

The management of outer space has been a major policy concern since the dawn of the space age in 1957. The associated challenges are familiar to government and industry, but they have become more complex and serious, bringing issues of considerable importance to conservation including the availability of data, and direct and indirect effects on the global environment. Now in its seventh decade, the space sector hosts a diversity of scientific and commercial activities that are vital to terrestrial security and welfare; space sustainability has become a necessary and urgent field of human endeavour.

History of the challenges

Earth observation through satellite technology has been the cornerstone of conservation science, providing understanding of Earth's environment and changes to it: 35 of 45 essential variables defined by the United Nations Framework Convention on Climate Change (United Nations 1992) are measured from space. Expanding public and, increasingly, commercial activities in space are raising challenges for space sustainability. Space conservation first became a challenge in 1957, when the Soviet Sputnik satellite entered orbit. Great as the scientific achievement and its geopolitical implications were, one mundane concern arose: would the satellite (and its successors) fall back to Earth, or pollute space, or both? In 1961, the remains of Sputnik IV, some 50 times heavier than the first, re-entered the Earth's atmosphere, falling on a town in Wisconsin (Greenfieldboyce, 2007). The management of space debris thereby became a problem of legitimate policy concern.

Six decades later, space technology provides essential tools for conservation science, including the provision of global spatial data and the tools to analyse it that have precipitated a step-change in ecosystem monitoring and mapping, species' distribution modelling, and flood and fire management (Elith & Leathwick 2009; Szpakowski & Jensen 2019). But space technology has also remained a cause for global concern. The issues include the dangers of falling debris, the potential for damage to orbiting satellites that provide vital data and communications, orbital crowding and atmospheric pollution. Timely creation of an agreed and effective global framework has the potential to tackle space sustainability


challenges, especially space debris mitigation and management (Madry & Pelton 2020).

Orbital crowding

The crowding of space can be thought of as the root problem; others stem from it. Space's expansive emptiness is illusory. Our orbital backyard is densely crowded with abandoned property. At present, more than 4000 active spacecraft orbit the Earth from distances as low as 500km (low Earth orbit or LEO) to up to 36 000km (geostationary orbit). These satellites circle the Earth together with more than 9000 tons of detritus comprising defunct spacecraft, launch vehicles and rocket parts. About one million objects larger than 1cm orbit our planet, each large enough to inflict structural or operational damage on assets such as the International Space Station (e.g. see ISAN 2021). Each also presents growing

Space conservation:

Joanne Wheeler and colleagues review the history of space sustainability challenges and discuss urgent contemporary issues in the effective environmental management of space



dangers to humans and property on Earth from uncontrolled re-entries (McDowell 2021). About half of the mass of deorbiting satellites will vaporise, creating re-entry smoke particles that deplete the ozone layer, depositing aluminium, scatter particles and gases (such as black carbon and carbon dioxide) directly into the mesosphere and ionosphere and compounding the corrosive effects of CFCs. The albedo effects of such deposits are unknown and potentially serious (Boley & Byers 2021). In the next decade, their number, particularly in LEO, is expected to increase exponentially – to as high as 100 000 (Scharping 2021) – as nations and private companies launch larger constellations (figure 1).

Risk estimation

No systematic studies have analysed the broader implications of deorbiting satellites and rocket

emissions for climate change or biodiversity. Physical models do not address many of the potential issues, including the probability of impacts (including financial impact). For example: What are the effects of methane-fuelled rockets on the ozone layer? How does space debris vaporise at different altitudes? What are the microphysics of the resulting dust particles? What is the likely quantum of loss of a conjunction in LEO and how does one predict the probability in years to come without having a valid prediction of likely orbital population numbers? Consistent with previous experience in technology governance (Kello 2017a,b), the problem of space pollution is outgrowing the design of theories which underpin risk estimates.

The 'Kessler syndrome' is a chain reaction of impacts that creates new debris causing further cascading collisions that render Earth's orbital pathways unusable (Boley & Byers 2021), amplifying atmospheric environmental impacts. The risk of the Kessler syndrome (Kessler & Cour-Palais 1978) grows with the growing numbers of LEO constellations. Tracking might mitigate this problem, but it will not reduce the dangers posed by untrackable debris and inevitable engineering failures.

