The Missing Ingredients for a Polycentric Governance System of Orbital Debris

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Abstract

The pollution of Earth's orbits by debris represents a pressing environmental problem. Recognizing that geopolitical factors hinder the adoption of a multilateral solution, several experts advocate for a polycentric governance system, inspired by Elinor Ostrom's work. This paper assesses the viability of such a proposal. It finds that the global network of space organizations exhibits some of the structural characteristics of a polycentric system. However, arrangements concluded among these organizations fail to promote sustainability norms and interviews with key stakeholders reveal the absence of several favorable factors for a sustainable polycentric governance system. The paper concludes that a polycentric structure alone does not guarantee the emergence of sustainable governance. As orbital space is a relatively "easy case" for applying polycentricity theory to the global commons, this research serves as a reminder about the limitations of polycentric approaches in global environmental politics.

Keywords

Polycentricity; Space sustainability; space debris; space governance.

Introduction

The proliferation of space debris is unsustainable. Earth's orbital space is polluted with defunct satellites, abandoned fuel tanks, and fragments from satellite collisions. The crash of the satellites Iridium 33 and Cosmos-2251 in 2009 alone generated thousands of pieces of debris. Some estimates suggest that there are currently over 1 100,000 debris larger than 1 cm orbiting around Earth, collectively weighting more than 13 000 tons (ESA 2024). This pollution already necessitates frequent avoidance maneuvers by satellite operators and is poised to worsen with the expanding space industry. Some analysts even fear that a chain reaction of collisions will create an exponential surge of new debris (Kessler and Cour-Palais, 1978).

The ramifications of such space pollution are profound. Even small debris, such as bolts, pose significant risks due to their high velocities in low earth orbit. The damages created by debris could have catastrophic consequences as satellites are essential for telecommunications, weather forecasting, navigation, earth observation, and geolocation.[1] Our daily reliance on these satellites extends to activities such as agricultural planning, flight navigation, maritime transport, access to the internet, television broadcasting, bank transfers, and natural disaster management. Collisions may also diminish societies' ability to address other environmental problems as satellites play an essential role in monitoring atmospheric pollution, deforestation, oceans' health, ozone depletion, and climate change. (UN 2021)[2]

Recent studies suggest that Elinor Ostrom's lessons on polycentric local resources management can be applied to orbital debris to foster a more sustainable space governance (Johnson-Freese and Weeden 2012; Weeden and Chow 2012; Shackelford 2014; Tepper 2014; Kurt 2015; Migaud et al. 2021; Lambach and Wesel 2021; Nordman 2021). However, most of these studies are theoretical and provide only anecdotal evidence. This paper takes a step further by empirically assessing the polycentricity of the space governance system. To conduct this empirical assessment, we establish a clear distinction between the *structural characteristics*, the *expected emerging properties*, and the *favorable factors* of a polycentric system that manage common pool resources sustainably.

Using a combination of network analysis, content analysis, and interview data, this study finds that, while the outer space governance system embodies a polycentric structure, sustainability norms governing orbital debris have not yet emerged from it. It further argues that this non-emergence could be explained by the absence of several favorable factors observed in well-functioning polycentric systems. At a time when polycentricity is presented as a potential model for various global environmental challenges (e.g. Lofthouse et al. 2023), this finding is a useful reminder that a polycentric structure alone is not sufficient to ensure sustainability.

The paper is divided into four sections. This first section reviews the literature and underscores the necessity of an empirical investigation. The second presents the results of a network analysis of space arrangements and establishes that space governance has the structural characteristics of a polycentric system. The third section relies on content analysis and finds that norms addressing orbital debris have only modestly emerged from this governance system. The fourth part draws on interview data to explore some of the missing favorable factors in an effort to explain why this governance system, despite its structural characteristics, has so far failed to manifest the emerging properties of a well-functioning polycentric system.

[1] A recent study estimates that "debris will cause negative damage of approximately 1.95% of global Gross Domestic Product (GDP) in the long term if no debris is remediated at all." (Nozawa et al. 2023: 101580)

[2] Wilson and Vasile (2023) call the "space sustainability paradox" the situation whereby the increasing use of space to address social and environmental problems on Earth contributes to an unsustainable number of orbital launches.

Applying polycentricity thinking to orbital debris

A sustainable space governance system would mitigate, monitor and remove orbital debris in a manner that reduces the risk of collision over time. Various technical and policy solutions are available to address the problem of orbital debris. These include requiring operators to deorbit their satellites immediately after their mission and actively removing large debris with service satellites (IGRC 2021; WEF 2023). However, these solutions have not been widely implemented due to many space actors' reluctance to incur these associated costs. This situation creates a collective action problem, wherein the interests of individual space actors conflict with those of the space community as a whole.

The resolution of this collective action problem is complicated by the fact that Earth's orbital space is a common-pool resource, as its consumption is both non-excludable and rivalrous (Ostrom 2003).[3] Orbital space is non-excludable because space law treaties guarantee free access to it, including for debris-emitting satellites. It is also rivalrous since each additional space object decreases the number of available orbital slots, increases congestion in orbit, and reduces safe orbiting options for future spacecraft. In this context, space actors have incentives to continue using the Earth's orbits unsustainably as each reaps the full benefits of their activities while sharing the added risks with others (Byers and Boley 2023; Lawrence et al. 2022).

Space experts have proposed different governance solutions to address this problem. These proposals can be grouped into three categories (Morin and Richard 2021). The first group advocates for stronger hierarchical regulations. They include calls for a new binding multilateral treaty on orbital debris and the creation of a specialized United Nations agency (Tan 2000; Mayer 2010; Imburgia 2011; Hollingsworth, 2013; Gupta 2016). The second category suggests leveraging market mechanisms to allocate orbit slots more sustainably. Proposals from this second group include the territorialization of orbits and tradable debris licenses (Cooper 2003; Elhefnawy 2003; Hudgins 2003; Taylor 2011; Salter and Leeson 2014; Salter 2017; Buchs, and Bernauer 2023). A third approach – which this paper critically assesses – is cultivating a polycentric governance system for orbital debris (Johnson-Freese and Weeden 2012; Weeden and Chow 2012; Shackelford 2014; Tepper 2014; Kurt 2015; Migaud et al. 2021; Nordman 2021; Lambach and Wesel 2021). In a polycentric governance system, cooperative arrangements governing common-pool resources are not hierarchically organized around a single central authority but instead involve interconnected decision-making centers, independent from each other (Ostrom *et al*. 1961: 831).

Ostrom (1990) observed that governance systems with a polycentric structure often display emerging properties conducive to the sustainable management of common-pool resources. In such systems, decision-making units can independently innovate, learn from failures, and self-correct. These lessons are then shared among interconnected units, fostering adaptability. This adaptability could enable more sustainable self-management of common-pool resources compared to centralized or market-driven approaches. Ostrom and her colleagues has found multiple empirical examples of

[3] Orbital space can also be described as a congested public good.

polycentric system that govern common pool resources in a sustainable manner, from lobster fishing in Maine to irrigation systems in Iran and mountain grazing in Switzerland (Ostrom 1990).

While Ostrom's research primarily focused on local commons, a similar logic can potentially apply to certain global commons (Ostrom *et al*. 1999; Dietz *et al.* 2003; Ostrom 2010b; Stern 2011; Cox 2014; Fleischman *et al.* 2014). It is often argued that polycentricity is more challenging at the global than at the local level since international relations are associated with a larger number of actors, a dilution of shared meta-norms, higher discount rates, more diffused interests, and higher transaction costs (Keohane and Ostrom 1994: 413). However, none of the obstacles are particularly pronounced for the case of orbital debris. Outer space governance involves fewer users than some local polycentric systems for watersheds or fisheries. Moreover, all space actors are bound together by the uncontested meta-norms provided in the Outer Space Treaty. They all favor low discount rates since they invest massively with long-term objectives in mind. Their collective interest in self-restraint is clear since several space actors that are responsible for the generation of debris are also among the primary victims of congestion and collision. They also frequently conclude bilateral agreements among themselves, suggesting manageable transaction costs. Ostrom's framework was developed around renewable resources, and usable slots in Earth's orbits can be conceptualized as analogous to renewable resources because they become available to host a new satellite once the previous one is deorbited.[4] Ostrom (2010b; 2012) and other scholars following in her footsteps (e.g. Dorsch and Flachsland 2017; Jordan et al. 2018; Cole 2015; Nordman 2021) believe that the lessons of polycentric governance can provide useful guidance for the more complex issue of climate change. In the governance of climate change, there are countless polluters, norms are hotly contested, discount rates seem high, negative externalities do not primarily affect polluters, transaction costs restrict negotiations, and the resources used are non-renewable. In comparison, the management of orbital debris is a much easier case for the application of polycentric framework to a global common, with lower structural obstacles.

