'Perspective'

Sustainability in a multi-planetary context: An exploration of implications for earth system governance

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Abstract

There has been an explosion of space activities by private enterprises in recent years, driving what is dubbed the New Space revolution. SpaceX, as a frontrunner, is working towards the goal of 'occupying' Mars by 2050, with a view to transforming humans into a multi-planetary species. The prospect of a multi-planetary society begins to impact the discourse of planetary sustainability, where Mars and other celestial objects are increasingly framed as a solution to earth system transformation. There is an imminent shift in the paradigm from 'planetary' to 'multi-planetary', which will have far-reaching implications for earth system governance. This Perspective explores these implications by focusing on the risk of increasing fragmentation of space governance through the proliferation of institutions and private space actors. We explicate how a few core assumptions of earth system governance may be impacted and argue for an expansion of the scope of governance beyond the Earth System.

Keywords:

Multi-planetary; earth-space; sustainability; earth system governance; outer space; institutional architecture

1. From 'planetary' to 'multi-planetary'

'Occupy Mars', Elon Musk tweeted in 2019. While the idea of colonizing Mars may still seem like a science fiction, the space sector is booming at a faster pace than ever, therefore increasing the likelihood of that idea becoming a reality. Elon Musk is 'highly confident' that SpaceX will land humans on Mars in 2029 (Mack, 2022), with humans settling by 2050 (Sheetz, 2020). Their long-term plan is to terraform Mars into a habitable planet, making humans and human societies multi-planetary (Musk, 2017; SpaceX, 2022; Williams, 2017). Elon Musk is not alone in this space endeavour. Over the past decade, there has been an exponential growth of space activities driven by private entrepreneurs such as Jeff Bezos and Richard Branson in partnership with NASA and other government space agencies. Small ventures like Relativity Space (2022) and Impulse Space (2022) are also joining the race to Mars. Dubbed the New Space revolution (Clormann, 2021; Robinson & Mazzucato, 2019), these developments are driving a paradigm shift from 'planetary' to 'multi-planetary'. The shift is expected to have far-reaching implications for, among others, earth system governance (Biermann, 2014; Burch et al., 2019), which is the focus of our exploration in this Perspective.

We start with an observation that the emerging imaginary of a multi-planetary society has started to have an impact on the discourse of sustainability. According to NASA (2014), the new space activities are geared towards promoting planetary sustainability in 'a multi-planetary society, where the resources of the Solar System are available to the people of Earth'. This framing has projected space as a key part of the answer to sustainability challenges here on Earth. Mars is, for example, being portrayed as a future habitat for humankind when Earth becomes less habitable due to global environmental change. Asteroids and the Moon are presented as sustainable and infinite supplies of mineral resources, including those needed for global energy transition. Mars and other celestial objects in space have, in essence, been perceived as places to be colonized for the benefit of humankind.

This narrative, however, is deeply problematic. The promised benefits are only one side of the story; there will be social and environmental consequences, which would most likely be unequally distributed across the globe. More fundamentally, the burst of space

activities driven by private enterprises is taking place in the absence of an adequate governance framework on a multi-planetary scale. For example, in 2020, Elon Musk announced that SpaceX, which remains a privately traded company, will make its own laws or 'self-governing principles' when they start establishing a human settlement on Mars (Cuthbertson, 2020). While this is not going to be as easy as he might think, Musk is not entirely delusional either. The current space governance framework is arguably weak and underdeveloped in view of the rising space activities.

We are not alone in problematizing the emerging discourse on planetary sustainability. While expressing concerns over the framing of space as an infinite source of resources and a dumping ground with an unlimited capacity, scholars have recently called for 'a more integrative approach including both our space environment and planet Earth' (Losch, 2020, p. 1; see also Galli & Losch, 2019). Yap and Truffer (2022) have proposed the concept of 'earth-space sustainability' to underline the interdependence between sustainability challenges on Earth and in space. There is no sustainability on Earth without sustainability in space, and vice versa. Such an opposing discourse demands us to revisit the notions of planetary integrity (Kotze & Kim, 2022), planetary justice (Biermann & Kalfagianni, 2020), and planetary stewardship (Steffen et al., 2011) to ones that recognize an imminent expansion of our social sphere from the Earth System to the Solar System. This paradigm shift from 'planetary' to 'multi-planetary', which we are firmly convinced will take place in the next few decades, will demand a new governance model that effectively integrates Earth with space.

