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The emerging global socio-technical regime for tackling space debris: A discourse network analysis

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ABSTRACT

The global space sector has to increasingly consider sustainability concerns in the orbit, given the rising challenge of space debris. In which direction the management of space debris will develop in terms of technological solutions, policies, and actor strategies remains still unclear. This paper applies the concept of 'global socio-technical regimes' to better understand how actors in the global space sector frame, conceive, and legitimize the space debris problem. More specifically, we apply a discourse network analysis method – sociotechnical configuration analysis – to identify and map different value orientations by core actors over the last fifteen years. This analysis reveals three development stages in the discourse: a problem identification period (2007–2011), followed by the rise of national interests amidst increasing promises of space-based infrastructures (2012–2015), and finally, the emergence of a global socio-technical regime that increasingly connects space sustainability with Earth-bound sustainability (2016–2019). Based on our analysis, we expect that ensuring future earth-space sustainability will include a broader mix of challenges. Future approaches to space debris management will have to consider a broader and clearer problem framing to help inform effective policy making.

1. Introduction

The rapid accumulation of space debris in Earth's orbit has gravitated much attention among international scientific experts, legal scholars, and policy circles in recent years [1–5]. Despite its urgency, the problem is often perceived as 'distant' in social sciences addressing grand challenges such as climate change, energy transition, and poverty. How environmental social science frameworks and methodologies may contribute to addressing space debris, therefore, remains poorly explored. In this article, we add an important perspective to the international debate on space debris by drawing on the field of sustainability transitions – an established interdisciplinary social science literature widely applied in Earth-bound sectors.

Situated at the intersection of institutional sociology and innovation studies, transition studies have coined important analytical frameworks to reconstruct long-term sectoral transformations ranging from energy, water, transport, to food [6]. It conceptualizes these transformation processes as deep reconfigurations of socio-technical systems [7], which emphasize the alignment among actors, technologies and institutions into socio-technical 'configurations that work' [8]. The core notion of the 'socio-technical regime' denotes the resulting rule system that guides strategies and means-end rationalities of actors in the given sector [9]. These rules define and legitimize in which directions a transition process will unfold.

Space debris is an emerging global challenge that only began to gain prominent public attention in about the last 15 years. Translating the above concepts to the exacerbating challenge of space debris means that the global space sector, which did not prioritize orbital sustainability for a long time, will now have to embrace sustainability concerns in its strategies and developmental visions. The prevailing socio-technical regime in the space sector engenders considerable inertia and might therefore delay the achievement of the required transition. The interplay of the different drivers and mechanisms that lead to a radical transformation is, however, still poorly understood. From a transition studies perspective, space debris can gain inspiration from the 'greening' of transitions in earthly sectors, and in particular of waste management. The latter suggests to integrate principles of reuse, recycle, and deposit in the design of products. In the case of space debris, we can observe similar approaches. However, there are no dominant solutions nor clear pathways emerging yet. Sustainability transition in the space sector requires developing and diffusing new technological solutions, revising existing rules and regulations, changing business practices, etc. All of

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these elements will have to co-evolve into a coherent 'socio-technical system'. We therefore need a systemic reconfiguration of the entire sector involving a multitude of actors with different value orientations or interests.

The aim of this paper is to unfold the emergence of a socio-technical regime for tackling the global space debris challenge through the identification of values, concepts and principles that are emerging in public debates about the topic. We propose a specific discourse network analysis approach, the socio-technical configuration analysis (STCA) to systematically analyze and map actors' value orientations, interests, concerns, and beliefs (hereinafter value orientations) around potential solutions for space debris. Structured in three time periods, the paper identifies the major development trends of the global socio-technical regime and unfolds how that might impact the future development of space debris management. Section 2 will introduce the STCA method and explain its relevance for the space debris challenge. Subsequently, Section 3 outlines the three development periods in this study. Section 4 will elaborate on the theoretical approach used for building the coding scheme for the discourse analysis. Section 5 will present the results, followed by a discussion and conclusion in Section 6.

2. Methodology and data

The STCA method was recently developed by transition scholars as a methodological tool to map and identify the re-alignment of socio-technical configurations in the course of sustainable transition processes [10,11]. STCA builds on the earlier Discourse Network Analysis (DNA) method developed in the field of political sciences, which was originally used to analyze policy related debates by coding text collections such as news articles, professional magazines, and policy documents, to generate relational data that connect different actors with regard to shared beliefs, arguments or policy stances [12,13]. Two types of networks may be generated accordingly: (1) actor congruence networks where links are established between actors who share similar views or beliefs based on their expressed statements, which allows identification of potential advocacy coalitions; and (2) concept congruence networks where links are established between concepts co-mentioned by different actors, which enables to identify prevalent themes and story lines (see Fig. 1).

STCA allows to capture a broader set of elements by coding statements of actors in news media, e.g. about how individual organizations assess and evaluate the emergence of a new technology (in this case the different forms of active space debris removal [14]) and how that relates to infrastructures, policies, regulations, sectoral paradigms or normative concerns. Given that the aim of the paper is to identify value orientations among actors, the analysis focuses on concept congruence networks (marked in red in Fig. 1), highlighting the interrelation among the different concepts as expressed by the different actors. The patterns revealed in these concept networks may be interpreted as emerging sociotechnical regimes shaping the future development of the sector, which may or may not be obvious to actors themselves. These concept congruence networks may then inform policymakers in which directions the sector may develop in the future.

In terms of data sources, the STCA for this study is based on discursive information drawing from an international English database namely LexisNexis, which provides legal, governmental, business, and technical information from newspapers, journals, and magazines, etc. We focused only on international news articles in this study in order to systematically trace the development trends of the international discourse on the space debris problem over time. Newspapers and magazines have increasingly been used as sources to capture discursive dynamics in transition studies [10,15] because they represent contributions to a sort of "public discourse" that journalists and editors of these outlets try to capture. Cited actor statements may then be interpreted as exemplary voices on how to best solve key challenges in a given field. Coherent combinations of such statements represent "narratives", which can be interpreted as representing existing or future regime structures.

