From Ozone Depletion to Orbital Debris: Lessons Learned from the Montreal Protocol

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1. INTRODUCTION

Increasing use and commercialization of the space environment and the growing accessibility of space launch have led to growing numbers of active satellites and orbital debris in Earth orbit. Orbital debris is defined as human-made, non-functional objects— including fragments and elements thereof— in Earth orbit or re-entering Earth's atmosphere; debris has far outnumbered operational spacecraft in orbit since the early days of space exploration [1]. In July 2022, the U.S. Space Surveillance Network catalog of space objects, which only accounts for debris larger than 5 centimeters in diameter, reported 8,943 spacecraft and 16,393 pieces of orbital debris. The planned deployment of mega-constellations, fleets that may include tens of thousands of networked satellites, signals a paradigm shift for satellite operations and will accelerate the densification of already highly populated low Earth orbit (LEO).

As satellite orbits become increasingly crowded with active spacecraft and orbital debris, the risk of collision grows. Fragmentation events could generate even more debris, potentially leading to Kessler Syndrome, a hypothetical worst-case scenario (first proposed by Dr. Donald Kessler in 1978) in which a cascading series of collisions and the cloud of debris it creates could render Earth orbits effectively unusable [2]. The immediate consequences of a Kessler event could be far-reaching, crippling terrestrial services such as telecommunications, broadband internet, and weather forecasting, while also hindering future space utilization or exploration [3].

Despite increasing awareness of risks posed by orbital debris, efforts to mitigate and prevent debris are limited by a regulatory and policy environment that lags behind the rapid development of space. International agreements and national legislation were designed to enable safe operation in a sparsely populated space environment that increasingly does not resemble today's crowded orbital domains.

The 1967 Outer Space Treaty (OST) and the subsequent 1976 Liability Convention underlie international space law and affirm the ownership of space objects, but do not directly address orbital debris. Under these rules, the launching state maintains ownership over objects launched within their borders and other nations may not collect these objects without consent of the launching state [3]. In addition, the launching state is responsible for providing compensation for damage caused by their space objects. Uncertainties remain when considering how these basic tenets of space law apply to orbital debris: although most states consider orbital debris to be space objects, the OST and Liability Convention do not provide an explicit definition, and identification of the launching state in the event of a collision is complicated by our limited ability to track and identify most space objects.

Without regulatory requirements or other immediate incentives to prevent orbital debris, spacecraft owners, operators, and launch providers have been slow to comply with voluntary guidelines that would reduce the creation and risk of orbital debris. The European Space Agency (ESA) reports that between 30 and 70 percent of payload mass (excluding human spaceflight) in LEO are estimated to adhere to end of life deorbit guidelines. ESA further notes that rates of compliance with debris mitigation measures are growing but still insufficient to significantly reduce collision risk in the long term [2].

The challenges posed by orbital debris have inherent similarities to global environmental challenges such as ozone depletion. Rather than delaying action because benefits are uncertain, jurisdictional authorities and international bodies are encouraged to exercise the *precautionary principle*—a long-standing tenet of environmental law—which recommends that states act on environmental problems that pose a long-term environmental threat, even if there is no proof that the harm will occur [4]. The signing and subsequent implementation of the Montreal Protocol on Substances that Deplete the Ozone Layer is a notable example of when the international community effectively mobilized, even while the science was evolving and uncertain, to address detrimental environmental impacts of anthropogenic activity. In May 2022, Garber and Rand published a paper suggesting looking at the Montreal protocol as a framework for thinking about orbital debris [5]. This AMOS paper similarly illustrates parallels between the two environmental problems. We provide a comparative analysis to identify lessons learned from the Montreal Protocol that may be applicable to orbital debris, with a focus on breaking down the challenges into a framework of mitigation, monitoring, remediation and adaptation.

2. HISTORY OF OZONE DEPLETION

2.1 INITIAL WARNINGS AND EARLY MOBILIZATION

Chlorofluorocarbons (CFCs) were first synthesized in 1928 as a nontoxic, non-flammable alternative to the hazardous, occasionally explosive gases previously used as refrigerants. DuPont's CFC product, Freon, became a popular refrigerant in commercial refrigerators and large air-conditioning systems. In the years following, CFCs were incorporated into a wide range of products and applications including aerosol sprays, electronics manufacturing, and household air-conditioning.