Here we put forward the concept of *earth-space governance*, which we define as an integrative governance model that aims to achieve sustainability for life in all forms in a multi-planetary context. This integrative sustainability governance model approaches Earth as *situated in* or *integrated with* space, instead of treating space as separable entities from Earth. Following this introduction, we will highlight the interdependencies between Earth sustainability and space sustainability. We then briefly discuss how the current space governance framework is unable to address sustainability challenges on Earth and in space in an integrative manner. We argue that the direction in which space governance is likely to evolve does not look promising either, as it is likely to go through increasing fragmentation through the proliferation of private actors and institutions. We then propose earth-

space governance as what humanity should strive towards, and offer a first sketch of the contours of earth-space governance.

2. Sustainability in a multi-planetary context

Sustainability challenges on Earth and in space have become more intertwined than ever. There are already policy attempts and media coverage where earth-space sustainability has been a key concern. The current COSPAR Planetary Protection Policy is working on the issue of contamination with micro-organisms from outer space (COSPAR, 2020). Another prominent concern is the carbon footprint resulting from space activities such as the consumption of fossil fuel from rocket launching. Depending on exact payloads, each rocket launch could result in approximately 150 metric tons of carbon dioxide, which makes every launch equivalent to about three transatlantic flights that carries 50-100 times more passengers (Whittaker, 2018). This issue has recently gravitated much interests in the public domain: The Guardian wrote 'How the billionaire space race could be one giant leap for pollution' (Gammon, 2021), while the headline of popular science article reads '[t]he cost … will be paid in carbon emissions' (Marais, 2021).

Another example that has turned into a heated debate in recent years is the rapid accumulation of space debris in Earth's orbit. Although satellites bring manifold benefits to Earth's development, the increasing density of satellites raises the likelihood of the so-called Kessler syndrome, which is a cascade of collisions that can be triggered when the density of objects in the orbital environment reaches a certain threshold (Adilov et al., 2018; Kessler & Cour-Palais, 1978; Kitfield, 2010). If that happens, the chaotic distribution of debris in orbit could significantly impede the use of satellites or access to space more generally for many generations to come. Space operators are already receiving dozens of collision warnings each day and the number of these alerts is expected to grow rapidly in the coming years (Greenbaum, 2020; Krag, 2021).

Beyond Earth's immediate orbital environment, mining activities on other celestial bodies have been promoted as either providing in-situ resources for space missions or addressing sustainability challenges on Earth. For instance, helium on the Moon is actively considered as a new source of energy for Earth's rising energy demands (Conocimiento,

2019). But not only mining the Moon and asteroids will leave permanent scars on these celestial bodies, these activities may also adversely impact sustainability on Earth. In particular, framing the Moon as a source for meeting Earth's demand can be a distraction to the ongoing sustainability transformation policies and reinforce current economic systems. Another critical question is whether developing countries would have equitable access to space given their less privileged technological and financial capabilities (Butkevičienė & Rabitz, 2022). In essence, the pursuit of space exploration and exploitation in the name of sustainability may in effect exacerbate environmental and societal challenges both on Earth and in space. Developing an integrative governance framework for simultaneously addressing sustainability issues within and beyond the Earth System, therefore, becomes a fundamental challenge in a multi-planetary era.

3. Outer space in earth system governance

In search for an integrative approach to address multi-planetary sustainability, it is pertinent to first examine the adequacy of the earth system governance framework in terms of its scope. The earth system governance literature has served as the frontier of governing earth system transformations in the Anthropocene (Biermann, 2014; Burch et al., 2019). Thus far, earth system governance, defined as 'the collective attempt at bringing our societal development paths in line with the exigencies of earth system boundaries' (Biermann, 2014, p. 47), has left outer space a rather distant concern. As far as planetary sustainability is concerned, celestial objects such as the Moon and Mars are seen as detached entities with no meaningful interaction with Earth. In a multi-planetary context, however, this will have to change. The boundary of Earth as a social-ecological system is expanding, and so will the scope of earth system governance.

While some of the institutions in extant space governance seek to hedge the negative effects of increasing Earth-space interdependencies highlighted above, these institutions have been insufficient. The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies of 1967 (or the Outer Space Treaty) has thus far served as the main governance framework for gov-

erning the use, occupation, and appropriation of outer space to prevent any claims of sovereignty in space and on celestial bodies, which emphasizes that space activities shall be carried out for the benefit of all humankind. However, this treaty has not been updated for over five decades, rendering it ineffective and ill-suited for tackling emerging challenges of the New Space age, including the well-established issue of space debris (Beck, 2009; Goguichvili et al., 2021; Hollingsworth, 2013). The 1979 Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (or the Moon Treaty) is similarly focused on governing activities relating to space resources, rather than addressing sustainability issues that might emerge from such activities. It imposes certain limitations to exploitation activities on the Moon and other celestial bodies only to prevent unrestricted competition over resources among leading spacefaring nations.