To retrieve the relevant set of data from LexisNexis, we first filtered out certain sources such as transcripts of oral testimonies, TV shows, and public speeches. To sort out sources in which the discussion was explicitly focusing on the topic of space debris, we ran a series of searchstring queries and finally arrived at a searchstring (shown below) that best fits the objective of our study:

(atleast3 ((space PRE/1 debris) OR (space PRE/1 junk))) AND (atleast3 (clean OR clear OR remov! OR mitigat!))

The above search string led to 587 articles covering the period from January 2007 to December 2019.[1] After manual filtration in terms of content relevance and exclusion of duplicates, the final dataset contains 124 news articles reporting about the challenge of space debris. The analysis was subsequently triangulated with diplomatic reports (e.g. annual meetings of Committee on the Peaceful Uses of Outer Space; the US House of Representatives Committee on Science, Space and Technology) and soliciting input from professional experts during expert meetings, seminars, and conference presentations. This allows the study to gather external validation and incorporate insights from the latest developments of the sector. Major development trends after this period, such as the potential of Space Sustainability Rating [16], are related to in the discussion section.

3. Periods of analysis

We divided the data stock into three distinct development periods, which we defined based on major events shaping the space debris discourse internationally. Phase I (2007–2011) was identified as a period in which major awareness emerged in international space communities, following the anti-satellite (ASAT) test of the Chinese government in 2007 [17] and two years later the collision between a Russian-owned and an American-owned communications satellite. Before the incidents, the amount of space debris was steadily growing, but the problem did not attract much public media interest. The exponential growth of space debris due to these two events prompted scientists and experts to warn about the urgency to prevent similar events in the future, while the European Union (EU) published a draft Code of Conduct for Outer Space Activities in 2008 (revised in 2010). Accordingly, the problem of space debris began to attract media as well as research interest, including the publication of the United States (US) National Research Council report at the end of 2011, which called for urgent international regulations to limit space junks and the importance of more research and development into active debris removal (ADR) technologies (US National Research [18]).

Phase II (2012–2015) represents a period in which space debris received increasing awareness. It marks the period in which the US was in consultation with the EU to establish an 'International Code of Conduct for Outer Space Activities'. In 2015, international negotiations on the Code took place at United Nations Headquarters in New York but did not lead to any consensus. These discourses gained further attention as commercial companies began announcing their interests in this period to construct satellite constellations in low-Earth-orbit (LEO) – often projected as new space-based infrastructures. Besides Earth monitoring satellites, companies such as SpaceX announced their internet satellite constellations plan. Other companies such as WorldVu Satellites (now OneWeb) also announced their respective interests. This period therefore witnessed a rather counteracting development of space sustainability discourses on one hand, and an emerging LEO sector for building space infrastructures on the other.

Phase III (2016–2019) began with a trend of broadening the framing

[1] This paper was presented during the IAC 2021 in Dubai. The data lags by one year due to the extensive time taken to adapt the methodology for the case of space debris.

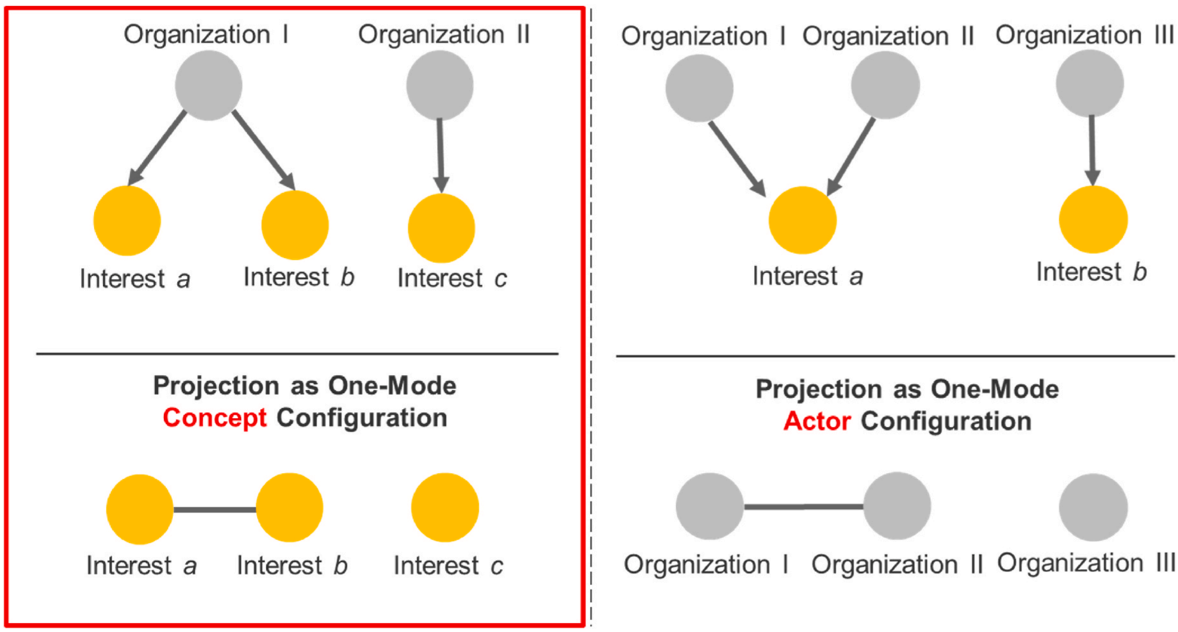

Fig. 1. Network representation of actor-concept affiliations. Red selection is the focus of analysis for this paper. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: Authors.

of space sustainability following the implementation of the United Nations Sustainable Development Goals (UN SDGs) in 2016. More specifically, United Nations Office for Outer Space Affairs (UNOOSA) positioned space-based technologies as a next-generation enabler for sustainable development on Earth. The United Nations played an important role in shaping this broadened discourse on space sustainability. For instance, UNOOSA published its first annual report in 2016, emphasizing the role of space infrastructures in addressing global sustainable development. Meanwhile, many new technical reports on space debris were published, generating more attention and concerns towards the challenge of space debris among the international space community (see for example [1]). Period III was also the period in which private companies began actual launches of satellite constellations in 2018. The period furthermore indicates increasing geopolitical conflicts in space. In March 2019, the Indian government led an ASAT test which destructed one of its own satellites using missiles. In July 2019, the French Defense Minister announced plans to develop ASAT laser weapons to defend French satellites in the orbit. In December 2019, the US government formally introduced the establishment of the new Space Force under the US Department of Defense. Period III was therefore characterized by a dynamic mix of different values and interests, which led to increasing contestations. Overall, the three periods allowed our discourse analysis to trace major development trends in the public news articles over time.