Ostrom did not view polycentric governance through rose-colored glasses (2010a). She warned against the "perverse and extensive uses of policy panaceas" (2007: 15181) While a polycentric structure can lead to sustainable resource management, it often comes at the cost of redundancies, inefficiencies, and ambiguities (Blomquist and Schröder 2019). Even when sustainability is achieved at the system-level, failures often persist at the unit level, generating inequities. Polycentricity might even exacerbate power asymmetries as powerful actors can navigate complex systems more easily than weaker actors (Morrison et al. 2019). Nevertheless, despite these shortcomings, Ostrom (1999) believed that polycentricity is often a more feasible and realistic option than centralized or market-based alternatives. Her empirical approach led her to conclude that abstract solutions conceived by theorists are rarely applicable in practice. She advocated for cultivating imperfect solutions from the messiness of social, historical, and political realities rather than imposing an ideal order on communities.

[4] That said, several debris will not deorbit on a human timescale and require active removal, a process that is not well conceptualized by Ostrom's framework.

This pragmatic approach motivates an increasing number of space experts to advocate for a polycentric governance system for orbital debris. They argue that a global arrangement on debris, based on either regulations or the market, is "unlikely to materialize" (Kurt 2015: 306), "not a realistic option" (Lambach and Wesel 2021: 5), "extremely limited" (Johnson-Freese and Weeden 2012: 77), and "no longer feasible" (Tepper 2019). This is because institutionalizing centralized regulations or a global market would require nearly universal support to function properly. If just a few states refuse to participate in a newly established regime, space companies could relocate to these recalcitrant states to benefit from "flags of convenience" and avoid costs associated with debris mitigation measures. In the last fifty years, power politics has prevented the adoption of multilateral treaties related to outer space and this unfavorable geopolitical context will likely persist or worsen. According to several space governance experts, applying the lessons of polycentricity to orbital debris is a more politically feasible alternative to centralized regulations or a global market.

Yet, scholars advocating for a polycentric governance system for orbital debris have not conducted a rigorous empirical assessment of the current governance system. There is uncertainty over whether the current system is already polycentric or only has the potential to become so. Studies argue that polycentricity *can*, in principle, contribute to the mitigation of debris pollution. However, without an empirical investigation, it is difficult to evaluate how much potential the current governance system has, and in which direction it should be steered.

To assess the governance system for orbital debris through the lens of polycentricity theory, it is useful to distinguish between a polycentric system's (1) defining structural characteristics, (2) expected emerging properties, (3) and favorable factors. The structural characteristics refer to the architectural features of a polycentric system, including the multiplicity and interconnectedness of distinct decision-making centers (Kim 2020). The emerging properties are the expected outcome of processes like experimentation and learning that a polycentric structure enables (Orsini et al. 2020). One of these expected outcomes is the emergence of sustainability norms (Winston 2023). Lastly, favorable factors are variables that have been found to facilitate the emergence of these expected outcomes (Ostrom 1990). This paper argues that a polycentric structure alone is not sufficient for a governance system to exhibit the emergence of sustainability norms, a claim that is not always acknowledged among enthusiasts of polycentricity for space governance. The following sections assess successively the structural characteristics, the emerging properties, and the favorable factors of the orbital debris governance system.

The polycentric structure of outer space governance

A distinctive structural feature of polycentric systems is their composition of several interacting governance centers, operating autonomously and at different levels (Ostrom *et al.* 1961: 831). Previous studies have found that several governing bodies do coexist in global space governance, such as the International Telecommunication Union and the United Nations Committee on the Peaceful Uses of Outer Space (Shackelford, 2014, p. 3; Tepper, 2014, p. 683). However, the mere presence of a variety of governance centers does not automatically qualify a governance system as polycentric. A governance system can encompass multiple and diverse organizations and yet remain centralized around a single decision-making center. Assessing the polycentricity of a governance system requires an examination of the ordering structure created by the connections linking the various governance units (Galaz et al. 2012: 24).

We use network analysis to examine the structural dimension of the space governance system. Following several studies in global environmental politics, we conceptualize this governance system as a network of actors connected by shared institutional arrangements, the main building blocks of global governance (e.g. Galaz et al. 2012; Kinne 2013; Kim, 2020; Hollway et al. 2020; Orsini, A. et al. 2020). To conduct this analysis, we built a list of nodes from a comprehensive dataset of space actors, which includes all organizations involved in designing, owning, launching, operating, tracking, monitoring, or regulating space objects (Morin and Beaumier 2024). This encompasses states (40%), governmental organizations (27%), international organizations (4%), for-profit entities (21%), universities (4%), and non-profit organizations (3%). The edges list is derived from a compilation of institutional arrangements concluded between at least two of these space organizations (Morin and Tepper 2023). These arrangements include treaties (17%), contracts (38%), certifications (3%), memorandums of understanding (30%), and guidelines (12%).[5] Each arrangement is an indication of at least minimal shared understandings and cooperative behavior. Using this data, the space governance system is made up of 499 space organizations interconnected by 1831 space arrangements, as of the year 2020.[6]

Kim (2020) argues that polycentric structures are characterized by three specific network measures: a low centralization score, a high degree of modularity and a high clustering coefficient. First, the centralization measure[7] examines whether the system is mono-centric. A high score suggests a star-shaped governance structure, while a low score hints to dispersed authority. Second, the modularity measure helps track to what extent actors have organized themselves around relatively independent collaborative clusters by examining the formation of communities[8] within the network and the extent to which they are segregated from each other. A highly modular governance system implies that actors within the same structural community are highly interconnected, while their connections with actors from other communities are limited. Third, the clustering coefficient[9] measures the cohesion among actors within these clusters, an important enabler of information sharing and trust-building. A high coefficient indicates that most actors connected to a given actor also share connections among themselves.

For each of these three measurements, there is no precise cutoff point or minimal threshold as the degree of polycentricity is a continuous variable (Galaz et al. 2012: 24). Nevertheless, whether

[5] Our collection of arrangements does not include domestic law and regulations as they do not *voluntary* unite at least two space actors.

[6] We look at the year 2020 as data available for later years may not be as exhaustive.

[7] The centralization score quantifies the difference between the most connected node and all other nodes, normalized by the theoretical maximum of this score.

[8] The term “community” refers to structural clusters of nodes that are densely connected. The community detection was done using the cluster_walktrap function of the igraph package in R (Pons and Latapy, 2005).

[9] The clustering coefficient represents the ratio of how much adjacent nodes are interconnected over the theoretical maximum number of connections among them.

values are closer to 0 or 1 provides useful indicators of the structural characteristics of the governance network. Using these metrics, we find the scores shown in Table 1 for space governance system.

Table 1. Polycentricity scores of the space governance system in 2020

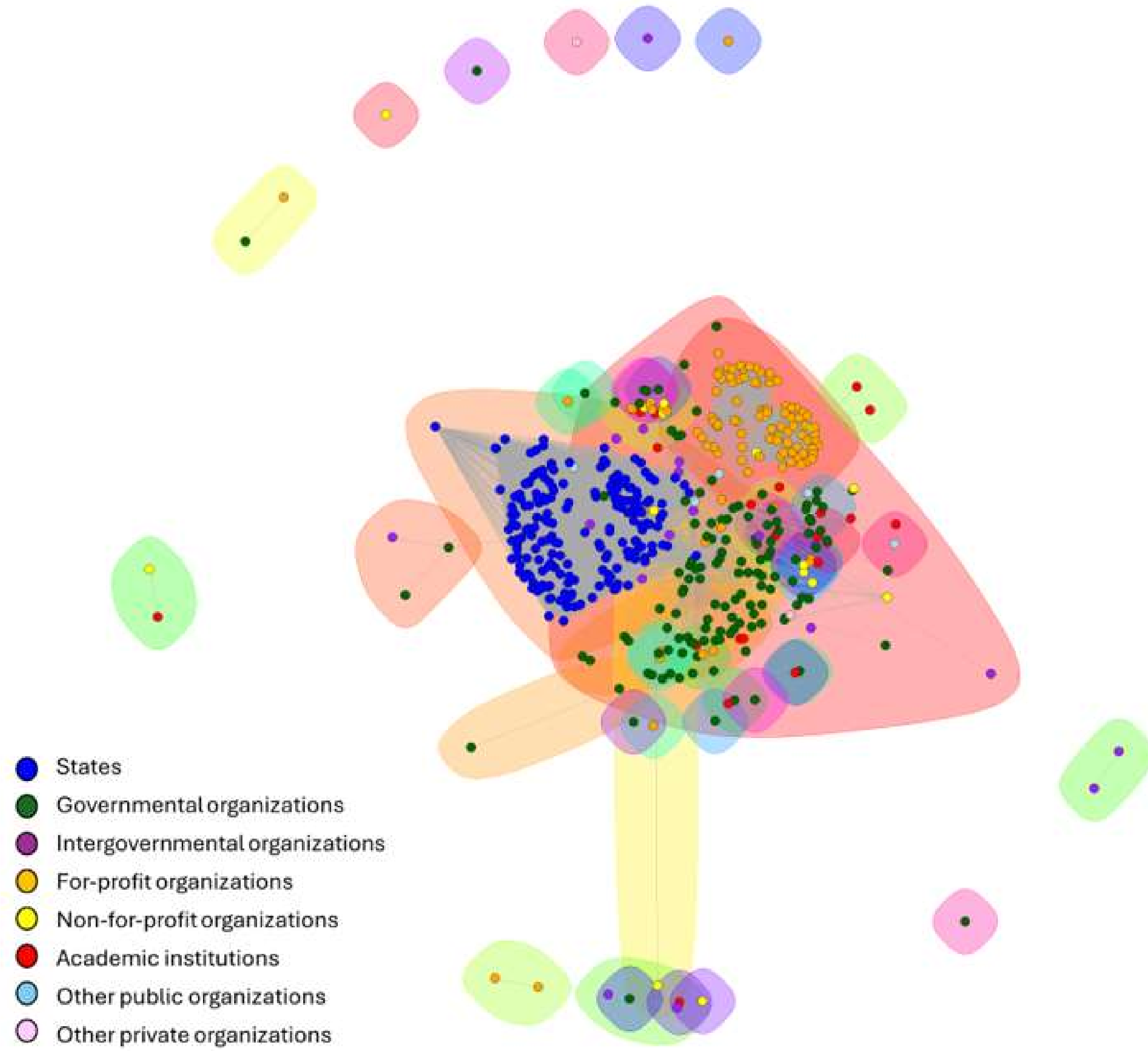
	Centrality	*Clustering coefficient*	*Modularity*
Complete network	0.247	0.975	0.038
Network of only binding arrangements	0.253	0.983	0.024
Network with only non-binding arrangements	0.259	0.985	0.049