By 1974, when Dr. Mario Molina and Dr. Sherwood Rowland first sounded the alarm that CFC emissions—long regarded as harmless—could deplete stratospheric ozone, CFC sales had peaked at annual sales of $1 billion USD and production levels of one million metric tons [6]. In the years following, additional types of ozone-depleting substances (ODS) were identified, but the ubiquity of CFCs in homes, commercial buildings, and industrial processes presented a significant barrier to reduction efforts. Even if production of the chemical were phased out, legacy products and devices would continue to leak CFCs into the atmosphere.

Molina and Rowland predicted that 50 percent of the ozone layer could be destroyed by 2050 if CFC production continued to rise until 1990 and then leveled off [7]. Government and industry were sufficiently alarmed about the potential threat of ozone depletion to study the issue more closely. The United Nations Environment Program (UNEP) and companies including DuPont formed committees to investigate Molina and Rowland's theories, and the Carter Administration took the precautionary step of banning aerosol spray products containing CFCs. With financial support from their governments, scientific researchers took steps to gather more information on ozone depletion. In 1978, NASA launched the Nimbus-7 satellite mission with the objective of measuring atmospheric ozone [8].

In 1985, 20 nations signed the Vienna Convention, acknowledging the problem of ozone depletion and agreeing to cooperate on research, information exchange, and policy-making to prevent degradation of the ozone layer. Although at that point scientists lacked definitive evidence linking ozone depletion with specific chemical emissions, CFCs were included in a list of many substances that scientists thought could potentially "modify the chemical and physical properties of the ozone layer" [7].

2.2 MEASUREMENT AND CONFIRMATION

The subsequent confirmation of the relationship between CFC emissions and ozone depletion was enabled by scientific advances and international coordination on atmospheric monitoring that began years before Molina and Rowland's discovery.

In 1956, the Halley Antarctic Research station was established as part of the International Geophysical Year, a collaboration on geophysical research involving scientists around the world [9]. 25 years later, measurements from Halley's spectrophotometers indicated a 20 percent reduction in stratospheric ozone. Although Antarctic scientists studying atmospheric ozone in 1981 were aware of the Molina-Rowland theory, the scientific community had not predicted an uneven distribution of depletion across the ozone layer – the researchers assumed the low readings were due to instrument error and did not publish their results or compare their data with other stations. By 1985, Halley station researchers realized the significance of the low ozone levels and were the first to publish on the potential connection between the drastic decrease in Antarctic ozone and CFC emissions. Shortly after, Bhartia et al. (1985) produced a map of the "ozone hole" using data from NASA's Total Ozone Mapping Spectrometer (TOMS) instrument (which had launched onboard the Nimbus-7 satellite) [7][10]. Images of the "hole" are often cited as a tipping point in creating public awareness of the problem of ozone depletion.

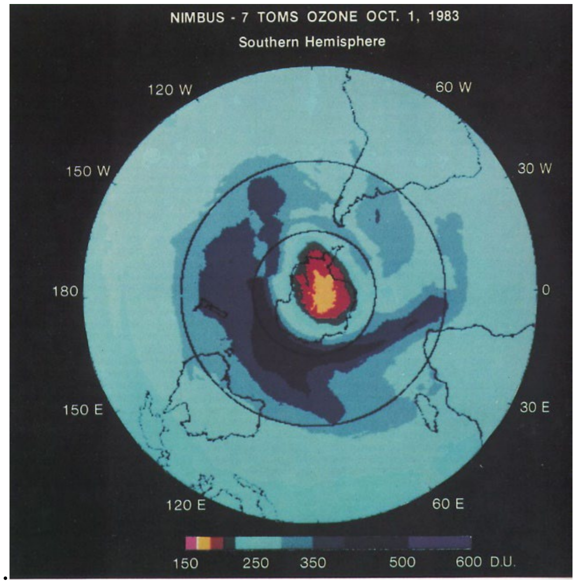

Figure 1: "Ozone Hole" Map (Source: NASA)

In 1986, NASA, the UNEP, Federal Aviation Administration (FAA), National Oceanic and Atmospheric Administration (NOAA), and World Meteorological Organization (WMO) partnered to form the International Ozone Trends Panel in response to the growing body of evidence of dramatic ozone depletion. The report that resulted is considered to be the first international consensus confirming drastic, localized depletion of Antarctic ozone [8].

2.3 SIGNING, IMPLEMENTATION, AND ONGOING EVOLUTION OF THE PROTOCOL

In 1987, 24 nations and the European Economic Community signed the Montreal Protocol [11]. The 1985 Vienna Convention provided a framework for evidence-gathering and discussions leading to the Protocol, but did not provide any concrete steps for ODS emissions reductions [12]. Determining how these reductions would be achieved and how quickly (e.g., which substances to control, whether to restrict production or consumption, when substances should be phased out) was a deliberative process that required balancing the disparate interests of many parties. Many factors ultimately contributed to the Protocol's success, but we highlight the document's flexibility, adaptability, and incentives for participation and compliance as particularly important.