4. Theoretical approach

The concept of global socio-technical regimes elaborated in sustainability transition studies enables capturing the evolution of value orientations, concerns, and interests of core actors in the international space community. The concept of global socio-technical regimes is defined as "the dominant institutional rationality in a sociotechnical system, which depicts a structural pattern between actors, institutions and technologies that has reached validity beyond specific territorial contexts, and which is diffused through internationalized networks" [19]. In particular, we argue that the global sociotechnical regime for approaching the problem of space debris has yet to unfold, hence the lack of a widely accepted solution. Socio-technical regimes often consist of rules, which stem from the application of specific 'institutional logics' [20]. Institutional logics can be understood as "the socially constructed, historical patterns of material practices, assumptions, values, beliefs, and rules by which individuals produce and reproduce their material subsistence, organize time and space, and provide meaning to their social reality" [21]. There are seven basic forms of institutional logics that actors can typically refer to for legitimizing their preferred courses of action: profession, state, market, community, corporation, religion, and family [22,23].

Specific actor groups have to accommodate to specific basic institutional logics to embed their actions in a wider social environment, giving rise to so-called field-logics. We may therefore empirically identify different field logics by aggregating actors that emphasize similar combinations of basic logics into more or less coherent field logics. Applying this approach to the case of the space debris challenge thus allows to identify the main combinations of values, visions, beliefs, and rules that guide actors' behavior in approaching the challenge [24]. Our coding scheme for analyzing basic institutional logics was developed iteratively, deductively informed by existing theories and inductively derived by the empirical data. We compared, (re) evaluated, and (re) categorized the institutional logics (and their associated elements - see Appendix 1 for details) multiple times before arriving at a final coding scheme. Based on the analysis of the texts, we aggregated five ideal-type institutional field logics, which surfaced as coherent configurations of basic logics that different actors referred to. In the empirical analysis we will use these field logics to identify specific value orientations that actors mobilized in the respective narratives. The five ideal-type institutional field logics for the global space debris challenge are listed in Table 1 below, namely the state, market, global governance, global community, and sustainability logics.

5. Results: an emerging global socio-technical regime

Adopting the concept of institutional logics allows this study to identify the core value orientations and interests of a growing set of actors in the space sector, and how different values and interests may align or conflict with each other over the periods of analysis. In terms of available solutions, there are three identifiable sustainability transition

Table 1
Institutional logics in the coding scheme of analysis.

Institutional logics	Description	Elements	Colour in network
State	Orientated towards the role of the state in regulating or governing activities in respective countries; strengthening national institutional frameworks by revising national mitigation policies; the importance of national supremacy due to geopolitical interests; interests in general citizen welfare and national economy (by leveraging on space-based infrastructures).	National economy; National supremacy; National state-industry; National security; National framework	Orange
Market	Concerns over shaping a business case for ADR or other space logistics businesses, e.g. on-orbit servicing.	R&D experimentation; ADR efficiency; Business case; Business opportunities; Industry standards	Green
Global governance	Discussions on the importance of revising international space law, the importance of the International Code of Conduct, the importance of reformulating the UN Guidelines, etc.	Global centralized governance; Debris mitigation guidelines; International space law; International standards and norms	Blue
Global community	The importance of global community values, such as the role of individual states in implementing international guidelines; willingness for nation states to decenter geopolitics and cooperate internationally; the importance of trust and confidence building among states; willingness of private companies to respect and comply with existing international guidelines; etc.	Trust and confidence building; Global responsibilities; Space disarmament; International cooperation; National responsibilities; Space access/global commons; Operators' responsibilities	Red
Sustainability	A growing and deeper awareness of sustainability challenges in space, which internalizes orbital sustainability challenges as closely related to earth-bound sustainability; earth-space interdependencies; anticipatory concerns; orbital resources to be safeguarded for inter-generational use; etc.	Global space-based infrastructures; Urgency; Space safety; Space weaponization concerns; Planetary sustainability; Kessler syndrome	Purple

Note: See Appendix 1 for elaborations on the coded elements.
Source: Authors.

pathways for addressing space debris, with the first being the *mitigation pathway*. The UN Debris Mitigation Guidelines put forward important considerations to mitigate the future accumulation of space debris. Within the Guidelines, the disposal rule suggests all operators to incorporate new pre-launch technological designs into their spacecraft or satellites. These technological innovations will enable the satellites to discard themselves at their end-of-life, by de-orbiting or re-entry into Earth's atmosphere to self-burn. A second pathway is known as the *remedial (or interventionist) pathway*, through technological innovations such as active debris removal. Universities and companies are developing technologies that can actively remove space debris, such as by sending a spacecraft with a robotic arm to low-Earth-orbit for capturing dead satellites or by launching a deployable sail to drag retired satellites back into Earth's atmosphere. A third major pathway is the *adaptation pathway*, which is essential to support the aforementioned two pathways. This includes space traffic management or a 'dumping site' for retired satellites, similar to the 'deposition approach' in landfills for solid waste management. Dealing with space debris in this context includes dragging or pushing the dead satellites into a special zone in Earth's orbit known as the 'graveyard zone'. Other alternatives in this third pathway may include space logistics, where companies begin providing on-orbit servicing to extend the lifespan of satellites (i.e. against planned obsolescence of satellites), etc. All three pathways have been discussed as equally important for a successful transition of the orbital environment. However, based on the news articles in this study, the third option only emerged in the last period of analysis. These pathways represent potential solutions to the space debris problem that may be promoted by different actors depending on the specific field logics they subscribe to.