The measures suggest that the space governance system exhibits a polycentric structure[10]. When breaking down the governance system into one network formed by only its legally binding arrangements (i.e. treaties and contracts) and another formed by only its legally non-binding arrangements (i.e. certifications, memorandums of understanding, group guidelines, general guidelines and others), we find similar tendencies towards polycentricity. Both types of arrangements contribute to fostering polycentric structures as they entail shared understandings, investment, trust and cooperative behavior (Galaz et al. 2012: 23). Additionally, a longitudinal analysis of all arrangements finds a slight increase in modularity, an increase in the clustering coefficient as well as a decrease in centralization, further marking a general tendency towards greater polycentricity.

Although a modularity score of 0.038 may appear low for a governance system, it is actually an intermediary score. Since scores partly depend on the number of nodes and links in addition to how they are arranged together, we generated 1,000 iterations of random networks with the same number of nodes and links as the space governance system has. The mean modularity of these 1,000 networks is only 0.0519, suggesting that a score of 0.038 is not exceptionally low. More importantly, too high modularity would imply that the clusters are fragmented, a structural characteristic that is not desirable for a polycentric system as connectivity between governance hubs remains essential for learning and adaptation to be possible at the network level (Jordan et al. 2018: 14). Overall, these findings support the argument that the space governance system is highly decentralized, comprising several independent yet interconnected centers within which actors are closely interconnected.

[10] Borowitz (2022) conducted a network analysis limited to the space situational awareness sector and found the existence of multiple clusters.

Figure 1. The space governance system in 2020 and its structural communities[11]



A close examination of communities within the space governance network, illustrated in Figure 1, reveals that they operate at varying scales. Firstly, space organizations operating at the same governance level often collaborate and establish institutional arrangements. For instance, within the three largest communities, one comprises 69% governmental organizations, another 96% for-profit organizations, and the third 95% states. Organizations with significant eigenvector centrality (indicating connections to other highly connected organizations) include NASA, the European Space Agency, and the China National Space Administration.[12] This indicates that global space governance is not

[11] The visualization of the network was done using the Kamada-Kawai layout from the igraph package in R.

[12] For this particular measure, we exclude states from the analysis as they exhibit exceptionally high centrality due to their involvement in multilateral treaties.

centralized around a single country or world region. Similarly, the organizations playing pivotal roles in maintaining network cohesion, demonstrated by high betweenness centrality, are distributed across various structural communities and operate at different levels. Notable examples include the European Space Agency, Airbus, and the China Meteorological Administration. This diversity further underscores that decision-making centers operate at various scales of governance.

In short, the space governance system exhibits polycentric characteristics in its components and their organization. In principle, this structure facilitates experimentation within decision-making units and the sharing of knowledge among them, potentially leading to network-level adaptation and, possibly, to the self-management of orbital debris. However, in the following section, we present evidence that the polycentric nature of the space governance system did not, in fact, result in the emergence of norms promoting the sustainable management of debris.

The non-emergence of norms regulating orbital debris

This section explores whether the polycentric structure of space governance has fostered the emergence of sustainability norms related to orbital debris. Scholars arguing that the outer space governance system has a polycentric architecture have so far paid scant attention to the norms that polycentricity theory expects such a structure to favor. For example, Tepper views polycentric governance in outer space as "advantageous," but explicitly focuses “on the architecture of global space governance, and not on the content of the norms.” (2022: 487). Similarly, Weeden and Chow (2012) write that “it remains to be seen whether or not the space governance regime has already demonstrated signs of adaptability” in response to unsustainable practices.

This focus on the governance system’s structural characteristics rather than its emerging properties is attributable to the challenges of collecting sufficient empirical data to assess the governance system as a whole. It is well known that some institutional arrangements, like the 1967 Outer Space Treaty, do not explicitly address space debris, whereas others, such as the United Nations Space Debris Mitigation Guidelines, do. However, assessing the emergence of norms at the system-level requires a thorough examination of multiple space arrangements.[13] Although not all space governance arrangements are expected to tackle orbital debris, advocates of polycentric governance anticipate that various decision-making centers would engage in norm experimentation on the issue of orbital debris, steering the system as a whole toward greater sustainability. One of the most ambitious empirical efforts to date to map these norms was undertaken by the American Institute of Aeronautics and Astronautics (AIAA), analyzing "76 space governance documents" (Oltrogge and Christensen 2020: 435). However, this AIAA study covers only a small fraction of all publicly available arrangements.

To fill this gap, we conducted a content analysis of the 1,108 space arrangements in force in 2020; these arrangements are all those used in the network analysis above that are also available in full text. We analyzed this collection of arrangements to identify various sustainability norms relevant

[13] The analysis of institutional arrangements provides a proxy for the emergence of sustainability norms. We acknowledge that such norms can be informal, unwritten, or implicit. Nevertheless, considering the rapid proliferation of written space arrangements, we would expect that they would partly reflect emerging practices.

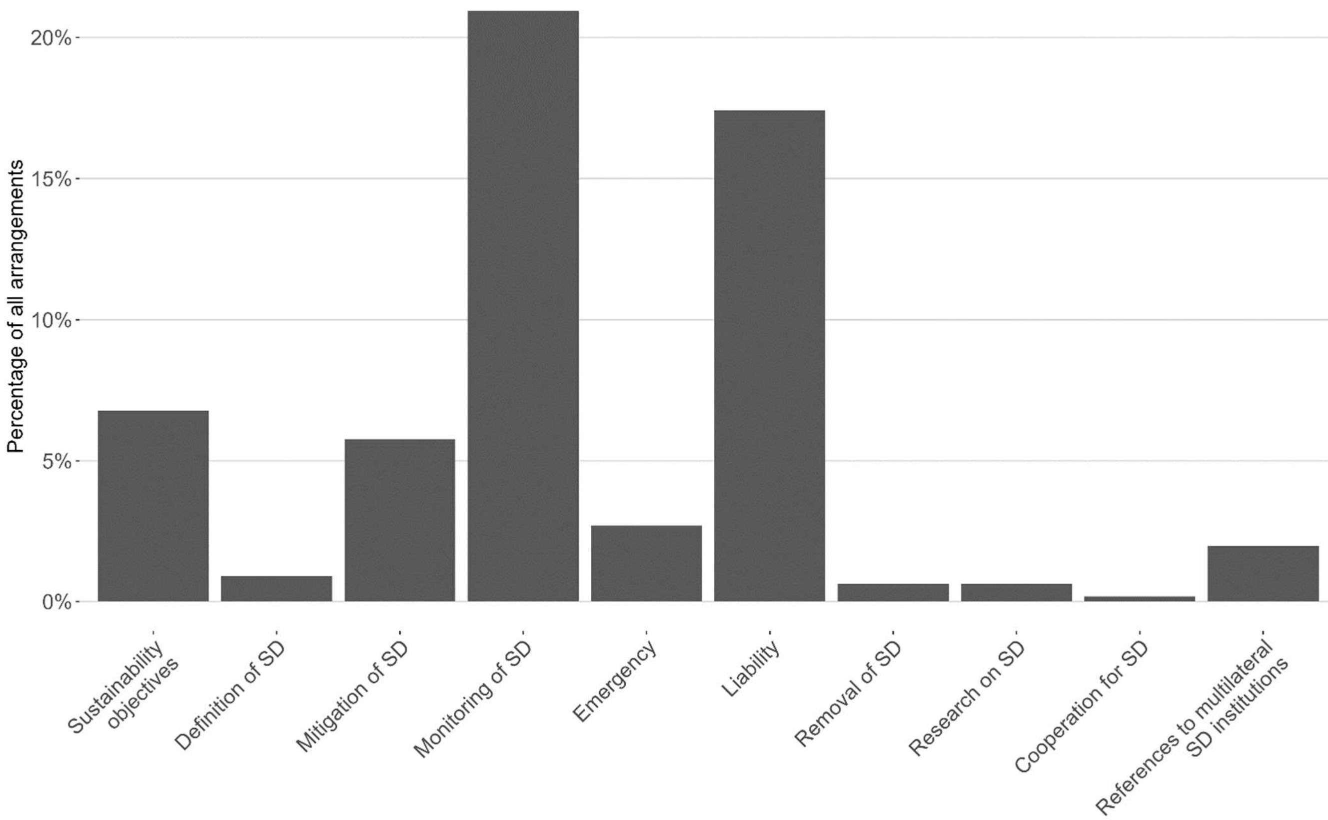
to the governance of orbital debris. We grouped these norms into ten categories: 1) declarations that the sustainable use of space is an objective; 2) definitions of debris; 3) commitments to mitigate debris; 4) procedures for debris monitoring; 5) protocols for on-orbit emergencies; 6) statements regarding liability in the event of collision; 7) commitments to debris removal; 8) commitments to conduct debris-related research; 9) general commitment to cooperate in debris management; 10) and reference to multilateral institutions involved in debris management (see codebook in Appendix 1).