An alternative to risk estimation is to undertake future scenario planning, used in other fields including medicine, intellectual property (Ramirez & Wilkinson 2016), chemistry (Ramirez *et al.* 2017) and nuclear safety (Ramirez *et al.* 2020). Scenario planning is rigorous and well suited to contexts of deep uncertainty (Ramirez *et al.* 2015). On this basis, the UK Space Agency adopted the Oxford Scenario Planning Approach to assess future contexts for its activities and intentions (Ramirez & Wilkinson 2016). The scenarios examined legal, political, societal, financial, economic and ecological implications including the plausible environmental impacts of space on sustainability and the Earth's environment. This outcome presents opportunities for proactive action to enhance conservation policies.

Policy solutions will involve trade-offs

Sustainable space activities would benefit from a clearer recognition that the social mandate to act is based on beliefs about the likelihoods and consequences of events held by individuals who are susceptible to a raft of psychological frailties and contextual biases that have little to do with technical risk – so much so that perceptions differ substantially across national regulators

A plea for urgency

and jurisdictions (Mazur 2006). Re-framing the discussion in terms of environmentally sustainable progress will help developers and regulators avoid such pitfalls. In that vein, there is an emerging paradigm in environmental management, which asserts that the creators of technology should remain responsible for their products throughout the product's lifetime (Voulvoulis & Burgman 2019).

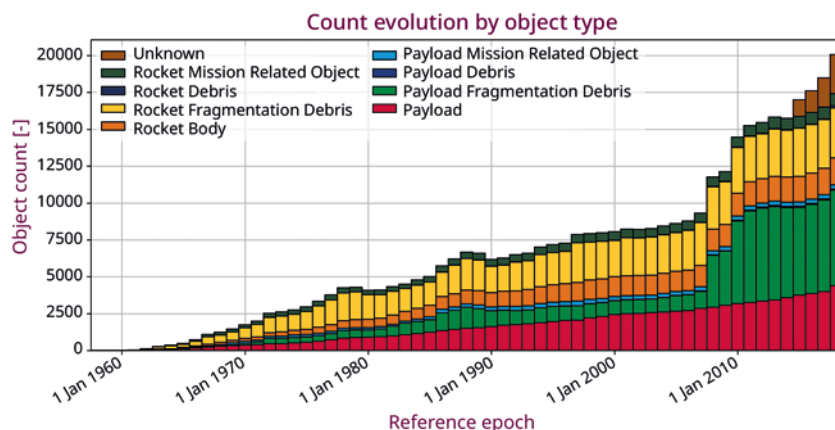
Developments in space will also depend on social, cultural, economic, security, political, geopolitical and environmental priorities. Decisions will involve trade-offs among competing aspirations that are inherently value-based and subjective, such as the trade-offs between short-term commercial gain, and the longer-term responsibility for managing space debris outlined above. Structured decision-making has developed over the last 50 years to accommodate challenging trade-offs and has been deployed effectively to conserve biodiversity (e.g. Guerrero *et al.* 2017; Hemming *et al.* 2022). A just transition to new space technologies will depend on the transparent assessments of trade-offs and processes for inclusive decision-making that provide a voice for all players who can influence decisions and are influenced by them. Negotiations around trade-offs emerge in the decisions by national regulators to license a particular space activity, balancing, on the one side, government risk, safety, security and the sustainable use and access to space against, on the other, the encouragement of commercialisation, innovation, and growth. One can imagine plausible scenarios where these objectives might diverge. Such potential conflicts may be minimised with early regulatory interventions such as the imposition of licensing conditions enforcing space sustainability guidelines (ISO 24113:2011; IADC 2020) and the safe deorbiting of satellites, through technological advances such as the demisability (Trisolini 2017) of space assets after they cease to operate.

Importantly, many environmental outcomes that to observers seem like surprises are, in fact, foreseeable – if only we take the trouble to think through the implications of new technologies more carefully. Strategic foresight (see Cook *et al.* 2014; Ramirez *et al.* 2017) can be deployed to anticipate currently unforeseen environmental impacts of space activities and to direct environmental policy research to topics where returns on the investment in research will be most beneficial.