5.1. Phase I: problem identification

Following the ASAT of the Chinese government in 2007, concerns over potential space weaponization gravitated quite some media interests in the news articles analyzed. Although the Outer Space Treaty of 1967 already led to the banning of stationing weapons of mass destruction in Earth's orbit, the ASAT spawned renewed concerns over space weaponization. In addition, the collision of the US and the Russian telecommunication satellites intensified media reporting where actors expressed concerns over future space safety. The constellation of major terms used in the media coverage in Phase I is shown in Fig. 2 below in a radial form. Overall, the network seems to be dispersed with several prominent concepts occupying the center of the discourse. Based on detailed interpretation of the networks, two relatively distinct narratives could be identified as elaborated below.

The first narrative reflects **responses triggered** by the two major incidents (the ASAT and an actual collision). Actors were stressing the importance of disarming space in view of the ASAT event and how actions of individual states could lead to an exponential rise in the number of space debris in Earth's orbit. Meanwhile, the importance of industry and technical standards for satellite operators was particularly stressed when discussing future collision risks. The UN Space Debris Mitigation Guidelines play an important role for addressing both challenges. Ensuring successful implementation of those guidelines, however, requires the commitment of individual states and the alignment of their national policies with principles in the international treaties or agreements (labeled as 'national responsibilities'). Overall, the core elements that constitute this narrative were presented in Fig. 2 as 'space disarmament', 'national responsibilities', 'debris mitigation guidelines', and 'industry standards'. The node sizes for 'national responsibilities' and 'space disarmament', for instance, are smaller compared to 'international cooperation' given that the latter was more frequently mentioned (i.e. the number of times this topic appeared was higher).

The second rather distinct narrative could be interpreted as discussions about **potential solutions**. The potential uses of ADR to address space debris were strongly associated with its feasibility given the lack of a business case. Here, actors raised the questions such as whose responsibility it should be to safeguard orbital sustainability, which satellites to be removed, who should pay for such expensive space cleaning missions, and who should remove whose satellite debris. The use of ADR was also strongly associated with space weaponization concerns due to the dual-use nature of this technology. Whether it is about creating a business case or minimizing the misuse of this technology, there was a strong adherence to the need for compatible international space law (indicated in blue as a part of *global governance logic*) requiring close international cooperation and coordination. The elements that constructed this narrative are presented in Fig. 2 as 'business case', 'space weaponization concerns', 'international cooperation', and 'international space law'.

Besides the two strong narratives, we observed weak value

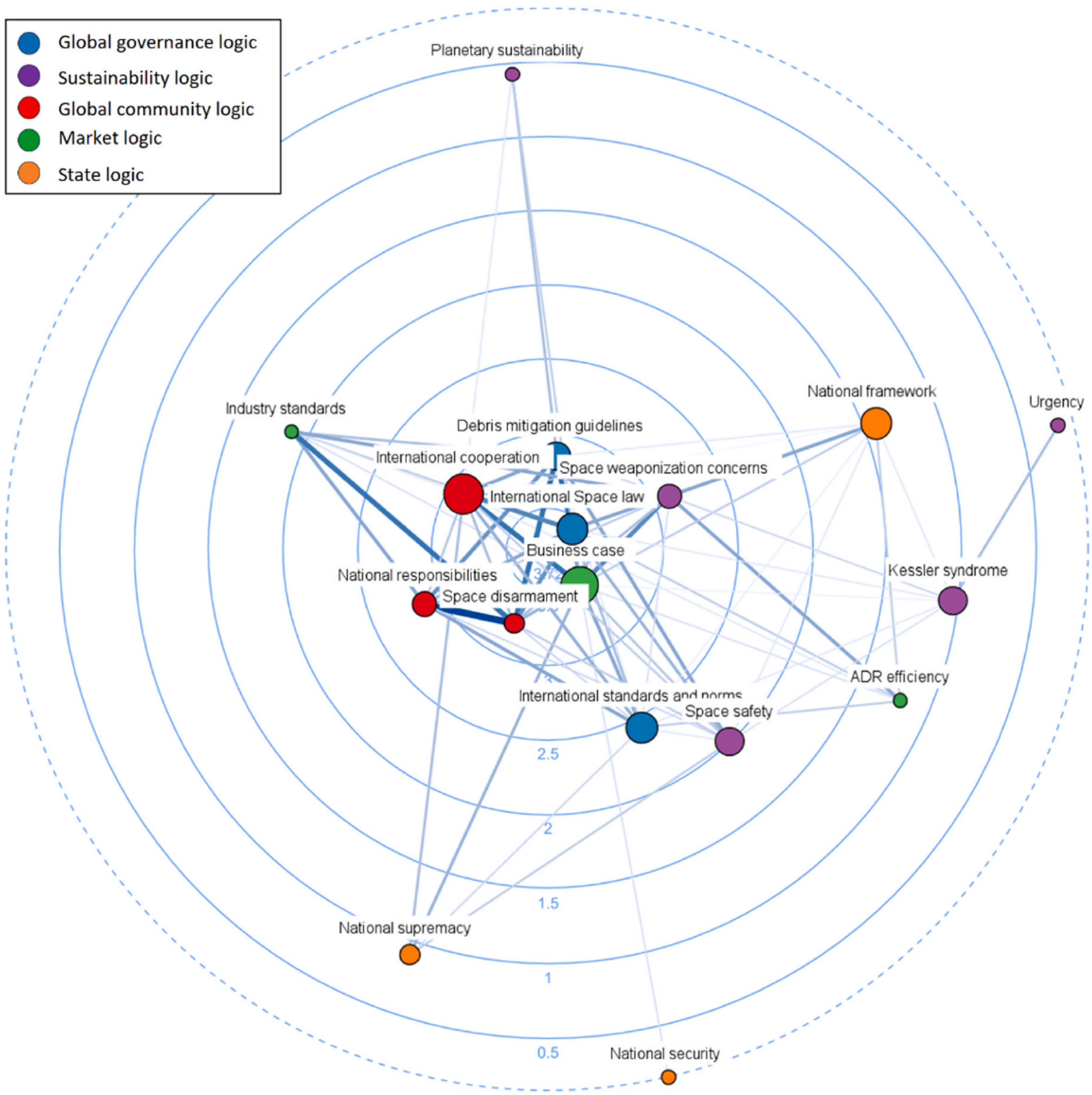

Fig. 2. Concept network for Phase I (2007–2011) showing how different values and field logics are interrelated. Nodes represent coded concepts (values, interests, policies, etc.). Node size indicates the number of actors that had mentioned a concept. Thickness of links is proportional to the number of actors that have co-mentioned the two concepts. Colors of nodes relate to institutional logics to which the concepts were associated. Finally, the radial layout puts those concepts at the center of the figure, which showed similarities/co-mentioning with other concepts, while concepts that were mentioned only occasionally and in isolation are positioned in the outer circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

