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Towards earth-space governance in a multi-planetary era

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ABSTRACT

The recent surge of private enterprise-led space activities is driving what is dubbed the New Space revolution. SpaceX as a frontrunner is working towards colonizing Mars by 2050, with the goal of transforming humans into a multi-planetary species. These developments and the imaginaries they generate are reshaping the discourse on planetary sustainability, where celestial bodies like Mars are seen as a solution to the challenges facing our Earth. Yet, space and its sustainability remain a rather distant concern in earth system governance. In this Perspective, we argue that the New Space revolution necessitates a corresponding shift in the governance paradigm from planetary to multi-planetary for a more integrated approach that recognizes the interdependencies of Earth and space sustainability. We propose a new governance model, earth-space governance, aimed at promoting justice and integrity for all forms of life in a multi-planetary context.

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

'Occupy Mars', Elon Musk tweeted in 2019. Although the idea of colonizing Mars may still seem like science fiction, the space industry is expanding at a faster pace than ever, increasing the likelihood of the idea becoming a reality. Elon Musk is 'highly confident' that SpaceX will land humans on Mars in 2029 (Mack, 2022), with settlements established 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 exponential growth in space activities driven by private entrepreneurs such as Jeff Bezos and Richard Branson in partnership with the United States National Aeronautics and Space Administration (NASA) and other government space agencies. Smaller ventures like Relativity Space, 2022 and Impulse Space, 2022 are also joining the race to Mars. Dubbed the New Space revolution (Jakhu et al., 2017; Robinson and 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 developments of 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 projects space as a key part of the solution to sustainability challenges on Earth. Mars is, for example, portrayed as a future habitat for humanity when Earth becomes less hospitable due to global environmental change. Asteroids and the Moon are seen as limitless sources of minerals needed for global energy transitions. Even if these plans do not materialize, the imaginary of a multi-planetary future generated by Elon Musk and others can still be performative. Their powerful imaginary may steer policy processes, redirect finances, or project an alternative social order (Tutton, 2018), with real and immediate implications for sustainability governance on Earth.

The narrative of a multi-planetary future is powerful and problematic in several ways. While it promises benefits, it overlooks the potential social and environmental consequences that may not be evenly distributed. Furthermore, it risks legitimizing space activities by private enterprises, which could lead to the appropriation of space resources for the benefit of a select few. For example, Elon Musk announced that SpaceX, a privately traded company, plans to create its own laws or 'self-governing principles' when establishing a human settlement on Mars (Cuthbertson, 2020). Although this may not be as straightforward as he thinks, Musk's vision raises concerns about the current state of space governance, which is inadequate and underdeveloped in light of the rapid growth in space activities.

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We are not the only ones to see this problem. Others have also raised concerns about the depiction of space as an inexhaustible source of resources and an indiscriminate dumping ground. They call for 'a more integrative approach including both our space environment and planet Earth' (Losch, 2020, p.1; see also Galli and Losch, 2019). In a similar vein, Yap and Truffer (2022) have introduced the concept of 'earth-space sustainability' to emphasize the interdependency between sustainability challenges on Earth and in space. For example, they caution that the increasing use of space resources, if not properly managed, may reinforce capitalist structures and worsen social injustice on Earth. In a multi-planetary society, sustainability on Earth and sustainability in space will be interrelated. This new perspective necessitates rethinking core concepts of earth system governance such as planetary integrity (Kotzé and Kim, 2022), planetary justice (Biermann and Kalfagianni, 2020), and planetary stewardship (Steffen et al., 2011; Chapin and Knapp, 2015) in view of the anticipated expansion of the anthroposphere from the Earth system to the solar system. The shift from a 'planetary' to a 'multi-planetary' paradigm will require a new governance model that integrates Earth with space effectively.

In this Perspective, 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 and integrated with space, instead of treating space as a separable entity from Earth. After this introduction, we explore the concept of sustainability in a multi-planetary context by highlighting how sustainability on Earth and sustainability in space are increasingly intertwined. We then discuss the worrying signs of development in space governance, which is expanding and fragmenting at the same time through the proliferation of private actors and institutions. We propose earth-space governance as a new model that is more fit for purpose for a multi-planetary future and outline research directions ahead.