Environmental law: grounds for an effective environmental policy

While space presents some unique conservation issues, many concepts of environmental law on Earth are applicable to it (Lyal 2000). Article III of the Outer Space Treaty (United Nations 1966) – the 'magna carta' of space – articulates that the exploration and use of space is to be carried out in accordance with international law. This concept is generally held to form part of customary law and is therefore binding on all states, even if they have not signed or ratified the Outer Space Treaty. To illustrate this, a state has a duty not to permit the use of its territory or property to the detriment of another state (see Trail Smelter 1938 and Corfu Channel 1949 cases).

Of course, environmental damage can be caused without the territory, property or personnel of another state being involved and beyond state jurisdiction. Space is an example of an area that is not subject to national appropriation through claims of sovereignty



1 The evolving number of debris objects across all Earth orbits, split into different sources of debris. (ESA)

by means of use or occupation (or some other means), as stated in Article II of the Outer Space Treaty. Principle 21 of the Stockholm Declaration of 1972 (United Nations 1972) notes that states have a responsibility to ensure that activities within their control do not cause harm to or damage the environment in areas beyond the limits of national jurisdiction. Principle 22 requires states to cooperate to develop international law regarding liability and compensation for damage. The Stockholm Declaration, although not binding, is persuasive as to the intention of the state signatories to it. An applicable body of international law exists, to some extent, on which to clarify and expand state responsibilities in space sustainability.

Overall, there is an emerging international duty to preserve the environment – the 'precautionary principle' (Cameron & Abouchar 1991), is gradually shaping the development of how environmental aspects are being applied to space activities (Haroun *et al.* 2021). The concept of the 'global commons' and a duty to respect and manage the space environment could be inferred from existing terrestrial international environmental law.

Under Article IV of the Outer Space Treaty (United Nations 1966), because states bear international responsibility for national activities in space, they must exercise effective regulatory control of activities on and from their territory by their nationals through the licensing and authorisation of space activities. The Outer Space Treaty stipulates that it is the duty of the 'responsible' state to exercise due diligence in enforcing national laws and regulations and ensuring the safekeeping and sustainable use of the space environment. Under Article VII, if a state is the 'launching State' of a space object (that is, if a state launches or procures the launch of an object into space or if its territory or facility is used to launch an object), then that state is internationally liable for damage caused by that object to another state party to the Outer Space Treaty. This is the case whether the object is an active satellite or non-functional space debris, whether the damage is caused by the object itself or its component parts on the Earth, or whether the damage occurs in air space or in outer space (liability is fault-based in relation to damage occurring in outer space, however a launching state shall be absolutely liable to pay compensation for damage caused by its space objects on Earth or in air space). If the state adds a space object to its national registry of objects, it retains 'jurisdiction and control' (Article XIII) over that object, whether the object remains in space, is space debris or returns to Earth. In practice, this understanding refers to 'ownership' over the space object.

In recent years, many more states have begun implementing national laws and regulations to supervise the activities of their private commercial

operators in space; not just to pass liability down to licensees, but also to attract foreign investment. From a private actor's perspective, regulatory forum shopping can lead to businesses to relocate to jurisdictions where the regulatory and operational environment is more permissive, cost-effective and lucrative. This trend, however, creates opportunities for private entities to evade responsibility and circumvent national licensing, and its requisite conditions (Henry 2018). In short, debris guidelines and standards establishing the responsibility of states (Wheeler 2020) are voluntary and non-binding and they are not applied consistently among states in national laws and regulations – if they are applied at all.

In June 2019, the UK supported the United Nations Guidelines for the Long-Term Sustainability of Outer Space Activities (LTS Guidelines). The LTS Guidelines provide a regulatory framework for space activities that covers the safety of space operations, international cooperation, capacity-building and awareness and scientific and technical research and development. They are important as new space nations (such as the Philippines, Estonia, Greece and Israel) and new categories of non-state actors (large industrial players, start-ups, and universities) enter the space domain.

In 2021, a multilateral agreement among the G7 nations pledged to promote “a safe and sustainable use of space to support humanity's ambitions” and promoted strong partnerships between nations and private enterprises. Recognition of space sustainability has taken place in the UK Parliament (Hansard 2021). These steps signal the importance of space and the compelling case to discuss its conservation in the heart of the political agenda. Bilateral and multilateral agreements between states and international institutions hold a wealth of potential to minimise environmental impacts of increased space activities.