adherence towards the *sustainability logic* in Phase I, as its elements appear rather at the periphery of the network (see Fig. 2). As elaborated above, the main discourse was naturally focusing on the major events that took place in this period which concerned space weaponization, growing space debris, and the potential uses of ADR. Concerns for Kessler Syndrome were discussed as a continuation from earlier times, but they did not appear at the center of discussion when compared to other elements that emerged directly as a response to those triggering events. Space debris was mainly discussed as causing space safety issues to spacecraft or satellite operations. The broader framing of sustainability was almost non-existent or only appeared as a distant subject in the public discourse. For instance, elements such as 'planetary sustainability' - which emphasizes space access for intergenerational use [25]- appeared at the periphery of the discourse.

5.2. *Phase II: the rise of national interests and a decentering of global community logic*

The challenge of space debris continued to gain traction in the public discourse throughout Phase II. In particular, the two original narratives identified in Phase I seem to extend and shift. First, as **space-based infrastructures** began to show promises for industrial applications and development opportunities, the concerns for peaceful and sustainable uses of the orbit began to attract more national policy attention from different states. Here, the call for nation states to disarm space began to be projected as a matter of national security to those countries not leading in space due to their growing reliance on others' space-based infrastructures. This element is therefore also strongly associated with the need for compatible standards and norms of behavior in space at the international level. Correspondingly, we identified coherent links between the elements of 'space disarmament', 'national security', 'national framework', and 'international standards and norms'.

The second narrative may be attributed to the one on **potential solutions** from Phase I. More specifically, the discussion on the business case for ADR continued to be associated with the importance of international space law to help shape a feasible industry plan for ADR. In this period, actors began to indicate the urgency of finding technological solutions. Interestingly, we observed the rise of value adherence towards national supremacy in this narrative. This could be explained as spacefaring nations began to value the importance of achieving national competitiveness in order to lead in shaping future technological solutions that are critical to space-based infrastructures. The elements that constructed this narrative consist of 'business case', 'urgency', 'international space law', and 'national supremacy'.

In terms of logics, we observed a clearer distribution pattern in Phase II. There seems to be an emerging group of terms relating to national state interests in this period. The corresponding value orientations were attributed to the *state logic* (orange nodes in Fig. 3). The growing prominence of the national *state logic* in this period led to a decentering of the *global community logic* (in red) and by this a relative weakening of coordinative approaches. Meanwhile, it is notable that certain elements of the *global governance logic* such as 'international space law' was also driven away from the center as compared to the previous phase. This could be attributed to the rise in national state interests in Phase II, which led to difficulties among the space actors in envisioning any new consensus in international space law. Therefore, the discussions in this period might have placed more emphasis on voluntary-based and non-legally binding options such as establishing norms and standards.

The above also led to the expansion of the *market logic* (in green) compared to Phase I. Broader elements associated with market interests began to emerge at the periphery of the network, e.g. the importance of R&D experimentation of different ADR options, finding solutions for improving ADR efficiency, and emphasis on the role of private actors in finding innovative solutions for ADR or for space debris management in general. These elements appeared as dispersed around the network with notable sizes, indicating that they were often mentioned while connected with elements in different logics but without representing a coherent narrative in their own terms. This is in line with major trends in the sector as several ADR initiatives emerged following the increasing commercial interests in launching satellites. For instance, the European Space Agency (ESA) had the first ADR program (later transferred to a spin-off from the Swiss Federal Institute of Technology Lausanne [EPFL]