The foregoing suggests that earth system governance remains exclusively Earth-centric in its approach to governing space activities. The focus of existing governance institutions remains on managing geopolitical and distributional tensions surrounding access to space resources and any benefits that might be derived from the use of such resources. The ultimate purpose is sustainable development *on* Earth, while space is considered something detached and 'out there' that can be exploited with little negative consequences on Earth. But when humans start 'occupying' the Moon and Mars, the sphere of governance concern will need expansion to include space in a more meaningful manner.

4. Increasing fragmentation and privatization of space governance

While the boundary between Earth and space remains firm in the architecture of earth system governance, space governance is under increasing risks of institutional fragmentation, due to the ramp-up of the colonial mind-set dominating the current New Space revolution and the concomitant proliferation of private actors.

More specifically, a variety of state and non-state actors have started to shape their own leeway to tap into new commercial opportunities. In particular, we have witnessed the rise of minilateralism, or smaller blocks of countries forming alliances based on shared interests. For instance, the United States changed their national legislations on the rights of

private commercial companies to allow private mining on the Moon or asteroids and legalize commercial profiting from such activities (Butkevičienė & Rabitz, 2022). In 2020, the United States put forward a 'shared vision for principles' to govern civil exploration and use of the Moon, Mars, comets and asteroids in a framework called the Artemis Accords, which are subsequently signed by over 20 countries. Although the new framework affirms the importance of compliance with the Outer Space Treaty, the Accords also risk fragmenting the global space governance framework to the extent they deviate and represent commercial interests. These leading spacefaring nations are, in effect, driving the development of space governance, with a view to facilitating commercialization of space (Nelson, 2020).

The fragmentation of space governance is furthermore exacerbated through privatization of governance, with proposals to adapt the international space law for accommodating the increasing role of private space enterprises (Yuan, 2021). Leading the New Space race are state agencies in the United States and the European Union, who have strong tendencies to partner with private actors in their space missions for strategic reasons (Al-Rodhan, 2012). As a consequence, these states are increasingly becoming dependent on technological innovations of the private sector. For instance, the United States government and NASA are contracting companies such as SpaceX, Blue Origin, and Dynetics for their missions near and on the Moon when it comes to producing lunar landers and developing resource mining technologies (Chang, 2020).

Due to the growing reliance on private actors for both finance and technology, companies are increasingly empowered to shape institutions and legitimize their space activities, from space tourism in low Earth orbit to building settlements on Mars. For instance, the Artemis Accords and the United States' Commercial Space Launch Competitiveness Act allow private companies (under the jurisdiction of a participating state) to commercially profit from space-based resource mining (US-Congress, 2015). Under such conditions, companies may transport resources back to Earth for trading purposes, which could disrupt future supply flows of minerals on Earth (Yarlagadda, 2022). In other words, institutional fragmentation leaves major cracks through which private actors can shape their own rules regarding exploitation and commercialization of space resources, implications of which are likely far-reaching. The example of SpaceX declaring to make its own 'self-governing principles' on Mars is another case in point. The issues of fragmentation and privatization of

space governance are mutually reinforcing. A new 'Wild West' could emerge beyond Earth's orbit, with leading spacefaring nations and a handful of wealthy billionaires ruling a multi-planetary society legitimized with their self-designed institutions.

Such a scenario might unfold faster than expected due to the ongoing institutional fragmentation of Earth's orbital environment, which serves as the 'gateway' to space. Private companies from the satellite sector, for example, have already started taking advantage of the weak and fragmented governance architecture. They engage in forum shopping, i.e., to 'shop' among nation states that have more lenient regulations for satellite launch. Some events already indicate that state agencies tend to steer institutions to work in favour of companies from their respective countries. For instance, when several companies (e.g., Viasat, Hughes, Dish Network, OneWeb, and Kuiper Systems) filed a claim to the United States' Federal Communications Commission against the placement of Starlink satellites in a lower orbit, the Commission dismissed the claims and granted permission for Starlink to follow through its corporate plan (a total of 12,000 satellites), for reasons such as improving the speed and latency of Starlink (Brodkin, 2021).