2. Sustainability in a multi-planetary context

Sustainability challenges on Earth and in space have become increasingly intertwined. There are some policy attempts and media coverage where earth-space sustainability is a key concern. The COSPAR Planetary Protection Policy, for instance, discusses the issue of bi-directional contamination with microorganisms between Earth and other celestial bodies (COSPAR, 2020). The carbon footprint of space activities is also being debated. Space rockets emit approximately 150 metric tons of carbon dioxide per launch, which is equivalent to three transatlantic flights carrying 50–100 times more passengers (Whittaker, 2018). This has caught public attention, with media outlets such as the Guardian reporting on 'how the billionaire space race could be one giant leap for pollution' (Gammon, 2021) with 'the cost … paid in carbon emissions' (Marais, 2021).

The accumulation of space debris in Earth's orbit has become a heated topic of debate in recent years. Although satellites bring numerous benefits, the increasing density of satellites poses a significant risk known as the Kessler syndrome, a chain reaction of collisions that can be triggered when the density of objects in orbit reaches a critical level (Adilov et al., 2018; Kessler and Cour-Palais, 1978; Kitfield, 2010). If that happens, the chaotic distribution of debris in orbit could significantly impede the use of satellite services and access to space for future generations. 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 are being promoted as solutions to sustainability challenges on Earth and as resources for space missions. For instance, helium on the Moon is actively being considered as a new source of energy to meet the rising energy demands on Earth (Conocimiento, 2019). However, these activities not only leave permanent scars on celestial bodies but may also perpetuate Earth-bound extractivism and create new sustainability problems. Framing the Moon as a solution to meeting Earth's demands risks distracting the ongoing sustainability transformation policies and reinforcing the dominant economic models. Moreover, concerns have been raised about whether developing countries will have equitable access to space, given their limited technological and financial capabilities (Butkevičienė and Rabitz, 2022).

In sum, pursuing space exploration and exploitation in the name of sustainability may exacerbate environmental and societal challenges both on Earth and in space. Developing an integrative governance framework to address sustainability issues within and beyond the Earth system is, therefore, a fundamental challenge in the era of multi-planetary activities.

3. Expansion and privatization of space governance

Despite efforts by space governance institutions to address the increasing interdependency between Earth and space, space governance has been inadequate in the face of new challenges. The Outer Space Treaty of 1967 is the primary framework for governing the use, occupation, and appropriation of outer space, aiming to benefit all humankind by ensuring access to space and equitable sharing of benefits derived from space activities. However, this treaty, which has not been updated in over five decades, is no longer effective in addressing the emerging challenges of the New Space age, such as the regulation of space debris (Beck, 2009; Hollingsworth, 2013; Goguichvili et al., 2021). The Moon Treaty of 1979 was originally designed to 'prevent the disruption of the existing balance of [the Moon's] environment' as well as potentially harmful consequences on Earth. However, only 18 parties have signed it as of 2023, whereas major spacefaring nations like the United States, China, and Russia are not among them.

In the absence of adequate space governance, various state and non-state actors are rapidly expanding their scope of influence in space through their own ways of governing to gain political interests and commercial opportunities (Nelson, 2020). To capitalize on new opportunities, minilateralism is becoming more prevalent as smaller groups of countries form alliances based on shared economic interests. For example, in 2020, the United States government introduced a 'shared vision for principles' for the governance of civil exploration and use of the Moon, Mars, comets, and asteroids through the Artemis Accords framework. Over 20 countries have since signed the Accords, which could allow companies from the member states to commercially profit from space resources. For instance, the United States Commercial Space Launch Competitiveness Act of 2015 supports a 'pro-growth environment' for its commercial space industry and allows private companies to transport and sell resources they recovered from space. While the Artemis Accords recognize the importance of compliance with the Outer Space Treaty, it also risks further fragmenting the global space governance framework by prioritizing commercial interests over other considerations. Such an expansion of self-driven space governance has prompted scholars to argue for an updated international space law that responds to the growing influence of private space enterprises (e.g., Herron, 2016; Yuan, 2021).