The Protocol required all parties to eventually cease consumption of specific ODSs, but provided flexibility in how each nation achieved these reductions. Control measures distinguished two groups of ODSs and outlined step-wise reductions leading to gradual phase-outs of each group's production. Each chemical was assigned an ozone depletion potential (ODP) value, and overall ODS consumption for each country was calculated by adding together the product of each chemical multiplied by its ODP. This approach allowed countries to choose which chemicals to target to achieve their reduction goals. Countries with industries dependent on a particular ODS lacking viable replacements could focus on reducing consumption of the other substances while acceptable substitutes could be developed.

The designers of the Protocol ensured that control measures were adaptable over time. Article 6 provided for ongoing assessments of these control measures at least once every 4 years "on the basis of available scientific, environmental, technical and economic information." Based on these scientific assessments, two-thirds of the Parties can make binding "adjustments" to the control measures without requiring a full ratification. This provision in particular has been praised by scholars as a legal innovation allowing the Protocol's original controls to be strengthened and expanded to more substances as scientific understanding has evolved [13].

Albrecht and Parker (2019) discuss how the Protocol's trade provisions and Multilateral Fund created incentives for joining and abiding by the rules of the Protocol [14]. The initial signatories of the Protocol represented a minority of nations but included the main producing countries of CFCs. Trade provisions restricted export of ODS to nonparties, with the result being “once the main producing countries joined the protocol, it was only a matter of time before all countries had to join or risk not having access to key chemicals” [14]. The Multilateral Fund provided positive incentives to developing nations that historically bore little responsibility for the production and consumption of ODSs to sign onto the Protocol by extending financial and technical support to phase-out efforts. Signatories that joined the Protocol but failed to comply with its terms could be subject to sanctions and withdrawal of support.

The Protocol eventually achieved universal ratification, with a total of 197 signatories [15]. In the years after it was signed, additional adjustments accelerating ODS phase-outs and adding new substances to the controlled list were passed, with reported CFC production decreasing to zero in 2010. Although compliance has generally been high, there have been challenges. Beginning in 2013, monitoring stations detected illicit CFC emissions originating from China. In response, China increased its national monitoring capabilities and increased penalties for violations of CFC production bans, and scientists report that the excess emissions have since declined [16].

3. HISTORY OF ORBITAL DEBRIS

3.1 U.S. GOVERNMENT AND INTERNATIONAL DEBRIS POLICY: HISTORY

The origins of orbital debris date back to the beginnings of the space age when the Soviet Union followed by the United States began launching satellites into space. The National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD) have long worked together to monitor, track, and catalog space objects. The 1988 National Space Policy directed U.S. agencies to minimize debris generation, and led to discussions within the United States on how to better understand and manage issues related to orbital debris. In February 1989, a U.S. Government interagency space group published the Report on Orbital Debris [17]. The report made several recommendations:

- Inform foreign governments of the United States’ own declared policies.
- Create a dialogue on exchanging space debris information for addressing the space debris problem.
- Seek interagency agreements on broad U.S. policy statements regarding space debris.
- Create agreements on specific proposals for technical and regulatory measures.

Following the implementation of the recommendations, the report proposed the United States engage with foreign governments and private sector operators. The report warned that without a U.S. policy on limiting orbital debris, growing debris could substantially threaten the operation of manned and unmanned spacecraft in the next century [17]. The U.S. Government continued working to develop guidelines and in 2001 published the Orbital Debris Mitigation Standard Practices (ODMSP) [18].

The 1989 U.S. Government Report on Orbital Debris also encouraged international collaboration. It highlighted that space debris was not an isolated problem created by one nation, but a collective challenge generated and faced by all users of space. The space debris problem would grow as more nations became space users. At the conclusion of the report, the group recommended the United States enter into discussions with other nations to coordinate debris minimization policies and practices [17]. In 1993 the United States, Europe (through ESA), Japan and Russia formally established the Inter-Agency Space Debris Coordination Committee (IADC) which has since grown to represent 13 countries [19]. The IADC published the first set of space debris mitigation guidelines in 2002, largely based on the U.S. ODMSP. Though the IADC is not formally part of the United Nations process, IADC provides updates and special technical presentations to the UN Committee on the Peaceful Uses of Outer Space (COPUOS). The UN COPUOS actively works to bring together the space community to discuss issues of space sustainability and after a decade of deliberation they adopted the Long-Term Sustainability (LTS) Guidelines in 2019 [20]. Around that same timeframe, the United States issued Space Policy Directive-3 which was focused more broadly on space situational awareness, but called for an update to the ODMSP and other actions related to debris mitigation [21]. Finally, in 2021, the U.S. Government issued a research and development (R&D) Plan on Orbital Debris, an interagency report identifying R&D priority topic areas to address orbital debris issues [22]. In July 2022, the interagency built upon the R&D plan and published an Orbital Debris R&D Implementation Plan with 44 actions to address orbital debris challenges across 3 major components: debris mitigation, tracking and characterization and debris removal [23].