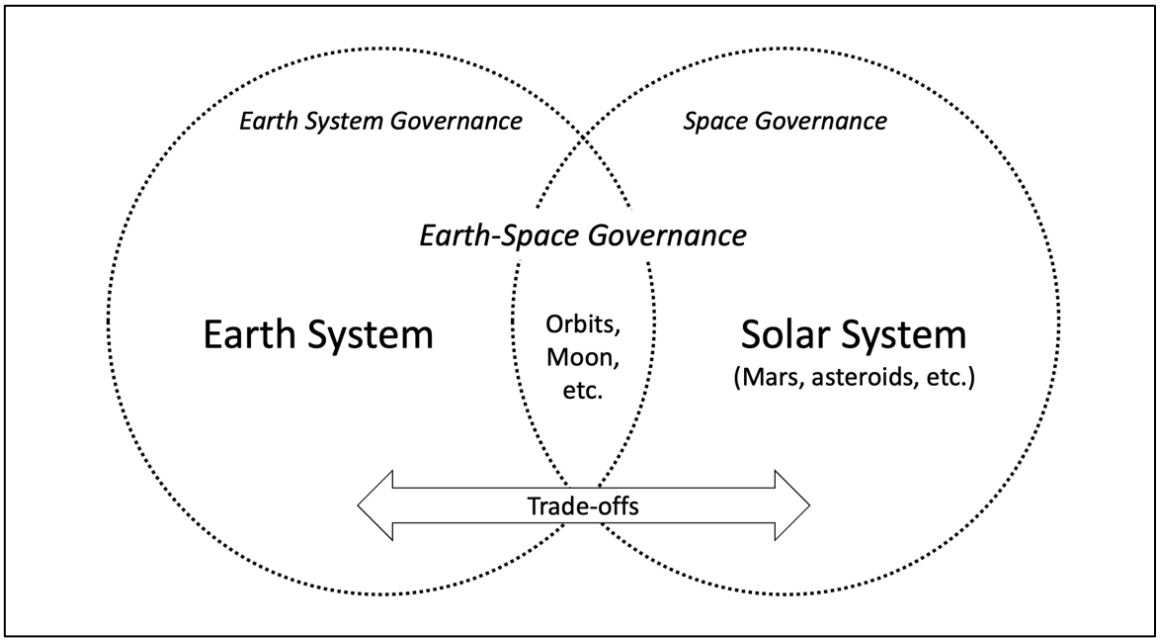
There are soft institutions introduced to mitigate the risk of unsustainable commercialization of space. Examples include the Space Debris Mitigation Guidelines of the United Nations Office for Outer Space Affairs from 2010 (UNOOSA, 2010), the Sustainable Space Rating from the World Economic Forum in 2021 (WEF, 2021), and the Net Zero Space initiative launched at the Paris Peace Forum in the same year. Despite their shared concern over space sustainability, the effectiveness of these emerging voluntary institutions is still an open question. On the contrary, they may in fact legitimize an exponential rise in commercial space activities as long as their operators fulfil certain industry expectations.

The concerns over the fragmentation and privatization of space governance have been shared by other scholars (Tepper, 2019; Weeden & Chow, 2012) . Reform proposals abound, ranging from establishing a centralized International Space Authority (Zhao, 2004) to adopting a more polycentric governance approach (Morin & Richard, 2021; Shackelford, 2014). We acknowledge the merit in many of such policy options. Yet we argue that it is imperative to consider these options not in a piecemeal manner, but under a fundamentally new governance model that is cognizant of the paradigm shift from planetary to multi-planetary sustainability in the New Space age.

5. Towards integrative 'earth-space' governance

We propose here the concept of *earth-space governance* as an alternative governance model for addressing sustainability in a multi-planetary context. It focuses on addressing sustainability challenges on Earth and in space in an integrative way with explicit considerations for their interdependencies. At the core of the proposed model lies a multi-planetary stewardship orientation where ethics, sense of belonging, and caring for the 'space' humanity lives in extends beyond Earth. In doing so, the proposed new model expands the scope of earth system governance beyond the orbits and the Moon to the rest of the Solar System. We outline below three key changing contextual conditions as we shift toward a multi-planetary sustainability paradigm.

Figure 1. Earth system governance, space governance, and earth-space governance.



Source: Authors.