The increasing expansion and privatization of space activities also risk fragmenting the architecture of space governance. Governments in the United States and the European Union are increasingly collaborating with private actors, promoting missions that are jointly led by public and private entities (Al-Rodhan, 2012; Robinson and Mazzucato, 2019). For instance, the United States government and NASA contracted companies such as SpaceX, Blue Origin, and Dynetics to develop lunar landers and resource mining technologies on and near the Moon (Chang, 2020). Private actors in these leading spacefaring nations have been driving the New Space revolution since the 2000s, resulting in these states becoming increasingly dependent on finance and technologies from the private sector. This growing reliance on private actors gives them increasing power to shape institutions and legitimize their various space activities, including space tourism in low Earth orbit.

The mutual reinforcement of privatization and fragmentation in space governance is a growing concern. The lack of a cohesive institutional framework provides private actors with opportunities to establish their own rules and exploit space resources, which in turn leads to further institutional fragmentation.

The impact of the private sector on the fragmentation of governance in Earth's orbital environment, a key gateway to outer space, is already evident. Private companies from the satellite sector have started taking advantage of the weak and fragmented governance architecture. They engage in forum shopping, seeking out states with more lenient regulations for satellite launches. But not all of them get a fair chance in all processes. There are some instances where state agencies prioritize the interests of specific companies that align with their political interests. For instance, the United States Federal Communications Commission dismissed claims from several companies against Starlink's placement of satellites in a lower orbit and approved its corporate plan to launch 12,000 satellites, citing improvements to the speed and latency of the service (Brodkin, 2021).

To mitigate the impact of commercial space activities, various soft institutions have been added to the fragmented mix of space governance structures. These include the Space Debris Mitigation Guidelines from the United Nations Office for Outer Space Affairs (UNOOSA, 2010), the Space Sustainability Rating initiative (World Economic Forum, 2021), and the Net Zero Space initiative launched at the Paris Peace Forum 2021. Although these examples of voluntary institutions share a common goal of promoting space sustainability, their long-term effectiveness remains an open question.

The rapid expansion of space governance through privatized rulemaking is likely to allow the rich and powerful to use the broad realm of space for their own benefits, either at the expense of more sustainability consequences on Earth or severe contestation and environmental degradation in space. Regardless of which direction the development of space governance takes, the current trend poses a serious risk to a multiplanetary future: Governance on Earth may be disintegrated from the one in space and vice versa, resulting in highly unsustainable consequences as a whole.

The challenges of privatization and fragmentation in space governance have been widely recognized by scholars (Weeden and Chow, 2012; Tepper, 2019). Various reform proposals have been put forward, ranging from establishing a centralized International Space Authority (Zhao, 2004) to adopting a more polycentric governance approach (Shackelford, 2014; Morin and Richard, 2021). We acknowledge merit in many of such policy options. However, we argue that these options should not be considered in isolation but rather as part of a fundamentally new governance model that recognizes the paradigm shift from planetary to multi-planetary sustainability in light of the development of New Space.

4. Towards earth-space governance

We propose 'earth-space governance' as a new approach to sustainability governance in a multi-planetary context. This model recognizes the interconnections between Earth and space sustainability and considers that the scope of ecological and social concerns must now extend far into space. The proposed governance model explicitly brings sustainability challenges of the rest of the solar system to the forefront of space governance needs, and integrates earth system governance with space governance through the recognition of their interlinkages (see Fig. 1).

Earth-space governance represents a significant departure from the current governance models, including earth system governance. While earth system governance is intended as a comprehensive framework for research and policy on global environmental change (Biermann, 2014; Burch et al., 2019), its scope is largely limited to the boundaries of the Earth system. Earth system governance fails to acknowledge the new and strengthening interconnections between Earth and space sustainability, and it does not consider space as an integral part of ecological and social concerns. Although the human-nature dichotomy has eroded in earth system governance, the classic dichotomy between Earth and space remains, often depicted as 'spaceship Earth' floating in outer space. Furthermore, gender stereotypes that portray Earth as a nurturing, feminine entity to be protected, and space as a frontier open for exploration, exploitation, and competition, persist in current governance models.