Our focus on publicly available arrangements could potentially bias our analysis. It is reasonable to assume that arrangements showcasing best practices in the field are more likely to be made public by their respective parties. This openness not only boosts their reputation but also facilitates the diffusion of norms that benefit the entire space community. Another bias arises from the greater availability of recently concluded arrangements compared to obsolete ones. 37.4% of arrangements from our collection were concluded after 2005, at a time when the proliferation of debris was already recognized as a major risk for the space sector. Consequently, we assume that the 1,108 arrangements from our collection are more likely to incorporate norms related to orbital debris than missing arrangements.

Despite these favorable biases, Figure 2 reveals that few space arrangements promote sustainability norms regarding orbital debris.[14] It presents the percentage of arrangements covering each of the 10 sustainability norms listed above. Strikingly, just 6.7% of arrangements identify space sustainability as a shared objective. This is noteworthy considering our broad interpretation of space sustainability, which encompasses not just the preservation of the outer space environment but also the safety of space activities. Only 5.8% of arrangements include a commitment to mitigate debris. Our understanding of debris mitigation potentially encompasses a wide array of activities, ranging from improved design of space objects and safe debris release during normal operations to measures for collision risk reduction and post-asset disposal preparation. Less than 3% of all arrangements include provisions for on-orbit emergencies, encompassing assistance to spacecraft and conjunction assessments. Furthermore, only 0.6% of all arrangements mention the active removal of space debris, even as a vague, distant and aspirational goal.

[14] Pic et al. (2023) also found that few space arrangements promote a view of outer space as a "global commons"

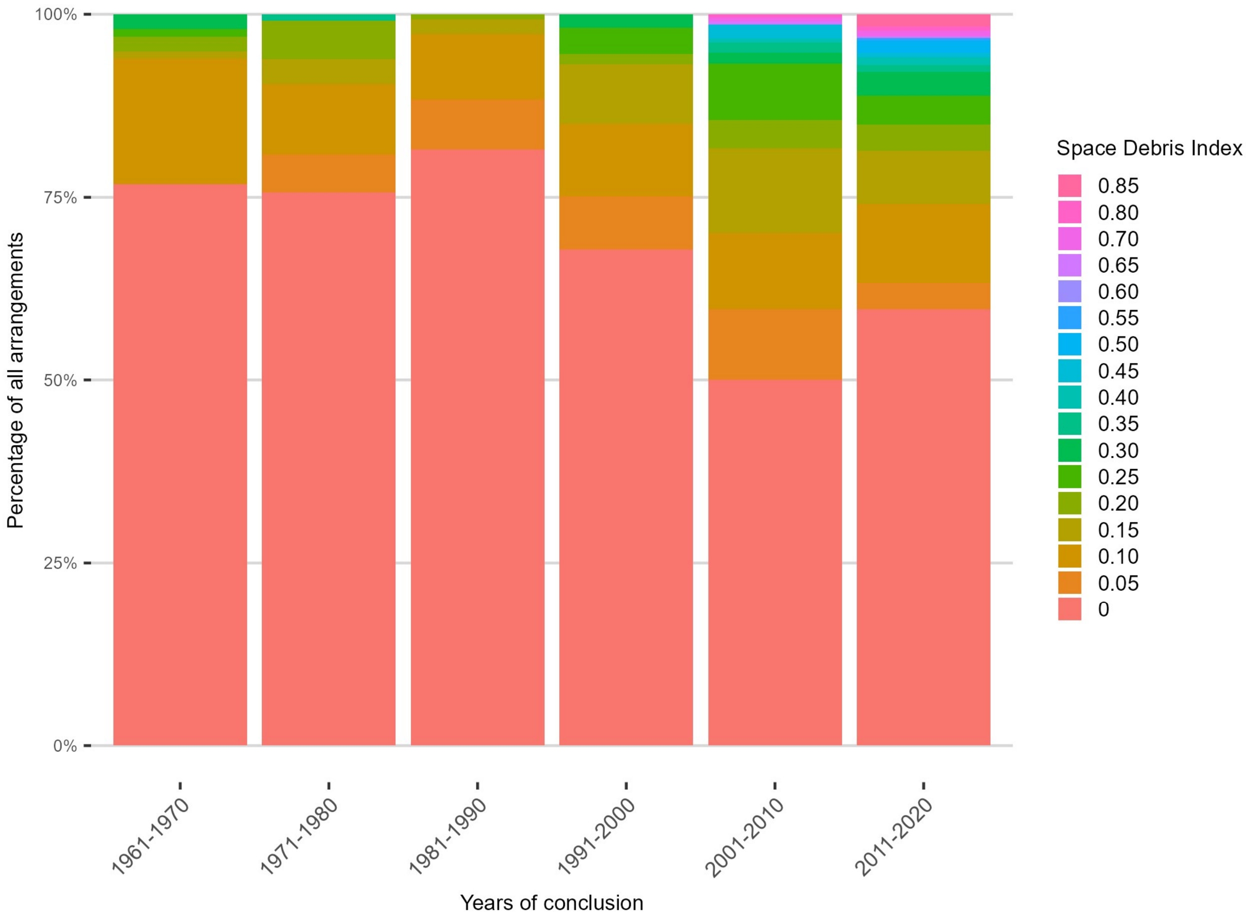
Figure 2. Frequency of each sustainability norm related to space debris (SD) in space arrangements.



Some norms are more frequent than others. Notably, 17.7% of institutional arrangements include a statement on liability in the event of a collision. Arrangements involving public actors more frequently contain provisions on liability (17.9%) compared to those among private actors (12.8%). These provisions typically reference the 1971 Convention on International Liability for Damage Caused by Space Objects. Another relatively common norm pertains to the monitoring of space objects, addressed in 20.9% of institutional arrangements. This includes provisions related to registration, tracking, traffic management, or situational awareness. These are well-established practices, and an increasing number of space organizations offer services in this sector.

To paint a more comprehensive picture of how the space governance system tackles orbital debris, we developed the Governance of Debris in Space (GODS) index. This index was created by categorizing various coded items into thematic dimensions, which were then assigned weights according to their relevance in space debris management (for index construction details, refer to Appendix 2). The GODS index scores range from 0 to 1. Figure 3 displays the evolution of orbital debris scores across 1,131 arrangements, segmented by decade starting from 1961.

Figure 3. Evolution of the Governance of Debris in Space (GODS) index from 1961 to 2020



Almost all arrangements (98.9%) score below 0.5 on the GODS index, and 65.4% of arrangements have a score of zero. Far-reaching sustainably norms that were experimented in just a few model arrangements, such as the 2012 McGill Declaration on Active Space Debris Removal and On-Orbit Satellite Servicing, have not diffused to other arrangements in the governance system. Even when we consider non-binding initiatives from organizations that present themselves as environmentally conscious, their GODS score remains remarkably low.[15] For instance, 91.3% of all of the European Space Agency's non-binding arrangements score 0.1 or less, despite the agency claiming it is "pioneering an eco-friendly approach" (ESA 2019).[16]

More disconcerting, there has been only a modest improvement over time, indicating that the space governance system has adapted only slightly to the rapid accumulation of orbital debris in recent decades. Despite increasing discussions about sustainability within the space community (Yap et al. 2023; Yap and Kim 2023), this awareness has yet to be translated into formalized norms on orbital debris in institutional arrangements. It appears that the polycentric structure of the space governance

[15] This supports the findings of Marino and Cheney, who analyzed a much smaller number of arrangements (2023: 101521)
[16] Thanks to its strategic position in the network of space arrangements (Beaumier et al. 2024), the ESA could significantly contribute to diffusing space debris norms at the system level by including them in its arrangements

system is an insufficient condition for the emerging properties that would have allowed for a sustainable self-management of orbital debris.