3.2 CAUSES OF DEBRIS

On-orbit debris can be divided into three categories: fragmentation-related debris, mission-related debris, and defunct rocket bodies. The U.S. Space Force's 18th Space Control Squadron (SPC) uses the Space Surveillance Network (SSN), a set of space-based and ground-based optical telescopes and radar, to track the largest objects in the near-Earth space environment and records these objects in the Space Catalog. Tracing the origin of debris to a mission or launching state is often not possible, and untraceable debris are registered as unknown sources of debris in the Space Catalog. ESA also publishes an annual Satellite Environmental Report describing sources, locations and sizes of various debris and spacecraft on orbit, and their latest report found that most debris come from rocket and payload fragmentation (defined as unintentional on-orbit creation of debris) followed by unidentified sources and rocket bodies [2].

Figure 2 helps illustrate the dramatic expansion in the number of satellites and orbital debris in Earth orbit since the turn of the century, apparent even when only accounting for objects of known origin tracked by the U.S. SSN. In addition to the objects represented in the chart below, NASA's Orbital Debris Program Office estimates there are 500,000 untracked objects less than 1 cm in orbit that are not represented in Fig. 1 [24].

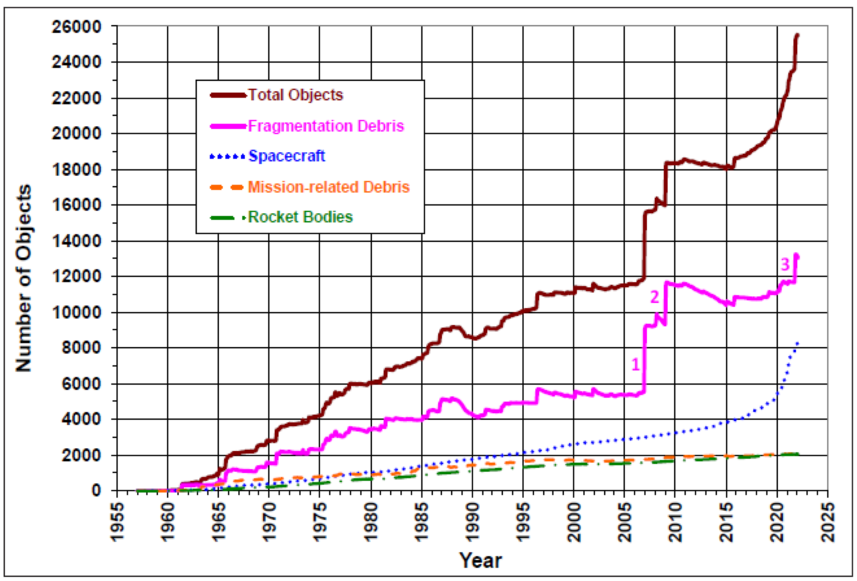

Fig. 2. Historical increase of the cataloged objects based on data available on 1 March 2022 (Source: NASA Orbital Debris Quarterly News Vol. 26, Issue 1)

Based on Fig 2., the debris population is largely dominated by fragmentation debris which includes debris caused by anti-satellite tests (ASAT) and accidental collisions. According to the note provided by NASA on Fig. 2, "the three upward jumps in fragmentation debris correspond to (1) the ASAT test conducted by China in 2007, (2) the accidental collision between Iridium 33 and Cosmos 2251 in 2009, and (3) the ASAT test conducted by the Russian Federation in November 2021. More Cosmos 1408 fragments are expected to the added to the catalog in the coming weeks and months." Debris accounts for about 64 percent of all currently tracked objects in space [25].

3.3 PRESENT DAY OPERATING ENVIRONMENT

The current operating environment in space is changing, particularly in LEO, as mega-constellations have entered the domain and a more diverse set of operators are relying on space for their missions. As of July 2022, the U.S. SSN tracks 46,400 objects, which include defunct spacecraft, active spacecraft, and debris of known and unknown origin. The 18th SPC satellite catalog, which is routinely updated with data from the U.S. SSN, recorded 25,182 objects of known origin as of March 2022 [26].