In contrast, earth-space governance challenges the notion of the Earth system as a closed, isolated system and reckons the expansion of human activities and ambitions into space. In the new model, such expansion causes a flow of influence that is no longer solely unidirectional from Earth to space but also increasingly from space back to Earth (section 2). On the one hand, earth system governance has to start considering the current expansion of space governance to planet Mars and other celestial bodies. On the other hand, the expansion and

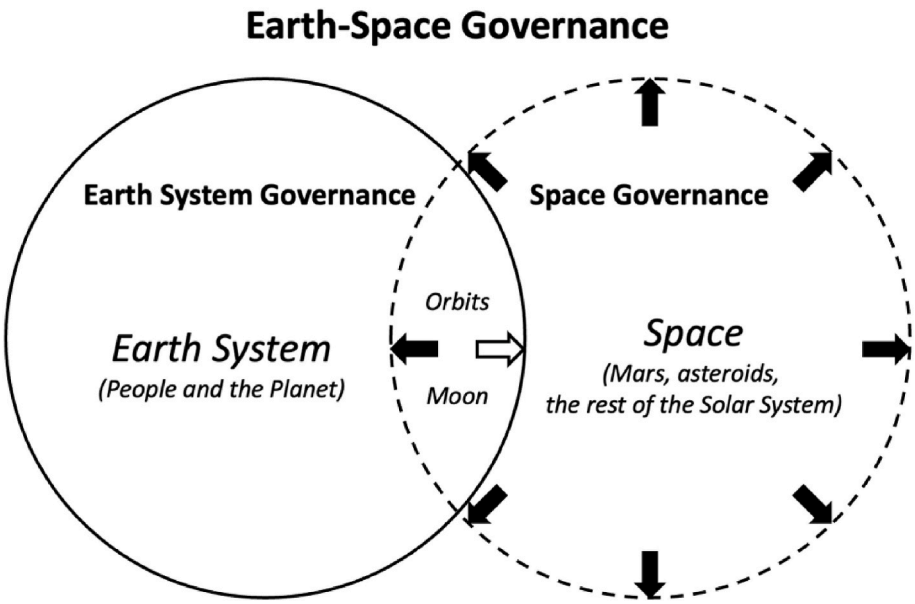

Fig. 1. Earth-space governance as a novel governance framework that integrates earth system governance and space governance.

fragmentation of space governance driven by the proliferation of private actors and institutions (section 3) urge closer engagement with core principles of earth system governance. Earth-space governance promotes a governance framework that effectively integrates institutions for earth-space sustainability. Its goal is to promote a just and sustainable future for all life forms on Earth and beyond in a multi-planetary setting, where environmental responsibility, ethics, and 'sense of place' extend beyond Earth.

In a multi-planetary society where space mining or human settlement on Mars is thinkable and practicable, planetary integrity may need to be reconceptualized as the current biophysical limits to growth (Meadows et al., 1972) could be impacted. Additionally, it is crucial to reconsider planetary justice, as space exploration and exploitation will create both economic and political winners and losers. The discovery or introduction of other life forms in space through human interventions will furthermore raise challenging questions about inter-species justice that must be addressed.

To achieve a shared sustainability objective, novel political institutions must address both Earth-bound and space-based challenges. For instance, restrictions on resource extraction on Earth may incentivize political and commercial interests in space mining. Mining minerals on other celestial bodies could affect the energy provision systems on Earth, alter geopolitical competition for rare minerals, create new material flows, and disrupt existing supply chains (Klinger, 2017; Yarlagadda, 2022; Moore et al., 2022). Some techno-scientific optimists have even suggested Moon mining as a way to facilitate space-based geoengineering (Milman, 2023). To govern these interconnected systems effectively, fragmented institutions must align and integrate across various levels, ranging from national to global, planetary, and multi-planetary. Any political institutions responsible for Mars settlements must uphold principles of sustainability and peace on Earth and avoid perpetuating inequalities or injustices on our home planet.