Favorable factors

A polycentric structure does not guarantee the sustainable management of common-pool resources. Advocates of polycentricity often highlight the challenges of centralized and market-based solutions in addressing orbital debris, but they might underestimate the difficulties of making a polycentric structure work for sustainability.[17] However, Ostrom herself did not believe in the spontaneous virtues of polycentric structures. She identified eight interacting "design principles" that can be conceptualized as factors favorable to a sustainable governance system: 1) well-defined resources; 2) congruence between norms and ecological conditions; 3) participation of community members in decision-making; 4) trusted monitoring systems; 5) graduated sanctions for rule violators; 6) accessible conflict resolution mechanisms; 7) self-determination; and 8) a multiscale governance system (Ostrom 1990: 90). These factors have been empirically supported by subsequent research on local resource management (e.g. Baland and Platteau 1996; Cox et al. 2010) and adapted for global commons governance (Dietz et al. 2003; Stern 2011; Fleischman et al. 2014). While not deterministic, they offer a framework for evaluating the potential for sustainable governance of common-pool resources. Since the preceding section already established that one of these factors —norms congruent with the ecological conditions—is unmet in the governance of orbital debris, this section examines the other seven factors to identify obstacles preventing the polycentric governance structure from fostering sustainability norms.

This analysis is informed by 31 semi-structured interviews with space experts (See Appendix 3). Among them, 14 hold management positions in private companies, 8 are senior managers for governmental organizations, 8 work for intergovernmental organizations, and 4 are in the non-profit sector. They are based in 13 different countries. We asked each of these interviewees whether, from their perspective, Ostrom's factors were met in space governance. Their perception is crucial to measure the fulfillment of Ostrom’s principles, which heavily depend on subjective elements, such as legitimacy, fairness, trust, reputation and shared understanding. Despite varying viewpoints, there were notable similarities among interviewees regarding the evaluation of these factors.

Meta-norms defining common-pool resources

A first favorable factor for a polycentric system to sustainably govern common-pool resources is a mutual understanding of the nature of these resources and the delineation of access rights. Clearly defining both the resources and their potential users is a prerequisite for the development of norms regulating the sustainable consumption of common-pool resources. Without this shared understanding, it would be unclear for whom sustainability norms should be adopted in the first place and what exactly these norms would regulate (Ostrom 1990: 91)

[17] A few space analysts (Migaud et al. 2021; Lambach and Wesel 2021; Johnson-Freese and Weeden 2012; Weeden and Chow 2012) discuss factors for the sustainable management of the Earth orbits. They rely on their own reflections and observations rather than on data collected from a sample of stakeholders as this paper does.

Some interviewees stress that the 1967 Outer Space Treaty provides a shared and clear general framework for space activities (Interviewees 5, 9 and 15). It declares the exploration and use of outer space as the province of all humankind and provides that states are responsible for activities conducted by their private companies in outer space. The 1972 Space Liability Convention specifies state liability for space objects launched from their territory, and the 1974 Registration Convention establishes clear rules for the identification of space objects. Besides a few dissenting opinions, the vast majority of interviewees also consider that the problem of orbital debris is widely acknowledged and understood within the space community. Its origin, extent, and potential consequences are broadly acknowledged.

Nevertheless, according to several interviewees, confusion persists regarding the allocation of rights and responsibilities in orbital space. Multilateral treaties do not specifically address orbital debris, which "leaves a lot of room for interpretation," (Interviewee 5). Similarly, the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space (COPUOS) are considered "very general" (interviewee 18). Consequently, interviewees perceive a lack of a "common language" (Interviewee 2) or "common lexicon" (Interviewee 8) in governing space debris.[18] While some specific obligations regarding orbital debris are outlined in a few domestic laws and contracts (Interviewees 3, 5 and 23), they do not apply globally. An interviewee from the industry reports that some of the countries where they have licenses have a permissive legal framework regarding orbital debris: "We don't have to do anything to comply with their rules and regulations, because they don't have any." (Interviewee 19) This lack of clarity led five interviewees to spontaneously use expressions such as the "far west" or "wild west", reflecting the ambiguous nature of rights and obligations regarding space debris.

Participation of community members

Another favorable factor for polycentric systems to be sustainable is the meaningful participation of resource users in the development and revision of sustainability norms (Ostrom 1990: 93). This participation increases the likelihood that norms remain practical, operational, and adapted, as circumstances change and new knowledge emerges. Moreover, users' participation favors the perceived legitimacy of sustainability norms, which results in higher rates of compliance.

Interviewees have mixed views on this matter. Many emphasize that a few national political environments allow for the voices of the private sector to be heard when developing domestic regulations (Interviewees 4, 12, 16, 20, 21, 22 and 23). Private actors can also make their voices heard in some international settings, such as ISO, the European Cooperation for Space Standardization, and the International Telecommunication Union (Interviewees 3, 13, 15, 21 and 30). While small start-ups may lack the capacity to engage directly in policy discussions, they can participate indirectly through their industry associations (Interviewees 4, 5, and 25).

[18] See Pic et al. 2023 for a discussion about the prevailing confusion related to the concepts of "commons", "province" and "heritage" in international space law.

However, about half of the interviewees recognize limitations in participation. Key platforms for orbital debris governance, such as the Inter-Agency Space Debris Coordination Committee, exhibit limited openness to private sector involvement (Interviewee 7).[19] The proliferation of bilateral institutions further limits opportunities for inclusive and global deliberations. At the same time, concerns arise that opening multilateral forums, such as UNCOPUOS, to a greater diversity of users of the orbits could exacerbate imbalances by disproportionately amplifying the voices of wealthier and more powerful organizations (Interviewees 16 and 29).

Trusted monitoring systems

Polycentric systems that govern common-pool resources sustainably typically have effective and trusted monitoring tools (Ostrom 1990: 94). These tools are necessary for documenting the fluctuating stock of available resources and the amount appropriated by specific actors. They should provide precise, reliable, and trustworthy information to users for them to be able to elaborate norms that ensure the sustainable use of resources.[20]

Three-quarters of our interviewees believe the current monitoring systems for orbital debris are inadequate. Several space actors are able to collect data on the position, velocity, and trajectory of large artificial space objects. Through their extensive network of sensors and tracking systems, the United States Strategic Command (USSTRATCOM) and the European Union Space Surveillance and Tracking (EU SST) maintain comprehensive catalogs of orbital debris and share data with selected space operators. However, the resulting datasets are not systematically verified, shared, and harmonized as no actors are effectively "policing" orbits (Interviewees 7 and 29). For example, there is no global authority tasked with the mandate to share information on spacecrafts that have failed to maneuver to a graveyard zone or deorbit into the Earth’s atmosphere at the end of their operational life. An intergovernmental space traffic management system could be a more robust alternative, but interviewees are skeptical that states would agree to share all their situational awareness data. According to interviewees, such mandatory disclosure would face resistance due to state security (Interviewees 8, 9 and 13) and sovereignty (Interviewees 7, 10, 11, 15, 25 and 28) concerns.

Some interviewees are more enthusiastic when discussing transnational initiatives, such as the Space Data Association, explaining that these initiatives contribute to the circulation and interoperability of data on space object locations (Interviewee 4, 14, 16 and 27).[21] Nevertheless, the data shared by these nonstate actors remains incomplete. As some interviewees report, military organizations still work to keep some critical spacecraft information classified, weakening monitoring systems more broadly (Interviewees 9 and 13). For instance, Interviewee 9 recalls a government agency filtering the data they were allowed to share with the science community to prevent disclosing a spacecraft's precise position.

[19] Some delegations would include, in the words of interviewee 25, “hidden observers” from the private sector.

[20] Some global commons, such as the ozone layer, are managed sustainably without such monitoring system (Fleischman et al. 2014)

[21] See Borowitz 2022 for a discussion on this global network of data exchange.

In addition to these secrecy challenges, technological limitations hinder the tracking of small debris. While private companies are developing solutions for monitoring debris of less than 10 centimeters, they sell their proprietary data to a limited number of clients.

Graduated sanctions for rule violators

Collective sanctions are an essential component of sustainable governance systems for common pool resources (Ostrom 1990). Non-compliance with sustainability norms should be sanctioned through legal, political, economic or social measures. Without a deterrent mechanism, users would have a strong incentive to overconsume their shared resources, rendering the establishment of sustainable norms meaningless. Sanctions, however, must be consistently applied and proportional to the offense to maintain the legitimacy of the governance system and preserve the full participation of one-time offenders.

Nearly all interviewees agree that a sanction system for rule violators is lacking. There is no global authority "to give you a fine if you dump something" in outer space (Interviewee 7)[22] and "there is nobody there who can do something against" harmful behavior (Interviewee 1). Interviewee 3 humorously observes, "I can launch your washing machine right in the middle of the constellation of Elon Musk no problem!" [23] While domestic laws can penalize nationals for illegal acts, several launch countries do not have a domestic space law, and some spacecrafts go unregistered (Interviewee 17). Offenders can even be governmental organizations themselves that also contribute to orbital debris. Interviewee 25 noted that cases in point are China's 2007 and Russia's 2021 anti-satellite missile tests, which each generated thousands of trackable debris pieces. This disregard for space sustainability led to public outrage and diplomatic condemnations, but China and Russia were not formally sanctioned by an international authority, underscoring, as Interviewee 3 states, that "sanctioning is not possible".