New environmental limits and social foundations. The idea of multi-planetary sustainability suggests that resources extracted or generated on Earth and on Mars will be used and shared for supporting life on both planets. As humans find stronger footholds in space, whether through building settlements or exploiting space resources, humanity's 'biophysical limits to growth' (Meadows et al., 1972) also changes. On one hand, the biophysical

limits might expand as other celestial bodies could be treated as resources to fuel development on Earth. On the other hand, Earth's orbital environment might set the new limits to growth if the problem of orbital space debris is not well addressed; future generations will not be able to access space. Any change in the biophysical limits would have implications for social foundations (Raworth, 2012, 2017). While the 'environmental ceiling' of the Earth system remains the same, human exploitation of resources on other planetary systems or celestial bodies could impact social equity on Earth. Earth-space governance will have to integrate the requirements of social foundations on a multi-planetary scale, such as in terms of stable economic incomes, improved living standards, and good-quality access to basic needs such as water and energy. Accounting for social justice in an Earth-space era helps ensure that the rich are not profiting even more from space resources while the poor remain deprived from basic needs on Earth. A key objective of earth-space governance would then be to effectively manage trade-offs between different issue regimes of the two planetary systems.

New functional and spatial interdependencies. Human settlement on Mars will create new functional and spatial interdependencies between Earth and space. These changes beg the question of how socio-technical systems of, for instance, energy and water provisions on Earth and in space may operate in parallel. An example would be that the extraction of minerals on a celestial body may impact energy provision systems on Earth by altering the geopolitical landscape of sources of rare minerals (Klinger, 2017) or through the creation of new competitions, value chains, or flows of raw material supply on Earth (Yarlagadda, 2022). New systems in space, as a consequence, may reconfigure future socio-technical systems on Earth. It is therefore imperative to govern a multi-planetary society by explicitly considering the new interdependencies between Earth and space.

New institutional coupling. An integrative earth-space paradigm considers political institutions in space as a continuity from Earth. More specifically, a multi-planetary view requires coupling of rules and institutions between Earth and other celestial bodies in space such as Mars. A clear example of how the two are interrelated is that restricted resource extraction on Earth (e.g., deep seabed, the Arctic, and mineral mining in Congo) could fuel the interest of commercial companies to mine resources in space. Earth-space governance

in this regard would require aligning and integrating the fragmented institutions across different levels and scales, from global to planetary and multi-planetary. Any political institution for the Mars settlement will have to align with principles that safeguard sustainability and peacefulness on Earth. This perspective is particularly important to emphasize that powerful actors building settlements on Mars shall not simply shape their own rules and institutions, and that any institutional considerations have to account for justice on Earth.

Beyond the abovementioned changes, an integrative earth-space governance model could bear implications to the current sustainability paradigm dominated by the planetary boundaries framework (Rockstrom et al., 2009) and the Anthropocene discourse. First, the aim of earth system governance in the Anthropocene can be conceived as "buying time for life on Earth" to adapt to the earth system changes (Biermann & Kim, 2020). The flurry of technological innovation and diffusion over the last two decades as well as socio-technical transitions of sectors in many countries have contributed to such humanity progress. However, techno-optimism is increasingly found to have led to rebound effects or unsustainable developments over time (Kolbert, 2021; Van Den Bergh et al., 2015). One could assume that the current space developments are the continuity of the current economic growth model and techno-optimism to delay Earth system deterioration. The role of earth system governance in this context, therefore, risks focusing on drawing in resources for Earth and 'bounding off' negative or undesirable effects from the Earth's environmental limits.

An integrative earth-space governance model, and perceivable as governing societal development and human actions beyond Earth, could deal with these challenges more comprehensively by simultaneously considering the trade-offs, causes, and outcomes among the planetary systems. The concept, however, should not be misconstrued as expanding anthropocentrism on a multi-planetary scale where human stressors could alter another planetary system. On the contrary, the integrative governance model focuses on mitigating the impacts of human actions and finding effective decisions to safeguard the sustainability of and justice for all life-beings.

6. Governing for sustainability in a multi-planetary context

A multi-planetary society is looming on the horizon through the New Space revolution. The meaning of sustainability in such a society transgressing the limits of the Earth System will need to be scrutinized; the architecture of earth system governance will need to be adjusted. In particular, the integrity of the Earth System is likely to be severely compromised when another planet is projected as Plan B. Societal injustice is likely to exacerbate to a multi-planetary scale. Can policies, monitoring, and measurements targeted at transforming societal developments on Earth toward sustainability be effective, with interferences from beyond Earth? Current and future institutional arrangements aiming at space sustainability or Earth sustainability in isolation have to proactively relate space developments to the planetary integrity of Earth. In so doing, these institutional arrangements must move beyond the Earth versus space dichotomy toward aiming for multi-planetary sustainability.