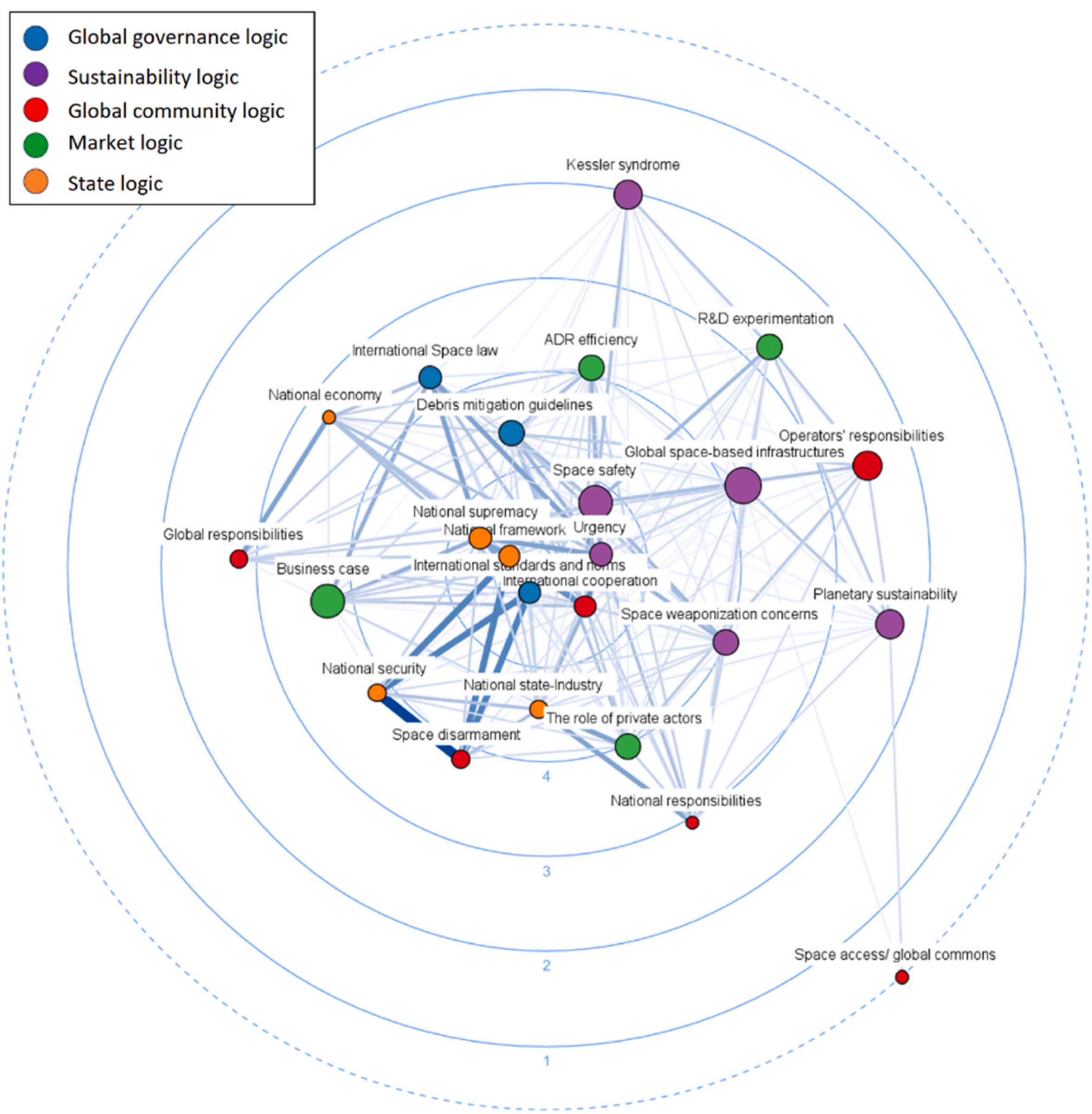

Fig. 3. Concept network for Phase II (2012–2015). For the interpretation of the graphical layout, refer to legend of Fig. 2.

in Phase III). A few commercial companies developing ADR technologies also started to appear in international news media. In addition, elements pertaining to the *sustainability logic* (in purple) began to be more aligned among themselves, which indicates an increasingly coherent narrative emerging from this logic, and moved relatively towards the center of the discourse. Space safety remained strongly associated as a condition to the sustainability of global space-based infrastructures such as the provision of satellite navigation, earth observation, and telecommunication.

5.3. Phase III: an emerging socio-technical regime for earth-space sustainability?

Phase III shows the emergence of a **broader sustainability** narrative at the center of the discourse, representing the major elements from the *sustainability logic* (in purple). This seems to have evolved from the narrative in Phase II on the promise of space-based infrastructures. The trend was probably supported by the introduction of the UN SDGs as well as the projection made by international organizations such as UNOOSA that space is a key enabler for global sustainable development. As shown in Fig. 4, the different value orientations (nodes) of the *sustainability logic* occupy the center of the discourse network such as ‘planetary sustainability’, ‘global space-based infrastructures’, ‘urgency’, and ‘space safety’. The discourses on planetary sustainability grew stronger as actors emphasized the critical role of space-based infrastructures for global society and safeguarding space access for future generations became projected as an urgent problem. Space safety for satellite operators remains important but appeared as only a component in the broader sustainability discourse.

Furthermore, in earlier phases, the problem of Kessler Syndrome was mostly perceived and approached as an ‘externality’ among space actors, i.e. an isolated problem of space safety mainly imposing harm to activities in space such as operations of satellites, spacecrafts and astronauts. However, in Phase III, reference to the Kessler Syndrome was increasingly associated with Earth-bound sustainability challenges. More specifically, the problem framing shifted towards one that perceives Earth and space as interdependent. In line with the United Nations advocacy for using space for sustainable development, actors referred to satellite systems as global, critical space-based infrastructures, such as for disaster management, climate monitoring, and