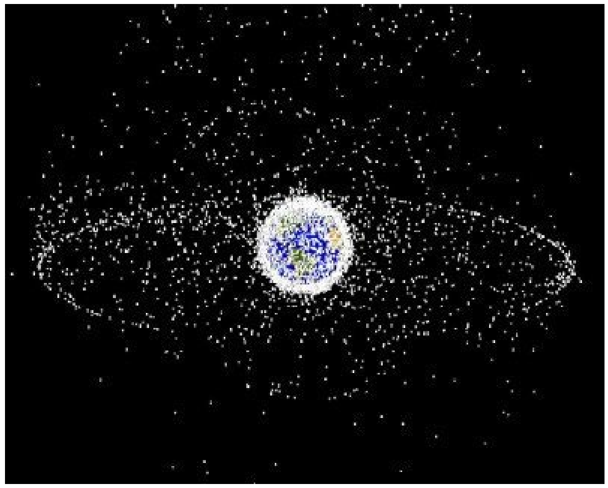

Figure 3: Orbital Debris (Source: ESA)

The 18th SPC tracks all objects in the catalog and uses their estimated position and trajectory to calculate and predict potential collisions [27]. The 18th SPC provides satellite operators conjunction data messages based on a predicted probability of collision in order for them to execute collision avoidance maneuvers. Numbers of conjunction messages and maneuvers have increased as more satellites are placed into orbit. NASA reported that the International Space Station (ISS) was forced to perform two collision avoidance maneuvers in 2021, the first to avoid a fragment generated from the 2007 Fengyun 1-C ASAT test and the second to avoid a fragment from the Pegasus rocket upper stage explosion in 1996 [28]. As more satellites are launched into orbit, there are growing concerns that the space operating environment will become more crowded and untenable without space traffic coordination. Furthermore, only active satellites can maneuver to de-orbit or avoid collisions, and orbital debris will remain in orbit unless it can reenter Earth's atmosphere.

4. COMMON POOL RESOURCES AND THE GLOBAL COMMONS

The Earth's atmosphere and densely populated orbits are physically adjacent but practically dissimilar in manifold ways. Nevertheless, in analyzing structural similarities of large-scale challenges posed by ozone depletion and orbital debris we identify a number of useful analogies that may help inform the design of policy approaches for orbital debris management. Chapters 4 and 5 discuss commonalities between these two issues, which provide the basis for policy recommendations described in Chapter 6.

The Earth's atmosphere and the space domain are both common pool resources, defined by Dr. Elinor Ostrom as resources with shared access [29]. Ostrom's theories build upon the idea of the "global commons," which is sometimes used to refer to "a form of collective ownership and governance" rather than the resource itself [30]. Access to and use of a global commons is non-exclusive, as it is difficult or impractical to restrict another party's access or use, and subtractive, as the resource can be depleted. Structural imbalances that often exist between the minority who most benefit from use of a global commons and the majority affected by its potential depletion necessitates the collective management of such resources to prevent their exhaustion and deterioration.

The Earth's atmosphere has been categorized as a global commons in various environmental management contexts, primarily for its function as a sink for anthropogenic emissions such as greenhouse gases and other chemicals [31]. Point sources of emissions may not pose an immediate risk to all users of the atmospheric global commons, but the cumulative impacts of human activity consume these resources and ultimately lead to deleterious consequences such as ozone depletion and climate change, which affect all of humankind.

The use of space resources is similarly non-exclusive and subtractive, motivating collective action to manage their use. Space law is a nascent field and the question of whether space is a global commons is sometimes debated and occasionally extended to discussions of whether and how property rights can be extended to the space domain; successive Presidential administrations have not consistently applied the definition of the global commons to space resources [30]. U.S. policy has sometimes been at odds with international law and coordinating bodies, in which outer space is generally understood as a global commons, along with the high seas, the atmosphere, and Antarctica. In 2021, UN Secretary-General António Guterres stated: “Outer space is a crucial global commons, but it remains undergoverned” [32]. We believe inherent similarities between the space environment and other domains accepted as global commons, such as the Earth’s atmosphere, and the clear need for global governance to manage common pool resources within these domains, justify the unequivocal classification of space as a global commons.