Future research aiming at tackling this integrative challenge should unfold the complexities of those relevant institutional architectures across different levels and scales, i.e., global, planetary, and multi-planetary. To capture the complexities of the challenge, it is imperative to understand the development of the different socio-technical and resource systems or 'meta-infrastructures' in space, and their potential multi-planetary cascading implications. In addition, multi-planetary injustice must be taken into account, to counter the growing power of the ultra-rich and identify opportunities for the vulnerable. Bearing in mind that the current rapid developments on foreign celestial bodies are mostly driven by individual interests, future research have to advance our existing understanding on the struggles between personal values and actual political and institutional changes (Chapin et al., 2022; O'Brien, 2018) to govern multi-planetary sustainability. Not only we are the first generation in human history with the knowledge, capability, and responsibility to alter our relationship with Earth (Crutzen, 2006; Steffen et al., 2011), the time has come that we should also ensure a sustainable future in a multi-planetary context. Multi-planetary stewardship will become increasingly important as we extend ethics, sense of belonging, and caring for the 'space' we live in beyond Earth. We shared our perspective on these challenges, and we welcome others to join the discussion.

References

Adilov, N., Alexander, P. J., & Cunningham, B. M. (2018). An economic "Kessler Syndrome": A dynamic model of earth orbit debris. *Economics Letters*, *166*, 79-82. https://doi.org/10.1016/j.econlet.2018.02.025

Al-Rodhan, N. R. F. (2012). *Meta-geopolitics of outer space: An analysis of space power, security and governance*. Palgrave.

Beck, B. (2009). The Next, Small, Step For Mankind: Fixing the Inadequacies of the International Space Law Treaty Regime to Accommodate the Modern Space Flight Industry. *Journal of Science and Technology*, *19*, 1-37.

Biermann, F. (2014). *Earth System Governance: World Politics in the Anthropocene.* The MIT Press.

Biermann, F., & Kalfagianni, A. (2020). Planetary justice: A research framework. *Earth System Governance*, *6*, 100049. https://doi.org/10.1016/j.esg.2020.100049

Biermann, F., & Kim, R. E. (2020). The Boundaries of the Planetary Boundary Framework: A Critical Appraisal of Approaches to Define a "Safe Operating Space" for Humanity. *Annual Review of Environment and Resources*, *45*(1), 497-521. https://doi.org/10.1146/annurev-environ-012320-080337

Brodkin, J. (2021). FCC lets SpaceX cut satellite altitude to improve Starlink speed and latency. https://arstechnica.com/tech-policy/2021/04/fcc-lets-spacex-cut-satellite-altitude-to-improve-starlink-speed-and-latency/

Burch, S., Gupta, A., Inoue, C. Y. A., Kalfagianni, A., Persson, Å., Gerlak, A. K., Ishii, A., Patterson, J., Pickering, J., Scobie, M., Van Der Heijden, J., Vervoort, J., Adler, C., Bloomfield, M., Djalante, R., Dryzek, J., Galaz, V., Gordon, C., Harmon, R., . . . Zondervan, R. (2019). New directions in earth system governance research. *Earth System Governance*, *1*, 100006. https://doi.org/10.1016/j.esg.2019.100006

Butkevičienė, E., & Rabitz, F. (2022). Sharing the Benefits of Asteroid Mining. *Global Policy*. https://doi.org/10.1111/1758-5899.13035

Chang, K. (2020). *NASA Picks Moon Lander Designs by Elon Musk and Jeff Bezos Rocket Companies*. The New York Times. Retrieved 14 November 2021 from https://www.nytimes.com/2020/04/30/science/nasa-moon-lander.html

Chapin, F. S., Weber, E. U., Bennett, E. M., Biggs, R., Van Den Bergh, J., Adger, W. N., Crépin, A.-S., Polasky, S., Folke, C., Scheffer, M., Segerson, K., Anderies, J. M., Barrett, S., Cardenas, J.-C., Carpenter, S. R., Fischer, J., Kautsky, N., Levin, S. A., Shogren, J. F., . . . De Zeeuw, A. (2022). Earth stewardship: Shaping a sustainable future through interacting policy and norm shifts. *Ambio*, *51*(9), 1907-1920. https://doi.org/10.1007/s13280-022-01721-3