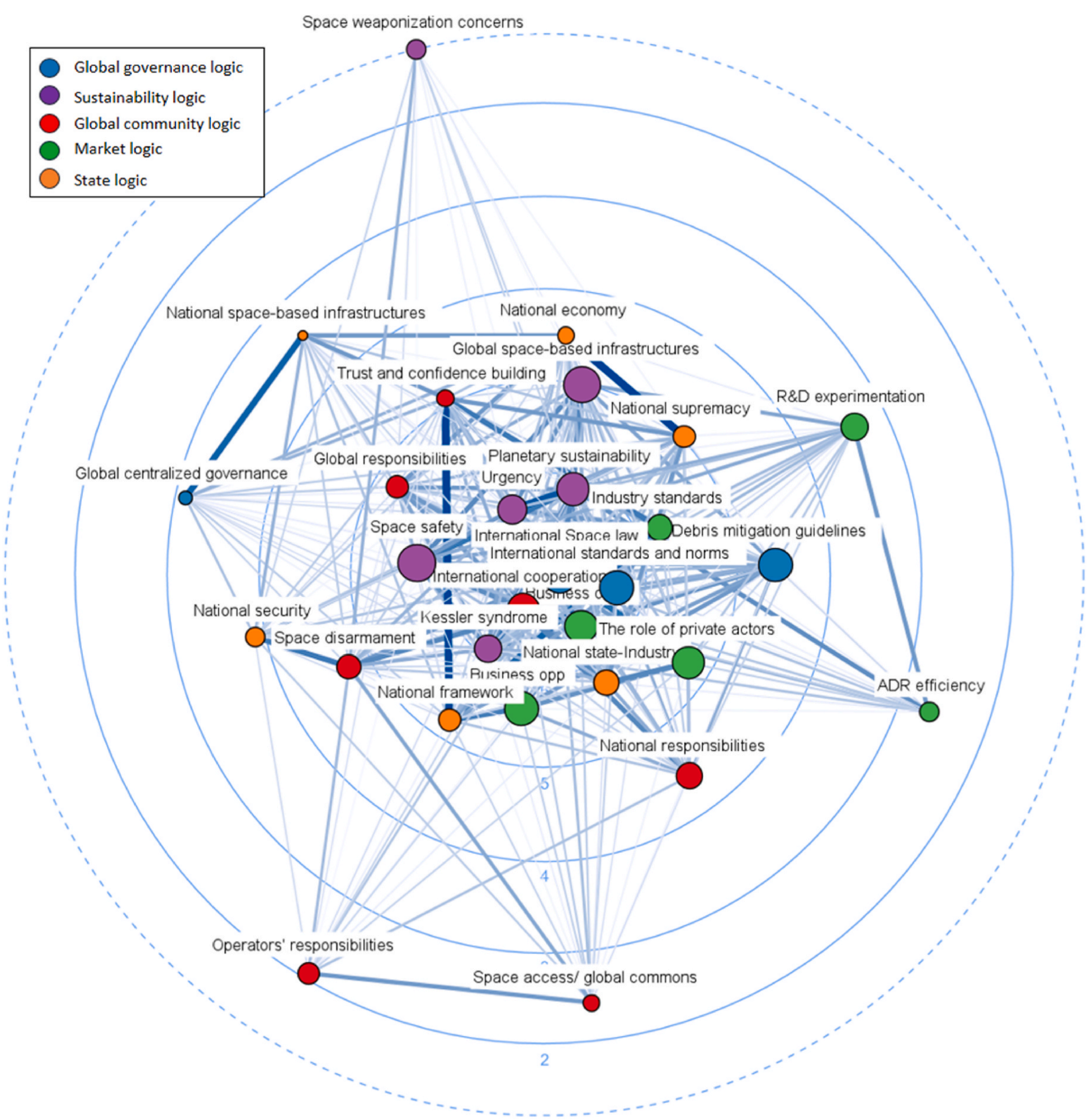

Fig. 4. Concept network for Phase III (2016–2019). For the interpretation of the graphical layout, refer to legend of Fig. 2.

communication. They argued that activities on Earth will be severely interrupted if these infrastructures no longer function well. This indicates that the emerging notion of 'earth-space sustainability' begins to institutionalize as a core element of the global socio-technical regime [26], in which sustainability challenges in space increasingly integrates with earth-bound sustainability challenges.

In Phase III, the second narrative on **potential solutions** seems to have also moved into a central position and therefore co-dominates the center of the discourse. In particular, we observed strong links between elements of 'national framework', 'business opportunities', 'national state-industry', 'the role of private actors', 'national supremacy', and 'trust and confidence building'. This narrative could be interpreted as a further maturation of the discussions on potential solutions in Phase II. In addition, building on the growing role of national interests (indicated as national supremacy) in Phase I, the narrative on potential solutions now expanded to include the role of national policies in promoting business opportunities and public-private partnerships, the role of private actors in finding solutions for orbital sustainability, and the importance of trust and confidence building among nation states as they design and implement their respective national policies.

Overall, the second narrative seems to have also stimulated a stronger discussion on the *market logic* (in green) compared to Phase II as elements of this logic appeared to be more aligned in Phase III. The co-dominance of the broader *sustainability logic* and the *market logic* in Phase III may be a sign of growing consensus among the international space community that the private sector may play a crucial role in driving systemic innovations for future earth-space sustainability. An emerging narrative on the side integrating elements from the two logics took shape, such as 'ADR efficiency', 'R&D experimentation', 'planetary sustainability', and 'global space-based infrastructures'. The diffusion of ADR remains challenging but technology developers and companies began expressing more optimistic views about the future of ADR. The discussion incorporated the co-mentioning of on-orbit experimentation, which is essential to achieve efficiency and lower costs that ensure the scalability of missions. In the EU, policymakers emphasized how European firms may play a major role in tackling the environmental challenges in space and in maintaining the sustainability of space-based infrastructures. This corresponds with the bottom-up innovation policy of the European space sector – which encourages commercial interests and private innovations to shape future dominant designs for ADR. Interestingly, concerns over the misuse of ADR seems to have subsided at least in the news articles analyzed (appeared as 'space weaponization concerns' in the network). This indicates that ADR may have gained increasing legitimacy among the international space community due to the growing *market logic* that often occupies the news platform.

It is also noteworthy to reflect on the distribution patterns of other logics in this period. The *global community logic* (in red) grew again more prominent in Phase III, although not occupying the center of the discourse. For instance, statements reported in the international news articles began to put more emphasis on space as a kind of global commons and that developing countries should be given equal access to space resources or space benefits - most of which will be disrupted if space becomes a geopolitical battlefield between powerful space nations. Meanwhile, there was also increasing reference to the need for individual nation states to play their role as members of the international space community. These actors emphasized the importance of a global community logic in which every player assumes its responsibility, such as by adopting the space debris mitigation guidelines, which were not directly associated with legally-binding regulations.

Meanwhile, there were increasing discussions on the role of the *state* for better tackling space debris. Since the US has been a leading space-faring nation, there were some discussions on whether the national policy framework of the US is sufficiently fit to deal with the exacerbating challenge of space debris. In particular, the US national framework can play a significant role in orbital sustainability, given that many satellite constellation companies are based in the US and that the international space community or developing countries often take the US model as a reference point for designing their own national policies. Other discussions include challenges of the existing US licensing policy for satellite launch, mainly led by state agencies such as the Federal Aviation Administration (FAA) and the Federal Communications Commission (FCC). In the last few years, discussion around the newly formed US Space Force began to gain traction in the media.

In the same period, the planned satellite constellation projects by large private companies gravitated more media discourses around orbital sustainability. In particular, certain elements related to the *global governance logic* (in blue) also moved towards the center in conjunction with other logics. For instance, the importance of the UN Space Debris Mitigation Guidelines and international standards in recommending disposal rules for all future satellite launches became very central among academics, scientists, and policymakers. Overall, Phase III observed that the different logics progressively integrated towards the center of the international discourse. In particular, the co-dominance of the broader *sustainability logic* and the *market logic* in the discourse may indicate an emerging consensus among space actors that managing earth-space sustainability will be closely associated with market-driven forces in the next phase. The effectiveness of this trend, however, remains an open question beyond the analysis of this study.