The primary sanction system for orbital debris management hinges on reputation costs. Several interviewees underlined that space actors remain sensitive to public opinion, making the threat of publicizing non-conformity a considerable incentive for public actors (Interviewees 6 and 25) and private actors (Interviewees 4, 9 and 16). In particular, large private space firms that undertake government contracts "cannot afford to be seen as the bad guys" (Interviewee 9). Leveraging these reputational concerns, some stakeholders are developing space sustainability ratings to shame violators (Interviewee 16). As Interviewee 4 notes, these mechanisms work because there are "enough people to call out" norm violators. To show this mechanism at play, two interviewees gave the example of how the astronomy community organized itself and pressured SpaceX into taking some measures to limit the night pollution created by its Starlink satellites. However, this approach is less effective with small private companies that are less vulnerable to public shaming campaigns. Consequently, as interviewees point out, guidelines and recommendations are not widely applied and many space companies fail to comply with post-mission disposal requirements (Interviewees 3, 24 and 26)

[22] In 2023, the US Federal Communications Commission issued a fine to Dish Network for failing to deorbit a satellite.
[23] In 2018, Musk himself sent into space a Tesla car he personally owned and used.

Accessible conflict resolution mechanisms

Disagreements regarding the interpretation of sustainability norms are inevitable among users of common pool resources. Norms can be ambiguous, and a changing context requires constant reinterpretation of agreed norms. Therefore, mechanisms should be in place to settle these conflicts at a low cost (Ostrom 1990: 100). Typically, this involves a third party acting as a trusted mediator or arbitrator. Otherwise, users may not trust their shared governance system to comply with sustainability norms. This is especially true for less powerful users who need reassurance that more powerful users will not exploit their power advantage to interpret and enforce suitability rules in their favor.

Interviewees largely agree that there are no effective dispute resolution mechanisms in place to resolve conflicts among space actors. Existing frameworks include the Protocol on the Compulsory Settlement of Disputes of the International Telecommunication Union, the Claims Commission of the 1971 Space Liability Convention, and the Optional Rules for Arbitration of Disputes Relating to Outer Space Activities of the Permanent Court of Arbitration. However, these mechanisms have limited scope and have rarely been used. The most notorious case of successful dispute settlement was the payment of $3 million by the Soviet Union to Canada for scattering radioactive debris over northern Canada. This case remains exceptional, and respondents express the view that most major disputes are resolved through power dynamics rather than legal channels. This leads Interviewee 27, a CEO from the private sector, to conclude that “if there was nothing, it would be the same.” Similarly, Interviewee 31 argues that “words are nothing in space”, suggesting that any actor who wants strong enforcement needs to “go out there and enforce [its] policies”. Interviewee 8 encapsulates the sentiment by stating, "we need a good sheriff, essentially."

Self-determination

Ostrom (1990: 101) argues that external political authorities can promote the development of appropriate sustainability norms by allowing users of common pool-resources to elaborate some of their own sustainability norms and acknowledging the legitimacy of such self-regulation. It remains an open question whether this factor is highly relevant for the management of global commons (Fleischman et al. 2014).

Most interviewees consider that users of orbital space have the capacity to build their own institutions. This is evidenced through a variety of intergovernmental, transnational, and international efforts, encompassing certification processes, guidelines, and cooperative platforms. Interviewees from the private sector argue that “the industry is self-regulating” (Interviewee 14) and that “the community is kind of organizing itself” (Interviewee 4). An illustrative example is the CONFERS initiative, which is a multi-stakeholder process dedicated to developing voluntary standards for on-orbit servicing and proximity operations. A number of interviewees (14, 26 and 28) expressed a preference for user-led initiatives over governmental regulations, viewing them as more pragmatic and forward-thinking. They argue that private regulations effectively address the shortcomings of governmental oversight (Interviewees 15, 16, 18, 19, 26, and 28). However, a few interviewees raise concerns about insufficient recognition that some governments give to norms and standards put forward by non-state actors, including NGOs and academics (Interviewees 19 and 23).

Multi-scalar system

The last favorable factor for a sustainable polycentric governance system, according to Ostrom (1990), is the coexistence of institutions operating at various scales of governance. This factor is particularly relevant when dealing with complex and global issues. Having multiple layers of nested institutions allows for a proper adequacy between the governance functions provided by institutions and the specific problem being addressed. Additionally, this redundancy favors some degree of competition among institutions, which in turn motivate them to be innovative and adaptive.

Interviewees widely acknowledge that the space governance system is decentralized. Their descriptions varied, with terms such as "fragmented" (Interviewee 27), "interconnected" (Interviewees 5 and 25), "polycentric" (Interviewee 7), "multi-dimensional" (Interviewee 13), "disconnected" (Interviewees 21 and 24), "complex" (Interviewee 23), and "chaotic" (Interviewee 18), to depict the diverse decision-making centers. Several interviewees also spontaneously highlight that these centers operate across different governance levels. They observed that multilateral treaties, domestic laws, and transitional initiatives not only complement but also mutually influence one another (Interviewees 3, 6, 9, 17, 23, and 24). Information, norms, and best practices flow across various levels. There are minimal inconsistencies among these various initiatives and sufficient scope for experimentation by like-minded space actors. As a result, national regulations vary significantly from one jurisdiction to another. Although there is a divergence of opinion among interviewees regarding whether the absence of a hierarchical, top-down system is beneficial or detrimental, there is a consensus that multi-scalarity characterizes the outer space governance system.

In summary, the governance system of orbital debris meets some, but not all, favorable factors of the Ostrom framework. Key missing ingredients are related to the enforcement of agreed norms: a monitoring system, a sanctions regime, and a dispute settlement mechanism. These deficiencies could not only hinder compliance with sustainability norms but also deter the development of such norms. One might question the utility of elaborating norms on orbital debris if these norms are unlikely to be adhered to. This evaluation, informed by the subjective perceptions of members within the space community, offers insights into why the governance system for orbital debris, despite its polycentric structure, has failed to produce ambitious norms regulating orbital debris.

Conclusion

This article makes several contributions to the literature. First, our network analysis reveals the polycentric structure of the governance system for outer space. Second, our content analysis of 1,108 arrangements provides evidence that this governance system has so far failed to adequately address the problem of orbital debris through the emergence of appropriate norms. Third, our series of interviews with 48 space experts points to critical institutional deficiencies within this governance system, emphasizing the need for institutional reforms. Taken together, these findings serve as a reminder that a polycentric structure alone does not guarantee the sustainability of a system, echoingOstrom's original but sometimes forgotten argument (1990).

This conclusion is particularly relevant in light of the growing interest in applying polycentric approaches to govern other common pool resources, such as the climate or the oceans (GEP 2024 special issue). Recent decades have highlighted the challenges of addressing global environmental issues through multilateralism, alongside the rise of bilateral and transnational institutions. Global governance scholars increasingly employ network analysis to map these proliferating institutions. However, analysts sometimes rely on unsubstantiated assumptions about the benefits associated with certain network topographies. They assume that, under specific structural conditions, information flows, learning is shared, innovation arises, and norms emerge, even without supporting empirical evidence. However, the case of orbital debris governance demonstrates that governance systems with a polycentric structure can nevertheless manage common pool resources unsustainably. Much-needed norms do not spontaneously arise from a polycentric framework. Given that space debris represents a relatively "easy" case for applying polycentricity theory to global commons, one should be particularly cautious in assuming its relevance for climate or ocean governance. Compared with orbital space, these other common pool resources involve additional obstacles, such as a larger number of actors, a higher discount rate, resources that are not renewable, and a greater disconnect between appropriators and negative externalities, making polycentric governance even more challenging.

However, we should remain prudent when interpreting our results. Communities that Ostrom found to govern their resources sustainably have developed their norms and practices over centuries, if not millennia. It is possible that fifty years of space governance is insufficient for such endogenous emergence to occur. Additionally, it is possible that the structure of the outer space governance system remains insufficiently modular, hindering the autonomy of the various decision-making centers in experimenting with new norms. Alternatively, norms regulating orbital debris may have already emerged through unilateral decisions, domestic regulations, or informal practices even if they are not readily observable in the international arrangements analyzed in this study.

Paradoxically, central institutions could play a pivotal role in enhancing the sustainability of polycentric governance systems. Ostrom herself referred to central institutions, such as assemblies of users (1999: 67) that organize polycentric systems. In the case of space debris, central mechanisms could be established to pool information and capacities for the shared monitoring of orbital debris. Another multilateral mechanism could enforce political or economic sanctions on operators who fail to deorbit their satellites. The policy literature offers numerous recommendations in this regard (e.g., IRGC 2021). If monitoring and sanctioning efforts are carried out effectively on a multilateral basis, space actors may be more inclined to develop norms on orbital debris within their respective bilateral agreements. From this perspective, multilateral initiatives should not be seen as alternatives, but as facilitators of polycentric governance.

Biographies

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References

Baland, J.M., and J.P Platteau. 1996. *Halting Degradation of Natural Resources: Is There a Role for Rural Communities?* Oxford: Clarendon Press.

Beaumier, G., Couette, C., and J-F Morin. 2024. Hybrid organisations and governance systems: the case of the European Space Agency. *Journal of European Public Policy*, 1-31.