Clormann, M. (2021). Switching between worlds apart: Negotiating European space sector cultures through innovation. *Science and Public Policy*, *48*(4), 521-530. https://doi.org/10.1093/scipol/scab038

Conocimiento, V. (2019). Helium-3: Lunar Gold Fever. https://www.bbvaopenmind.com/en/science/physics/helium-3-lunar-gold-fever/

COSPAR. (2020). Panel on planetary protection (PPP). https://cosparhq.cnes.fr/scientific-structure/panels/panel-on-planetary-protection-ppp/

Crutzen, P. J. (2006). The "Anthropocene". In E. Ehlers, Krafft, T. (Ed.), *Earth System Science in the Anthropocene* (pp. 13-18). Springer-Verlag. https://doi.org/10.1007/3-540-26590-2_3

Cuthbertson, A. (2020). *Elon Musk's SpaceX will 'make its own laws on Mars'*. Independent. Retrieved 13 November 2021 from https://www.independent.co.uk/life-style/gadgets-and-tech/elon-musk-spacex-mars-laws-starlink-b1396023.html

Gammon, K. (2021). *How the billionaire space race could be one giant leap for pollution*. The Guardian. Retrieved 11 March 2022 from https://www.theguardian.com/science/2021/jul/19/billionaires-space-tourism-environment-emissions

Goguichvili, S., Linenberger, A., Gillette, A., & Novak, A. (2021). The Global Legal Landscape of Space: Who Writes the Rules on the Final Frontier? *Wilson Center*. https://www.wilsoncenter.org/article/global-legal-landscape-space-who-writes-rules-final-frontier

Greenbaum, D. (2020). Space debris puts exploration at risk. *Science*, *370*(6519), 922-922. https://doi.org/10.1126/science.abf2682

Hollingsworth, G. (2013). Space Junk: Why the United Naions Must Step in to Save Access to Space. *Santa Clara Law Review*, *53*(1), 239-266.

ImpulseSpace. (2022). *The first commercial mission to Mars*. https://www.impulsespace.com/mars

Kessler, D. J., & Cour-Palais, B. G. (1978). Collision frequency of artificial satellites: The creation of a debris belt. *Journal of Geophysical Research*, *83*(A6), 2637. https://doi.org/10.1029/ja083ia06p02637

Kitfield, J. (2010). *Crowded, Congested Space*. Retrieved 10 January 2021 from https://www.airforcemag.com/article/0810space/

Klinger, J. M. (2017). *Rare earth frontiers: From terrestrial subsoils to lunar landscapes*. Cornell University Press.

Kolbert, E. (2021). *Under a White Sky: The Nature of the Future* Crown Publishing Group.

Kotze, L., & Kim, R. (2022). Planetary integrity. In F. Biermann, T. Hickmann, & C.-A. Senit (Eds.), *The Political Impact of the Sustainable Development Goals: Transforming Governance through Global Goals?* (pp. 140-171). Cambridge University Press.

Krag, H. (2021). A sustainable use of space. *Science*, *373*(6552), 259. https://doi.org/DOI: 10.1126/science.abk3135

Marais, E. (2021). *The cost of the billionaire space race will be paid in carbon emissions*. Popular Science. Retrieved 15 March 2022 from https://www.popsci.com/space/space-tourism-climate-change/

Meadows, D., Meadows, D., Randers, J., & Behrens Iii, W. (1972). *Limits to Growth*. Universe Books.

Morin, J. F., & Richard, B. (2021). Astro-Environmentalism: Towards a Polycentric Governance of Space Debris. *Global Policy*. https://doi.org/10.1111/1758-5899.12950

Musk, E. (2017). Making Humans a Multi-Planetary Species. *New Space*, *5*(2), 46-61. https://doi.org/DOI: 10.1089/space.2017.29009.emu

NASA. (2014). *Our Vision for Planetary Sustainability*. National Aeronautics and Space Administration (NASA). Retrieved 19 March 2022 from https://www.nasa.gov/content/planetary-sustainability-our-vision/#.WBgtmiTBZsl.

Nelson, J. (2020). The Artemis Accords and the Future of International Space Law. *American Society of International Law*, *24*(31). https://www.asil.org/insights/volume/24/issue/31/artemis-accords-and-future-international-space-law

O'Brien, K. (2018). Is the 1.5°C target possible? Exploring the three spheres of transformation. *Current Opinion in Environmental Sustainability*, *31*(April 2018), 153-160.