Developing an international consensus around the space domain’s status as a global commons could inform international action to address orbital debris [33]. Ostrom identified eight design principles frequently observed in sustainable institutional regimes. Although academics have raised and continue to discuss important questions about the scalability of these principles to larger-scale environmental problems, Ostrom highlights the Montreal Protocol as one example of successful international governance of a large-scale resource [29].

5. COMPARING OZONE DEPLETION AND ORBITAL DEBRIS

In this chapter, we compare strategies used to address ozone depletion and orbital debris by sorting them into functional categories using a framework common to environmental management problems. We will consider parallels between the two issues, using Ostrom’s principles to help explain the Protocol’s successes that could in turn inform institutional governance strategies for orbital debris.

5.1 MONITORING AND MEASUREMENT

Monitoring and measurement are often one of the earliest steps taken toward addressing environmental management problems and contribute to every step of the solutions development, deployment, and reassessment process. Monitoring and measurement capabilities are critical for identifying and characterizing negative externalities; implementing mitigation and remediation strategies; and determining the effectiveness of such strategies to inform adaptations to institutional governance. Ostrom notes that in successful governance, monitors should be “at least partially accountable to users and/or are users themselves,” as users that bear some responsibility for monitoring activities may also be more motivated to comply with and enforce agreed upon rules [29]. The Montreal Protocol follows this principle in distributing monitoring and measurement activities among scientific researchers around the world who verify each other’s’ results and alert the international community to potential violations—while coordination on and sharing of orbital debris monitoring and measurement information is increasing, these systems are largely disparate and isolated.

Starting in 1978, measurements of atmospheric ozone collected by NASA’s Nimbus-7 satellite provided quantitative evidence of the harm caused by CFC emissions, confirming Molina and Rowland’s theories of ozone depletion. The subsequent public outcry helped motivate the international community to mobilize; the Carter administration took an early precautionary step of banning the use of CFCs in aerosol sprays. In the years following this initial discovery, public interest and international appetite for urgent action waned as scientific uncertainties around the scope of the problem and its potential consequences became evident and major industry stakeholders resisted a rapid phase-out of CFCs. Ultimately, the 1985 discovery of a hole in the ozone layer reignited public interest in the issue and in part provided the impetus for the signing of the Protocol in 1987.

Since the Montreal Protocol was established, regular monitoring and measurement has been critical to ensuring compliance with CFC reduction efforts. An international network of scientists collects and analyzes atmospheric trace gases sampled from locations around the world to detect potential violations of the Protocol. Traceability is imperfect; modeling techniques can approximate the source of emissions but cannot pinpoint exact locations. Thus far, these measurement capabilities have been effective in allowing the international community to identify and notify member nations responsible for illicit emissions [16].

At present, monitoring of orbital debris and other space objects is primarily conducted by ground based radar and telescopes. Unlike ozone depletion, the mechanisms behind orbital debris have long been well-understood by the scientific community, but modeling the orbital debris environment to accurately predict collision risks requires further study. That said, more sophisticated measurement and monitoring capabilities are not necessarily needed to establish the potential danger of orbital debris; the causal link between abandoned objects moving uncontrollably through space and potential collisions with valuable assets is obvious.

Space situational awareness (SSA) capabilities measure the debris environment and enable mitigation actions by detecting and characterizing potential risks—for orbital debris, the likelihood of collisions—but preventing potential conjunctions requires a speedier response compared to ozone emissions, increasing the importance of frequent and high-quality monitoring data to manage orbital debris. DoD's Space Surveillance Network shares relevant SSA information with satellite operators as needed and publishes some lower-accuracy data online. NASA and DoD collaborate on conjunction assessments for NASA assets, and DOD was directed to "…provide close approach warnings to all satellite operators and expand the range of data and analysis products they offer to commercial and foreign entities" by the 2010 National Defense Authorization Act, although 2018 legislation transferred responsibility for providing SSA data to civil, commercial, and international space operators to the Department of Commerce [34][35]. Monitoring capabilities are limited, especially for the smallest pieces of orbital debris less than two inches in diameter, which may still present a significant threat to satellite operations [36].

5.2 MITIGATION

Mitigation strategies are employed to reduce or prevent behaviors that contribute to negative externalities of resource use.

The Montreal Protocol's mitigation strategy was to slow the degradation of the ozone layer by reducing and eventually cutting off emissions of ODS. Drastic reductions in global ODS emissions were achieved through extensive cooperation between international governments, industry players, and the scientific community. Binding international agreements developed through a lengthy negotiations process set ODS phase-out goals, outlined penalties for non-compliance, and established resources to support ODS reductions in nations that historically bore less responsibility for ODS emissions.