Blomquist, W.A. and N.J.S. Schröder. 2019. Seeing Polycentrically. In *Governing complexity: Analyzing and applying polycentricity*, 45-64. Cambridge: Cambridge University Press.

Borowitz, M. 2022. Examining the Growth of the Global Space Situational Awareness Sector: A Network Analysis Approach. *Space Policy 59*: 101444.

Buchs, R., and T. Bernauer. 2023. Market-based instruments to incentivize more sustainable practices in outer space. *Current Opinion in Environmental Sustainability* 60: 101247.

Byers, M., and A. Boley. 2023. *Who Owns Outer Space? International Law, Astrophysics, and the Sustainable Development of Space*. Cambridge: Cambridge University Press.

Cole, D.H. 2015. Advantages of a Polycentric Approach to Climate Change Policy. *Nature Climate Change 5*(2): 114-118.

Cooper, L.A. 2003. 'Encouraging Space Exploration Through a New Application of Space Property Rights. *Space Policy* 19(2): 111-118.

Cox, M. 2014. Understanding large social-ecological systems: introducing the SESMAD project. *International Journal of the Commons*, 8(2), 265-276.

Cox, M., G. Arnold, and S.V. Tomás. 2010. A Review of Design Principles for Community-Based Natural Resource Management. *Ecology and Society* 15(4): 38.

Dietz, T., E. Ostrom, and P.C. Stern. 2003. The Struggle to Govern the Commons. *Science 302*(5652): 1907-1912.

Dorsch, M.J., and C. Flachsland. 2017. A Polycentric Approach to Global Climate Governance. *Global Environmental Politics* 17(2): 45-64.

Elhefnawy, N. 2003. Territorializing Space? Revisiting an Old Idea. *Astropolitics* 1(2): 55- 63.

ESA Space Debris Office. 20241. Space Debris by the Numbers. [online]. Available from: https://www.esa.int/Safety_Security/Space_Debris/Space_debris_by_the_numbers

European Space Agency. 2019. Clear and Eco-Friendly Space. https://www.esa.int/

Fleischman, F.D., N.C. Ban, L.S. Evans, G. Epstein, G. Garcia-Lopez, and S. Villamayor-Tomas. 2014. Governing large-scale social-ecological systems: Lessons from five cases. *International Journal of the Commons*, 8(2), 428-456.

Galaz, V., B. Crona, H. Österblom, P. Olsson, and Folke, C. 2012. Polycentric systems and interacting planetary boundaries—Emerging governance of climate change–ocean acidification–marine biodiversity. *Ecological Economics*, 81, 21-32.

Gupta, V. 2016. Critique of the International Law on Protection of the Outer Space Environment. *Astropolitics* 14(1): 20-43.

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

Hollway, J., JF Morin and J. Pauwelyn. 2020. Structural conditions for novelty: The introduction of new environmental clauses to the trade regime complex. *International Environmental Agreements: Politics, Law and Economics*, 20(1), 61-83.

Hudgins, E.L., ed. 2002. *Space: the free-market frontier*. Cato Institute.

Imburgia, J.S. 2011. Space Debris and its Threat to National Security: A Proposal for a Binding International Agreement to Clean Up the Junk. *Vanderbilt Journal of Transnational Law* 44(3): 589-641.

IRGC. 2021. Policy Options to Address Collision Risk from Space Debris. Lausanne: EPFL

Johnson-Freese, J., and B. Weeden. 2012. Application of Ostrom's Principles for Sustainable Governance of Common-Pool Resources to Near-Earth Orbit. *Global Policy* 3(1): 72-81.

Jordan, A., D. Huitema, H. Van Asselt, and J. Forster, eds. 2018. *Governing climate change: Polycentricity in action?*. Cambridge University Press.

Keohane, R., and E. Ostrom. 1994. *Local Commons and Global Interdependence*. Sage.

Kessler, D.J., and B.G. Cour-Palais. 1978. Collision Frequency of Artificial Satellites: The Creation of a Debris Belt. *Journal of Geophysical Research: Space Physics* 83(A6): 2637- 2646.

Kim, R.E. 2020. Is Global Governance Fragmented, Polycentric, or Complex? The State of the Art of the Network Approach. *International Studies Review 22*(4): 903-931.

Kinne, B. J. 2013. Network dynamics and the evolution of international cooperation. *American Political Science Review*, 107(4), 766-785.

Koinova, M. et al. 2021. It's Ordered Chaos: What Really Makes Polycentrism Work. *International Studies Review* 23(4): 1988-2018.

Kurt, J. 2015. Triumph of the Space Commons: Addressing the Impending Space Debris Crisis without an International Treaty. *William & Mary Environmental Law & Policy Review* 40(1): 305-334.

Lambach, D., and L. Wesel. 2021. Tackling the Space Debris Problem: A Global Commons Perspective. In *Proc. 8th European Conference on Space Debris*.

Lawrence, A., et al. 2022. The case for space environmentalism. *Nature Astronomy 6*(4): 428-435.

Lofthouse, J.K., and R.Q. Herzberg. 2023. The continuing case for a polycentric approach for coping with climate change. *Sustainability*, *15*(4), 3770.

Marino, A., and T. Cheney. 2023. Centring Environmentalism in Space Governance: Interrogating Dominance and Authority Through a Critical Legal Geography of Outer Space. *Space Policy 63*: 101521.

Migaud, M.R., R.A. Greer, and J.B. Bullock. 2021. Developing an Adaptive Space Governance Framework. *Space Policy*, 55: 101400.

Morin, J.F., and E. Tepper. 2023. The Empire Strikes Back: Comparing US and China's Structural Power in Outer Space. *Global Studies Quarterly 3*(4): ksad067.

Morrison, T.H. et al. 2019. The Black Box of Power in Polycentric Environmental Governance. *Global Environmental Change* 57: 101934.

Nordman, E. 2021. *The Uncommon Knowledge of Elinor Ostrom: Essential Lessons for Collective Action*. Washington: Island Press.

Nozawa, W., K. Kurita, T. Tamaki, and S. Managi. 2023. To What Extent Will Space Debris Impact the Economy?. *Space Policy*, *66*: 101580.

Oltrogge, D.L., and I.A. Christensen. 2020. Space Governance in the New Space Era. *Journal of Space Safety Engineering* 7(3): 432-438.

Orsini, A. et al. 2020. Complex Systems and International Governance. *International Studies Review 22*(4): 1008-1038.

Ostrom, E. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge: Cambridge University Press.

Ostrom, E. 1999. Coping with Tragedies of the Commons. *Annual Review of Political Science 2*(1): 493-535.

Ostrom, E. 2003. How Types of Goods and Property Rights Jointly Affect Collective Action. *Journal of theoretical Politics 15*(3): 239-270.

Ostrom, E. 2007. A Diagnostic Approach for Going Beyond Panaceas. *Proceedings of the National Academy of Sciences*, 104(39): 15181-15187.

Ostrom, E. 2010a. Beyond Markets and States: Polycentric Governance of Complex Economic Systems. *American Economic Review*, *100*(3): 641-672.

Ostrom, E. 2010b. Polycentric Systems for Coping with Collective Action and Global Environmental Change. *Global Environmental Change* 20(4): 550-557.

Ostrom, V., et al., 1961. The Organization of Government in Metropolitan Areas: A Theoretical Inquiry. *American Political Science Review* 55, 831–842

Pic, P., Evoy, P., and J.F. Morin. 2023. Outer Space as a Global Commons: An Empirical Study of Space Arrangements. *International Journal of the Commons*, 17(1): 288-302.

Pons, P., and M. Latapy. 2005. Computing communities in large networks using random walks. Presented at the *Computer and Information Sciences-ISCIS 2005: 20th International Symposium*. Turkey. Proceedings 20: 284-293.

Salter, A.W. 2017. Ordering the cosmos: Private law and celestial property rights. *Journal of Air Law & Commerce.* 82: 311-332.

Salter, A.W., and P.T. Leeson. 2014. Celestial Anarchy: A Threat to Outer Space Commerce? *Cato Journal* 34(3): 581-596.

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.

Tan, D. 2000. Towards a New Regime for the Protection of Outer Space as the Province of All Mankind. *Yale Journal of International Law* 25: 145-194.

Taylor, J.B. 2011. Tragedy of the Space Commons: A Market Mechanism Solution to the Space Debris Problem. *Columbia Journal of Transnational Law* 50(1): 253-279.

Tepper, E. 2014. Applying Ostrom's Nobel Winning Study to International Cooperation in Space Activities. In *Proceedings of the International Institute of Space Law 2014*, 675-686. The Hague: Eleven International Publishing.

Tepper, E. 2019 Structuring the Discourse on the Exploitation of Space Resources: Between Economic and Legal Commons. *Space Policy* 49: 101290.

Tepper, E. 2022. The Big Bang of Space Governance: Towards Polycentric Governance of Space Activities. *New York University Journal of International Law and Policy* 54: 485-558.

United Nations. 2021 Space2030 Agenda. A/76/L.3

Vogler, J. 2012. Global Commons Revisited. *Global Policy* 3(1): 61-71.

Weeden, B., and T. Chow. 2012. Taking a Common-Pool Resources Approach to Space Sustainability: A Framework and Potential Policies. *Space Policy* 28(3): 166-172.