6. Discussion and conclusion

Using insights from the field of sustainability transitions, our analysis identified the broader institutional structures (i.e. value orientations, norms, as well as cognitive and regulative elements) shaping the emergent global socio-technical regime of space debris management. In particular, our analysis identified notable shifts in problem framing over the last 15 years. The early developments showcased how the issue of space debris began to gain traction in the public discourse, but was identified rather as a problem of externality among the international space community. Ensuring space safety for operating satellites or spacecrafts was the core rationale in maintaining orbital sustainability. The second period was then marked by an increasing acceptance of space debris as a global problem due to the increasing potentials of space-based infrastructures. However, rising geopolitical tensions drove the discourse towards weak coordination structures for solving the problem. We therefore saw the *global community logic* weakening at the expense of rising state interests. Only in the third phase, we see strong elements of a broader *sustainability logic* emerging and moving to the center stage of the discourse.

Our analysis unfolds the opportunities and challenges for a successful transition of the space sector. The remedial pathway through ADR reflects the initial 'typical' response from the international space community, which was to consider whether external, private businesses could solve the matter through debris removal technologies. However, the context conditions did not yet exist for such a market to emerge. This is in line with insights from dealing with externalities in conventional sectors such as wastewater treatment, where separate infrastructures and industries were built up to solve the problem, while not interfering with the core commercial activities. Over time, the ADR industry has attracted growing interests and innovations among private actors and research institutes. The case of space debris management seems to resonate with the experience of the wastewater treatment sector, which originally "solved" the urban water management problem through extensive centralized infrastructures and state-based governance structures. Only recently, consideration about the sustainability of this sector called for more decentralized approaches and an increased need for radical innovations in this sector (Hoffmann et al., 2020; Larsen et al., 2016). For the case of space debris, this means that sustainability concerns will require a broad portfolio of radical innovations to reduce the cluttering of Earth's orbit.

However, cleaning up will not be sufficient. Mitigation measures will have to play an increasing role as well. The UN Space Debris Mitigation

Guidelines as well as other incentive-based instruments such as the recently proposed Space Sustainability Rating gained increasing media attention [16]. These instruments may help prevent the future accumulation of space debris by encouraging the implementation of disposal rules on the designs of spacecraft and satellites. Through this, externalities are internalized into the space technology innovation process. For both remedial and mitigation pathways, we therefore expect increasing innovation activities by actors striving towards market dominance or national technological supremacy. While companies compete on lower costs through innovations, states are motivated by classical industrial policy concerns as each country wishes to host the industry for such a 'future technology area'. Finally, new ideas for managing the Earth's orbit are also emerging. These include the provision of sustainable space logistic services and building a space recycling center.

Drawing from historical sustainability transition cases, we found inspiration for approaching the increasingly pressing space debris case. It is important to reiterate that our analysis has focused on international news articles in English instead of other languages or other sense-making platforms such as government documents, policy reports, or transcripts of policy-related meetings. The latter document stocks are likely to feature different interest groups and address different audiences (e.g. state representatives, policymakers, lawmakers), which may highlight different aspects of the international discourses. Future studies adopting the proposed method should therefore incorporate data sources from other languages and different sense-making platforms. We however maintain that the present analysis illustrates what the proposed approach could likely deliver in future research on earth-space sustainability challenges.

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.

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Appendix. Elaborations on the coded elements

Institutional logics	Elements/value orientations	Elaboration
State	National economy	The importance of the space sector in general or space-based infrastructures in particular to generate new economic activities within nations.
	National supremacy	The importance for individual nations to achieve international leadership in certain technological realms.
	National state-industry	Promoting public-private partnerships through national industry policies.
	National security	The framing of sustainable space-based infrastructures as a matter of national security.
	National framework	The role of national policies and regulatory frameworks in contributing to international space sustainability, addressing space debris, promoting international cooperation, etc.
Market	R&D experimentation	The importance of having the appropriate opportunities and platforms for companies or universities to test out their technological services or initiatives.
	ADR efficiency	The importance of achieving cost efficiency for ADR missions.
	Business case	The importance of shaping a feasible business model for ADR, most often relates to the lack of a coherent space governance framework that defines the features of an ADR industry.
	Business opportunities	The emphasis on the various business opportunities the space sector could generate in general.
	Industry standards	The importance of having industry standards to foster the development and growth of the space sector.
Global governance	Global centralized governance	The importance of having an international centralized authority to govern the activities of the space sector.
	Debris mitigation guidelines	The importance of having sound mitigation guidelines; the importance of compliance with those voluntary-based guidelines.
	International space law	The emphasis on formal, legally-binding law and regulations.
	International standards and norms	The importance of shaping international standards and norms of behavior as opposed to legally-binding instruments.
Global community	Trust and confidence building	The importance for nation states to cultivate trust and confidence building among actors, e.g. transparency in their respective space activities, better communication, information sharing.
	Global responsibilities	The importance of globally integrated efforts or collective action to address space sustainability problems.
	Space disarmament	The importance for leading nation states to disarm space.
	International cooperation	The importance of international cooperation among nation states.
	National responsibilities	The importance of each individual nation state to play their part in forming a global space community.
	Space access/global commons	The understanding of space-based infrastructures should be accessible to global society and that these infrastructures or space resources are perceived as global commons.
	Operators' responsibilities	The importance of satellite operators (private or public) to be responsible for their respective satellite debris; in line with the disposal rule.
Sustainability	Global space-based infrastructures	An understanding that space as the place that hosts global infrastructures critical to Earth-bound sustainability challenges.
	Urgency	The urgency of the matter in particular when anticipating the needs of future generation or inter-generational accessibility to space.
	Space safety	The importance of maintaining space safety for satellite operators, astronauts, and spacecrafts (often closely related to mitigating debris, collision risks, conjunctions in congested environments, etc.)
	Space weaponization concerns	The concern of space weaponization in general or the dual-use of ADR in particular, and how such scenarios could impact the Earth's orbital environment and global society as a whole.
	Kessler Syndrome	The reference to the syndrome (to track how it is associated with other elements over time, e.g. space safety, planetary sustainability, urgency).
	Planetary sustainability	An emerging notion that perceives space-related challenges on a planetary scale, such as by referring to the increasing interdependencies between Earth-bound and space-based sustainability.

Source: Authors.

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