Ostrom's principles of "graduated sanctions" and "collective-choice arrangements" are reflected in the Protocol's design. Graduated sanctions create negative consequences for rule-breaking, which are mutually enforced by users. Collective-choice arrangements ensure that all affected parties are at the negotiating table and rules are mutually agreed upon, which helps to avoid conflict and non-compliance. Industry participation in intergovernmental discussions was key to the Protocol's success as conflicts were resolved during the design process rather than arising afterwards.

The goal of orbital debris mitigation is to avoid or minimize the creation of additional debris through use of best practices in satellite design, operations, and end-of-life procedures [22]. This may include impact-resistant design, maneuverability to avoid potential collisions, and design for disposal. As discussed in Chapter 3, IADC and UN COPUOS have adopted non-binding consensus guidelines for mitigation [37]. Industry associations contribute to international standards-making bodies that contribute to UN COPUOS and IADC debris mitigation guidelines [38]. However, there are no penalties for satellite operators or launch providers that do not comply with these guidelines. Although compliance with mitigation guidelines is increasing graduated sanctions for orbital debris, ESA reports that current rates of adoption are projected to lead to unsustainable levels of collision risk [2].

The barriers to mitigation for ozone depletion and orbital debris have notable differences. Whereas the Protocol's mitigation measures enabled the eventual phase-out of the most harmful ODS emissions by replacing them with less-harmful substitutes, orbital debris mitigation actions seek to change the ongoing and future behavior of space object owners and operators. At present, there is no list of materials to exclude or technological silver bullet all space users can adopt to prevent debris. We highlight this difference not to minimize the challenges the designers of the Protocol faced in mitigating ODSs, but to note that mitigation options for orbital debris are wide-ranging and complex, which may require additional considerations.

5.3 REMEDIATION

Remediation strategies include actions intended to reverse the impact of negative externalities with the ultimate goal of restoring the environment to its unaltered state. Remediation may not be an effective or practical solution for all problems.

In the case of ozone depletion, mitigation strategies were effective, and remediation activities were never seriously considered. A 1989 paper proposes using powerful lasers to break up CFC molecules in the atmosphere but concluded that deployment of such a technology would be prohibitively expensive [39]. A non-exhaustive review of literature did not reveal any additional proposed remediation strategies for removal of atmospheric CFC, and none have ultimately been pursued.

Multiple space agencies have stated that active debris removal (ADR) will be necessary for space sustainability. Technologies are in development and some subsystem demonstrations have occurred [40]. However, a full-scale demonstration removing or moving debris on orbit has yet to take place Even if debris removal capabilities are realized, such services are likely to be expensive and may suffer from the “free rider” problem if there are no direct incentives for satellite owners or stakeholders to contribute or be required to use to ADR.

Although remediation strategies were not pursued by the Montreal Protocol, we can consider how the emergence of technologically viable remediation technologies would affect institutional governance for orbital debris. Currently, the only options to prevent collision risk are monitoring and mitigation, and international coordination has largely focused on these activities. Due to unsettled questions around liability and ownership of orbital debris, there are major legal uncertainties surrounding ADR that may disincentivize the use of such technologies. Ostrom’s principle of clearly defined boundaries in governance may be applicable in this case—although ADR is not yet a reality, it may be prudent for international stakeholders that have voiced their support of ADR to collaborate on legal and political frameworks that would enable ADR’s deployment.

5.4 ADAPTATION

Each of the above strategies ideally consists of ongoing and iterative processes that can be conducted in parallel and as they are adopted. Ostrom notes that sustainable institutional regimes “cannot be fixed for the long-term” and should encourage adaptation and change [41]. In our framework, adaptation strategies include the development of new practices in response to negative externalities that cannot be sufficiently mitigated and the process of integrating new information into monitoring, mitigation, or remediation strategies.

Action on ozone depletion reflected both the precautionary principle and Ostrom’s adaptation strategies. During the decade that elapsed between Molina and Rowland’s discovery and the signing of the Montreal Protocol, government officials, industry bodies, and the public initiated efforts to begin addressing the issue of ODS emissions, while the scientific community worked in parallel to study the scope of the problem and industry considered technological solutions. Whitesides (2020) stresses that the Protocol was signed despite remaining scientific uncertainties, emphasizing that policymakers should not overstate the influence of scientific evidence on policy and that technological solutions were not available or apparent at the time that the Protocol was signed [8].