Winston, C. 2023. International Norms as Emergent Properties of Complex Adaptive Systems. *International Studies Quarterly*, 67(3): sqad063.

World Economic Forum (WEC) 2003. Space Industry Debris Mitigation Recommendations. https://www3.weforum.org/docs/WEF_Space_Industry_Debris_Mitigation_Recommendations_2023.pdf

Yap, X.S. et al. 2023. Emerging Global Socio-Technical Regimes for Tackling Space Debris: A Discourse Network Analysis. *Acta Astronautica* 207: 445-454.

Yap, X.S., and R.E. Kim. 2023. Towards Earth-Space Governance in a Multi-Planetary Era. *Earth System Governance* 16: 1-5.

Online Appendix 1: Codebook

Sustainable use of space is an objective

- Any objective related to the protection, preservation of space environment, sustainable use of space, sustainability of space activities, or the safe use of space.
- Does not need to be explicitly related to space debris, to concreate measure to be implemented.
- Does not need to the primary objective of the arrangement.
- Excludes objective related to the sustainable development limited to Earth.
- Example: “The Satellite Industry Association ("SIA") is committed to responsible space operations to ensure a sustainable environment in space.” (Satellite Industry Association - Mitigation of Orbital Debris in the New Space Age, IB Docket 18-313)

Definitions of debris

- Any definition of space debris
- Example: “Space debris are all man made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non functional.” (CNES Standards Collection, Method and Procedure Space Debris – Safety Requirements, RNC-CNES-Q-40-512)

Commitments to mitigate debris

- Includes commitment on how space objects should be designed, how debris should be released during normal operation, procedures reducing the probability of accidental explosion, reducing risk of debris generation, and preparing for safe post-mission asset disposal.
- Example: “Constellation architectures should include a safety-by-design approach.” (Best Practices for the Sustainability of Space Operations)

Procedures for debris monitoring

- Includes procedure for the monitoring of space debris and other space objects, space traffic management, space situational awareness, registration of space objects.
- Example: we recommend: [….] An increased effort to collect accurate data and make it publicly available and readily useable, and thus improve predictions about the locations of objects in orbit.” (Salt Spring Recommendations on Space Debris)

Protocols for on-orbit emergencies

- Includes protocols related to the rescue of astronauts/spacecrafts, statements on conjunction assessment, and provision on the prevention of on-orbit emergencies.
- Example: “States shall regard astronauts as envoys of mankind in outer space and shall render to them all possible assistance in the event of accident, distress, or emergency landing on the territory of a foreign State or on the high seas.” (UN General Assembly Resolution 1962 (XVIII): Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space)

Statements regarding liability in event of collision

- Includes collision with a space object that is not space debris.
- Includes provisions on insurance for damages from collision.
- Excludes liability for damages on earth (e.g. in case of crash), not a result of a collision with space object.
- Example: “Each State Party to the Treaty that launches or procures the launching of an object into outer space […] is internationally liable for damage to another State Party to the […].” (Outer Space Treaty)

Commitments to debris removal

- Includes removal or remediation about current, potential or eventual debris.
- Example: “Active removal of space debris and on-orbit satellite servicing should be undertaken by all stakeholders as soon as possible.” (McGill Declaration on Active Space Debris Removal and On-Orbit Satellite Servicing)

Commitments to conduct debris-related research

- Includes academic and industrial research and development.
- Includes development of new technology.
- Example: “In addressing the problem of space debris in its work, the Subcommittee at its thirty- second session, in 1995, agreed to focus on understanding aspects of research related to space debris […].” (Space debris mitigation guidelines of the Committee on the Peaceful Uses of Outer Space)

General commitment to cooperate in debris management

- More general statements than other statements listed above, but can co-exist with more specific statements.
- Example: “States and international intergovernmental organizations should investigate the necessity and feasibility of possible new measures, including technological solutions, and consider implementation thereof, in order to address the evolution of and manage the space debris population in the long term.” (Guidelines for the Long-term Sustainability of Outer Space Activities of the Committee on the Peaceful Uses of Outer Space)

Reference to multilateral institutions involved in debris management

- References to the Space Debris Mitigation Guidelines and References to the Inter-Agency Space Debris Coordination Committee.
- Does not include vague reference to “previous agreements”. Arrangement must be named.
- Example : “[…] establish and document a Space Debris Mitigation Plan in accordance with the Space Debris Mitigation Guidelines of the Inter-Agency Space Debris Coordination Committee (IADC) of October 15, 2002, as amended;” (Memorandum of Understanding Between the National Aeronautics and Space Administration of the United States of America and the European Space Agency Concerning the Solar Orbiter Mission)

Online Appendix 2: The Governing of Debris in Space (GODS) Index

Total of the 10 dimensions varies between 0 and 14. This sum is then divided by 14 to give a score between 0 and 1.

Dimension 1. Objective (Highest of 4 indicators. Score of this dimension between 0 and 1)
1.1. Protection, preservation of space environment, sustainable use of space (value 1)
1.2. Sustainability of space activities (value 0.5)
1.3. Mention objective of safe use of space (value 0.5)
1.4. General statement on space as a common (value 0.5)

Dimension 2. Definition (Score of this dimension between 0 and 1)
2.1. Definition of space debris (value 1)

Dimension 3. Mitigation (Sum of the six indicators. Score of this dimension between 0 and 3. Max =3)
3.1. How space objects should be designed to mitigate debris (value 1)
3.2. How debris should be released during normal operation (value 1)
3.3. Reducing the probability of accidents (value 1)
3.4. Reducing risk of debris generation (value 1)
3.5. Preparing for safe post-mission asset disposal (value 1)
3.6. Others (value 1)

Dimension 4. Monitoring (Sum of the four indicators. Score of this dimension between 0 and 2. Max =2)
4.1. Registration with the United Nations (value 1)
4.2. Others (value 1)
4.3. Data on location of space debris and space objects (value 1)
4.4. Commitments on space traffic management, situational awareness, tracking, telemetry (value 1)

Dimension 5. Emergency (Sum of the three indicators. Score of this dimension between 0 and 2. Max =2)
5.1. On-orbit emergency assistance, rescue of astronauts (value 1)
5.2. Conjunction assessment (value 1)
5.3. Others (value 1)

Dimension 6. Liability (Highest indicator of the two. Score of this dimension between 0 and 1)
6.1. Liability (value 1)
6.2. Reference to the Liability Convention (0.5)

Dimension 7. Removal (Score of this dimension between 0 and 1)
7.1. Statements on removal of space debris (value 1)

Dimension 8. Research (Score of this dimension between 0 and 1)
8.1. Statements on research related to space debris (value 1)

Dimension 9. Cooperation (Score of this dimension between 0 and 1)
9.1. General statements to cooperate in the field of space debris (value 1)

Dimension 10. References (Highest of the two indicators. Score of this dimension between 0 and 1)
11.1. Reference to Space Debris Mitigation Guidelines (value 1)
11.2. Reference to inter-agency space debris coordination (value 1)

Online Appendix 3: Interviews

Participants were contacted through their professional email addresses if publicly available. The interviews occurred online and the approximative duration was 45 min. The notes and transcripts from interviews, if interviewees had agreed to audio recording, were analyzed with thematic summaries.

#	Type of organization	General title	World Region	Date
1	For profit	Co-Founder and CEO	Europe	13 August 2021
2	Intergovernmental	Lead/Representative	Regional	25 August 2021
3	Governmental	Senior Expert	Europe	28 September 2021
4	For profit	Co-Founder	Asia	12 October 2021
5	For profit	Legal Counsel	Europe	29 October 2021
6	Intergovernmental	Chief	International	26 November 2021
7	Non-profit	CEO/Chair	International	29 November 2021
8	For profit	Senior Vice President	Europe	7 December 2021
9	Intergovernmental	Director	Regional	14 December 2021
10	Intergovernmental	Chief of Section	International	16 December 2021
11	Governmental	Senior Legal Advisor	Middle East	20 December 2021
12	For profit	Founder and CEO	Europe	20 December 2021
13	Intergovernmental	Chair	Regional	21 December 2021
14	For profit	Founder and CEO	Europe	21 December 2021
15	Intergovernmental	Chief Strategy Officer	Regional	18 January 2022
16	Non-profit	Senior Director	North America	18 January 2022
17	Intergovernmental	Director/Representative	International	28 January 2022
18	For profit	CEO	North America	11 February 2022
19	For profit	Counsel	North America	15 February 2022
20	Non-profit	Senior Policy Advisor	North America	15 February 2022
21	For profit	Senior Vice President	North America	18 February 2022
22	For profit	Lead	Asia	23 February 2022
23	For profit	Director	North America	24 February 2022
24	For profit	Director	North America	3 March 2022
25	Governmental	Senior Executive	North America	19 May 2022
26	Intergovernmental	Lead	International	8 July 2022
27	For profit	Head of Section	Europe	19 July 2022
28	Governmental	Policy Officer	Europe	20 July 2022
29	For profit	Co-Founder and CEO	Asia	29 July 2022
30	Governmental	Director	Africa	3 August 2022
31	Non-profit	Founder	South America	4 August 2022