The LTS Guidelines and related international standards, however, remain voluntary. They contain no enforcement mechanism and they offer few incentives for national regulators to implement them at the national level and even fewer incentives for commercial operators to apply them. Their application in the furtherance of sustainability goals, therefore, requires new incentives to catalyse voluntary responsible behaviour.

Investment: creation of more authentic incentives

Underlying incentivisation of private capital for sustainability purposes is not always perceived as authentic. Various guidelines and vehicles that are already in place can help to strengthen the perception of authenticity, while also achieving financial return in pursuit of space sustainability.

The need for investment portfolio diversification is driving the year-on-year record-breaking magnitudes of private equity being invested into sustainability activities. In 2019, impact investing amounted to US\$502 billion of assets under management (Mudaliar & Dithrich 2019). Thus, the financial community is already addressing global conservation issues authentically. Private capital remains focused on maximising capital returns, which in turn creates economic sustainability in terms of job creation, and human knowledge growth and equity. Without commercial sustainability, activities thus financed remain transient. Drawing on the framework of ‘Adaptable Authenticity’ (Goffee & Jones 2006), both environmental science and the space sector communities should accept that financial markets, and the ventures they sponsor, are responding

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to environmentally focused challenges, while still giving priority to investors' beliefs and core values.

The aims of the LTS Guidelines and the concept of ‘environmental, social and governance’ (ESG) for commercial companies and investors appear to be well aligned; they are acting as an incentive for investment portfolios. Investors are increasingly applying non-financial factors to identify risks and growth opportunities, thereby encouraging sustainable behaviour amongst commercial operators (Streck 2021). Ideally, governments and businesses will adopt a holistic approach to include the design, manufacture, launch, operations, in-orbit management and decommissioning of spacecraft.

Regulators whose countries compete internationally to attract satellite and space investments could deploy appropriately incentivised regulations, applying current ESG concepts for companies seeking favourable bases from which to license their operations. Regulators successfully implementing the LTS Guidelines might encourage a ‘stamp of approval’ reputation that effectively supports the commercial sector, the insurance sector (Lloyds 2022) and aligns with its commercial aims and investors' needs. Enhanced, authentically sustainable behaviour underpinned by both LTS and ESG frameworks will lead to investing activity being further legitimised, dousing biases based on scepticism (e.g. green washing, green scepticism).

Another possible incentive mechanism concerns the lens of ‘omission neglect’, whereby sustainable operations that should have been coupled with a financial return were ignored. For example, an opportunity exists for space companies to work with the environmental scientific community to showcase how their operations, in-orbit technologies, and products support responsible environmental behaviour. Leveraging Principle 21, showcasing could occur in the form of company-specific case studies focused on declaring how a company mitigates incidents of technological malfeasance (e.g. in-orbit debris creation, collisions, etc.) and irresponsible environmental behaviour (e.g. low Earth orbit chemical pollution). Such showcasing would be useful for pro-environmental investors.

Optimistically, one could expect that the space investment community will establish more relationships with the environmental community to develop narratives supporting sustainability-friendly investment. The UK Space Agency scenarios, for example, showed that climate change will increasingly become a priority in space development. This pressure is likely to translate into investors leaning towards green investments in the space sector. Alternatively, space may provide new opportunities for rezoning, which may in turn reduce sustainability in space activities if governance and regulation are ineffective.

The concept of ‘New Space’, referring to the emergence of the private spaceflight industry (Scharping 2021), has emerged over the last 20 years providing faster and cheaper access to space and high-quality, high-resolution and affordable data. It is underpinned by the primary focus of ‘easy access to space’ and has precipitated significant growth in the number of private actors designing, building and operating satellites at significantly lower cost. A parallel theme has emerged: ‘data is the black oil’, which has produced vast quantities of space originated data (e.g. Earth observation, telecommunications, and satellite navigation data) that are offered free of charge. A wealth of ‘downstream applications’ has arisen that

has itself become a significant investment target, with ventures using data collected in space (accounting for about half of all commercial space activity).