5. Future research directions

The New Space revolution is shaping a multi-planetary era, which calls for a rethinking of sustainability governance of the Earth system. The future governance models should move beyond the 'Earth versus space' mentality, which focuses solely on either Earth or space sustainability in isolation. Instead, an integrated approach that considers multi-planetary sustainability should be pursued. This shift in focus is necessary to ensure that space activities promote integrity and justice for both Earth and space, whose sustainability is increasingly interconnected.

There are several avenues for future research. Understanding the rapid development of socio-technical systems, 'meta-infrastructures' (Yap and Truffer, 2022), or resource systems across the earth-space interface is a crucial starting point for exploring governance for multi-planetary sustainability. In particular, research has to derive a better understanding of how these developments interrelate or interfere with the ongoing global sustainability transitions and transformations (Schot and Kanger, 2018; Kanger and Schot, 2019; Markard et al., 2021). Identifying the agents leading and shaping these developments, which are often groups of techno-elites, is another crucial step in addressing justice-related questions. Earth-space governance research should also examine the emerging patterns of contestation between actor values, political and institutional changes, and public policy ideologies that inform decisions (Dryzek, 2013; O'Brien, 2018; Chapin et al., 2022; Yap et al., in press) in a multi-planetary context. Addressing future earth-space sustainability must be at the forefront of the global governance agenda.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

Adilov, N., Alexander, P.J., Cunningham, B.M., 2018. An economic "Kessler Syndrome": a dynamic model of earth orbit debris. Econ. Lett. 166, 79–82.
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. J. Sci. Technol. 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.
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.
Butkevičienė, E., Rabitz, F., 2022. Sharing the Benefits of Asteroid Mining. Global 13, 247–258.
Chang, K., 2020. NASA Picks Moon Lander Designs by Elon Musk and Jeff Bezos Rocket Companies. https://www.nytimes.com/2020/04/30/science/nasa-moon-lander.html.
Chapin, F.S., Knapp, C.N., 2015. Sense of place: a process for identifying and negotiating potentially contested visions of sustainability. Environ. Sci. Pol. 53, 38–46.
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, 1907–1920.
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/.
Cuthbertson, A., 2020. Elon Musk's SpaceX will 'make its own laws on Mars'. . https://www.independent.co.uk/life-style/gadgets-and-tech/elon-musk-spacex-mars-laws-starlink-b1396023.html.
Dryzek, J.S., 2013. The Politics of the Earth, Third ed. Oxford University Press.
Galli, A., Losch, A., 2019. Beyond planetary protection: What is planetary sustainability and what are its implications for space research? Life Sciences in Space Research 23, 3–9.
Gammon, K., 2021. How the Billionaire Space Race Could Be One Giant Leap for Pollution. 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? 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, 922.
Herron, T.J., 2016. Deep space thinking: what Elon musk's idea to nuke Mars teaches us about regulating the visionaries and daredevils of outer space. Colum. J. envtl. l. 41, 553.
Hollingsworth, G., 2013. Space junk: why the united naions must step in to save access to space. St. Clara Law Rev. 53, 239–266.
Impulse Space, 2022. The first commercial mission to Mars. https://www.impulsespace.com/mars.
Jakhu, R., Pelton, J., Nyampong, Y.O.M., 2017. Space Mining and its Regulation. Springer Praxis Books, Switzerland.
Kanger, L., Schot, J., 2019. Deep transitions: theorizing the long-term patterns of socio-technical change. Environ. Innov. Soc. Transit. 32, 7–21.
Kessler, D.J., Cour-Palais, B.G., 1978. Collision frequency of artificial satellites: the creation of a debris belt. J. Geophys. Res. 83, 2637.

