakeholders, recognition that near-Earth is a limited shared resource with the characteristics of a common-pool resource is a stepping stone to managing it effectively at the global level.

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