Data are essential to reinforce investment narratives for sustainable space activities. The expertise of the environmental community could develop data collection mechanisms that quantify public value and ultimately provide information and insight that is meaningful to investors building sustainable space portfolios. Looking ahead, one can expect the investment community to partner more with space agencies and banks to implement the public-private infrastructure portion of their future portfolios, which will be de-risked accordingly. The expanding and transnational epistemic community of conservation and environment experts can play a crucial role in brokering competing needs and translating diverse interests.

To bring about effective environmental management of space requires the development of new persuasive outlooks that encourage intrinsic motivation (i.e. capital return), self-discipline, and consistency across short- and long-term horizons for governments and investors. The crowding of space has created a sense of urgency that can be described by Cialdini's principle of scarcity (Cialdini 1984), but there are other forms of persuasion to incentivise private capital to create new investment approaches. In addition to the national application of the LTS Guidelines, mapping United Nations Sustainability Goals to the impact of commercial services has been, and continues to be, an effective framework to access increasing investment opportunities among space ventures focusing on downstream applications.

A difficult but necessary and urgent effort

The growing challenge of space sustainability is truly global. Concerted effort is needed by

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established and emerging spacefaring nations to mitigate negative externalities arising from the crowding of space. We advocated for the application – as a matter of urgency – of lessons learned from conservation science to the preservation of space (Yonyilang 2019) for investors, space actors and future generations on Earth. In particular, the conservation and environmental science community could apply its learnings regarding the importance of social-ecological systems in defining and implementing practical and effective governance of common global resources. It could deploy its techniques in structured, inclusive decision making to identify socially acceptable and just transitions towards sustainable space activities. It could orchestrate structured expert judgement protocols to fill data gaps and build models that are robust to deep uncertainties. Finally, it could build the data-gathering and monitoring systems that would encourage effective private investment in sustainable innovation.

In short, the community of scientific experts, governments, specialised space actors and investors is a vital engine of knowledge generation and policy reform within the realm of space sustainability. The global space community should, as the UK Space Agency has, support research that explores new governance models and which includes the use of plausible scenarios of unfolding sustainability challenges (Neumayer 2003). These collaborative scientific efforts would help to clarify core sustainability values, identify policy options available to governments and investors, and map out the trade-offs that policy must address. Space sustainability research and investing are both promising and necessary. The chosen path could have a lasting impact on the risks that governments, the private sector and civil society are willing to accept or wish to avoid. ●

AUTHORS

Joanne Wheeler MBE

(joanne.wheeler@wearealden.com) is a leading expert in the field of satellite and space law, policy, regulation, spectrum issues and commercial contracts, having worked at Ofcom, the European Space Agency and for over 20 years in private legal practice in this area. She is managing partner of Alden Legal and was appointed honorary professor by the University of Leicester in 2022.



Mark Burgman

(m.burgman@imperial.ac.uk) is professor of risk analysis and environmental policy at Imperial College London. Previously, he was head of the Centre for Environmental Policy at Imperial College, following positions as head of the School of Biosciences, director of the Australian and New Zealand Centre of Excellence for Biosecurity Risk Analysis and Adrienne Clarke Chair of Botany at the University of Melbourne.



Jason

Marrothynaden (jmarrothynaden@hespace.com) is the UK managing director of HE Space Operations Ltd. With 20 years in aerospace and venture capital, he is an internationally experienced investor, director, board advisor and start-up mentor. He is a specialist in access to finance, particularly working



in partnership with Venture Capital.

Rafael Ramirez (rafael.ramirez@sbs.ox.ac.uk)

is a professor of practice and director of the Oxford Scenarios Programme at the Saïd Business School and a Governing Body Fellow at Green Templeton College, both at the University of Oxford. He was visiting professor at Shell International from 2000 to 2003, and from 2008 to 2010 chairman of the WEF Global Agenda Council on Strategic Foresight.



Lucas Kello (lucas.kello@politics.ox.ac.uk)

is associate professor in the Department of Politics and International Relations at Oxford University. His research focuses on technology and global affairs, with a special emphasis on cyber issues and space governance.



Taskeen Ali

(taskeenali@gmail.com) is the head of futures at HM Revenue and Customs where she leads on tax bases on emerging jurisdictions including Space, Arctic, Oceans and the Metaverse. Previously, she held a position as head of Horizon Scanning at the UK Space Agency, where she led futures research, developed space policy, strategy and engaged in international and cross-governmental activities related to commercial space and exploration.



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