Kitfield, J., 2010. Crowded, congested space. https://www.airforcemag.com/article/0810space/.
Klinger, J.M., 2017. Rare Earth Frontiers: from Terrestrial Subsoils to Lunar Landscapes. Cornell University Press.
Kotzé, L., Kim, R., 2022. Planetary integrity. In: Biermann, F., Hickmann, T., Senit, C.-A. (Eds.), The Political Impact of the Sustainable Development Goals: Transforming Governance through Global Goals? Cambridge University Press, pp. 140–171.
Krag, H., 2021. A sustainable use of space. Science 373, 259.
Mack, E., 2022. Elon Musk Has New Estimate for When Humans Might First Step on Mars. https://www.cnet.com/science/space/elon-musk-has-new-estimate-for-when-humans-might-first-step-on-mars/.
Losch, A., 2020. Planetary sustainability collection. Global Sustainability 3, 1–3.
Marais, E., 2021. The cost of the billionaire space race will be paid in carbon emissions. https://www.popsci.com/space/space-tourism-climate-change/.
Markard, J., Van Lente, H., Wells, P., Yap, X.-S., 2021. Neglected developments undermining sustainability transitions. Environ. Innov. Soc. Transit. 41, 39–41.
Meadows, D., Meadows, D., Randers, J., Behrens Iii, W., 1972. Limits to Growth. Universe Books.
Milman, O., 2023. A solution to the climate crisis: mining the moon, researchers say. https://www.theguardian.com/science/2023/feb/08/moon-dust-moonshot-geoengineering-climate-crisis.
Moore, K.R., Segura-Salazar, J., Bridges, L., Diallo, P., Doyle, K., Johnson, C., Foster, P., Pollard, N., Whyte, N., Wright, O., 2022. The out-of-this-world hype cycle: progression towards sustainable terrestrial resource production. Resour. Conserv. Recycl. 186, 106519.
Morin, J.F., Richard, B., 2021. Astro-environmentalism: towards a polycentric governance of space debris. Global Policy 12, 568–573.
Musk, E., 2017. Making humans a multi-planetary species. New Space 5, 46–61.
NASA, 2014. Our vision for planetary sustainability.. 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.
O'Brien, K., 2018. Is the 1.5°C target possible? Exploring the three spheres of transformation. Curr. Opin. Environ. Sustain. 31, 153–160.
Relativity Space, 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. Res. Pol. 48, 936–948.
Schot, J., Kanger, L., 2018. Deep transitions: emergence, acceleration, stabilization and directionality. Res. Pol. 47, 1045–1059.
Shackelford, S.J., 2014. Governing the final frontier: a polycentric approach to managing space weaponization and debris. Am. Bus. Law J. 51, 429–513.
Sheetz, M., 2020. Elon Musk is 'highly confident' SpaceX will land humans on Mars by 2026. 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, 739–761.
Tepper, E., 2019. Structuring the discourse on the exploitation of space resources: between economic and legal commons. Space Pol. 49, 101290.
Tutton, R., 2018. Multiplanetary imaginaries and utopia. Sci. Technol. Hum. Val. 43, 518–539.
UNOOSA, 2010. Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space. https://www.unoosa.org/pdf/publications/st_space_49E.pdf.
Weeden, B., Chow, T., 2012. Taking a common-pool resources approach to space sustainability: a framework and potential policies. Space Pol. 28, 166–172.
Yap, X.-S., Heiberg, J., Truffer, B., in press. The emerging global socio-technical regime for tackling space debris: A discourse network analysis. Acta Astronautica.
Whittaker, I., 2018. Is SpaceX Being Environmentally Responsible? Falcon Heavy's flashy space car may not have been the best idea—for Mars. https://www.smithsonianmag.com/science-nature/spacex-environmentally-responsible-180968098/.
Williams, M., 2017. The future of space colonization – terraforming or space habitats? . https://phys.org/news/2017-03-future-space-colonization-terraforming-habitats.html#google_vignette.
World Economic Forum, 2021. New Space Sustainability Rating Addresses Space Debris with Mission Certification System. https://www.weforum.org/press/2021/06/new-space-sustainability-rating-addresses-space-debris-with-mission-certification-system.
Yap, X.-S., Truffer, B., 2022. Contouring 'earth-space sustainability'. Environ. Innov. Soc. Transit. 44, 185–193.
Yarlagadda 2022., S.. Economics of the stars: the future of asteroid mining and the global economy. 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 J. Int. Law policy 49, 27–56.
Zhao, Y., 2004. An international space authority: a governance model for a space commercialization regime. J. Space Law 30, 277–296.