Raworth, K. (2012). A safe and just space for humanity: Can we live within the doughnut? *Oxfam Discussion Papers*. https://www-cdn.oxfam.org/s3fs-public/file_attachments/dp-a-safe-and-just-space-for-humanity-130212-en_5.pdf

Raworth, K. (2017). *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist*. Random House.

RelativitySpace. (2022). *Printing entire rockets*. https://www.relativityspace.com/

Robinson, D., & Mazzucato, M. (2019). The evolution of mission-oriented policies: Exploring changing market creating policies in the US and European space sector. *Research Policy*, *48*(4), 936-948. https://doi.org/10.1016/j.respol.2018.10.005

Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., III, Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sorlin, S., Snyder, P. K., Costanza, R., Svedin, U., . . . Foley, J. A. (2009). A safe operating space for humanity. *Nature*, *461*(7263), 472-475. https://doi.org/10.1038/461472a

Shackelford, S. J. (2014). Governing the Final Frontier: A Polycentric Approach to Managing Space Weaponization and Debris. *American Business Law Journal*, *51*(2), 429–513.

Sheetz, M. (2020). *Elon Musk is 'highly confident' SpaceX will land humans on Mars by 2026*. CNBC. Retrieved 10 March 2022 from https://www.cnbc.com/2020/12/01/elon-musk-highly-confident-spacex-will-land-humans-on-mars-by-2026.html

SpaceX. (2022). Mars & Beyond: The Road to Making Humanity Multiplanetary. https://www.spacex.com/human-spaceflight/mars/

Steffen, W., Persson, Å., Deutsch, L., Zalasiewicz, J., Williams, M., Richardson, K., Crumley, C., Crutzen, P., Folke, C., Gordon, L., Molina, M., Ramanathan, V., Rockström, J., Scheffer, M., Schellnhuber, H. J., & Svedin, U. (2011). The Anthropocene: From Global Change to Planetary Stewardship. *Ambio*, *40*(7), 739-761. https://doi.org/10.1007/s13280-011-0185-x

Tepper, E. (2019). Structuring the Discourse on the Exploitation of Space Resources: Between Economic and Legal Commons. *Space Policy*, *49*, 101290. https://doi.org/10.1016/j.spacepol.2018.06.004

UNOOSA. (2010). Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space. *United Nations Office for Outer Space Affairs (UNOOSA)*. https://www.unoosa.org/pdf/publications/st_space_49E.pdf

US-Congress. (2015). *U.S. Commercial Space Launch Competitiveness Act*. https://www.congress.gov/114/plaws/publ90/PLAW-114publ90.pdf

Van Den Bergh, Folke, C., Polasky, S., Scheffer, M., & Steffen, W. (2015). What if solar energy becomes really cheap? A thought experiment on environmental problem shifting. *Current Opinion in Environmental Sustainability*, *14*, 170-179. https://doi.org/10.1016/j.cosust.2015.05.007

Weeden, B., & Chow, T. (2012). Taking a common-pool resources approach to space sustainability: A framework and potential policies. *Space Policy*, *28*, 166-172.

WEF, W. E. F.-. (2021). *New Space Sustainability Rating addresses space debris with mission certification system*. World Economic Forum. https://www.weforum.org/press/2021/06/new-space-sustainability-rating-addresses-space-debris-with-mission-certification-system

Whittaker, I. (2018). Is SpaceX Being Environmentally Responsible? Falcon Heavy's flashy space car may not have been the best idea—for Mars. *Science, The Conversation*, *2021*(20 July). https://www.smithsonianmag.com/science-nature/spacex-environmentally-responsible-180968098/

Williams, M. (2017). *The future of space colonization – terraforming or space habitats?* Retrieved 4 May 2022 from https://phys.org/news/2017-03-future-space-colonization-terraforming-habitats.html#google_vignette

Yap, X.-S., & Truffer, B. (2022). Contouring Earth-Space Sustainability. *Environmental Innovation and Societal Transitions*, *44*, 185-193.

Yarlagadda, S. (2022). Economics of the Stars: The Future of Asteroid Mining and the Global Economy. *Harvard International Review*. https://hir.harvard.edu/economics-of-the-stars/

Yuan, A. (2021). Filling the vacuum: Adapting international space law to meet the pressures created by private space enterprises. *Denver Journal of International Law and Policy 49*, 27-56.

Zhao, Y. (2004). An international space authority: A governance model for a space commercialization regime. *Journal of Space Law*, *30*(2), 277-296.