The Montreal Protocol’s design enabled a compromise to be reached in the presence of remaining uncertainties. The Protocol provides adaptive measures that have been deployed over time in response to scientific discoveries and developments. The Parties of the Protocol meet annually to consider and vote upon adjustments or other actions to ensure successful implementation of the Protocol. Six amendments have been adopted by the Parties since 1990, accelerating phase-out timelines of ODSs and expanding the original list of 6 substances to nearly 100. The initial emissions reductions goals set out in the Protocol were based on the scientific consensus and political realities the time; as the state of the science and technology evolved, the Parties updated their goals to leverage new understandings and advancements. The Kigali Amendment, signed in 2016, adds hydrofluorocarbons (HFCs) to the controlled list. Although HFCs have comparably lower ozone depletion potential compared to other ODSs, the Parties leveraged the adaptability of the Protocol’s framework to restrict production of a class of chemicals with high global warming potential [14].

The international community regularly coordinates on the problem of orbital debris through IADC, UN COPUOS, and other organizations. However, these institutional bodies have yet to establish a governance system like the Protocol that could provide a coordinated, effective response to a rapidly changing orbital debris environment. Although its benefits are relevant to aspects beyond adaptation, Ostrom describes a polycentric approach, characterized by “multiple governing authorities at differing scales” as more effective than other systems due to its inherent flexibility and mechanisms for self-correction, especially for larger-scale environmental management challenges [42]. The Protocol’s structure, in which the UN provided a forum to set collective goals for emissions but nations designed and enforced their own mitigation strategies, somewhat embodies the polycentric approach. Morin and Richard (2021) state that orbital debris governance, which includes space agencies, military organizations, and operators, among others, presents polycentric qualities [43]. Lambach and Wesel (2021) argue that orbital debris governance is decentralized but not polycentric due to weak linkages among stakeholders and insufficient trust [27]. It is possible that the current framework of orbital debris governance presents opportunities for polycentricity, but lacks strong ties between actors that facilitate collective decision making.

6. RECOMMENDATIONS

In this chapter, we apply Ostrom's strategies for management of global commons to the problems of ozone depletion and orbital debris, developing recommendations for orbital debris. Table 1 summarizes the discussions in chapters 4 and 5 and the recommendations, which are discussed in greater detail following the table. We show how the Montreal Protocol embodies some of Elinor Ostrom's theories for successful governance of global commons and consider how these concepts could be applied to each component of our solutions framework for orbital debris. As noted previously, there are important differences between the two issues, and while solutions that led to success for the Protocol are not directly applicable to orbital debris, they could inform ongoing and future actions. In addition, components like remediation do not provide a convenient parallel to solutions pursued for ozone depletion, although we still consider how Ostrom's theories could apply to remediation scenarios.

Table 1: Considering lessons learned from ozone depletion and common-pool resources for orbital debris

	Summary of Relevant Principle/Theory	Ozone Depletion	Orbital Debris
Monitoring and Measurement	Monitoring: Monitors accountable to users or who are users themselves actively measure and audit resource conditions and user behavior [29].	Responsibility for monitoring and measurement is distributed among the Protocol's Parties; scientists around the world share monitoring data and can verify each other's results.	While systems such as the SSN provide monitoring and measurement capabilities, these efforts are disparate and isolated. Where possible, orbital debris stakeholders should encourage space users to share positional vector data with organizations performing conjunction assessments or each other to improve conjunction assessments.
Mitigation	Graduated sanctions: Depending on the seriousness and context of violations of rules-in-use, other users or accountable officials impose graduated sanctions on the offending user [29].	Establishment of graduated sanctions to enforce mitigation through ODS reductions is key to the Protocol's success. Public perception of the risks posed by the "ozone hole" helped secure buy-in from diverse groups to take such measures.	Orbital debris stakeholders have agreed on best practices for mitigation, but lack graduated sanctions or other incentives to encourage compliance. Science communications and effective messaging could provide political incentives for action.
Remediation	Clearly defined boundaries: Resource system boundaries and rights of users to harvest resources are clearly defined [29].	Not applicable – remediation strategies never seriously considered.	ADR is not yet a reality, but legal uncertainties surrounding space objects may hinder the development and deployment of promising ADR technologies. Orbital debris stakeholders should define legal frameworks that enable ADR.
Adaptation	Sustainable institutional regimes encourage adaptation and change; polycentric and nested governance with multiple governing authorities at differing scales may be appropriate for global problems [41][42].	The Montreal Protocol's adaptation strategies allowed the Parties to update and revise the Protocol as science and technology evolved. The Protocol has some polycentric and nested qualities by allowing individual nations to distribute enforcement and other authorities to lower levels.	Orbital debris stakeholders should promote adaptable governance strategies that allow for regular updates based on group consensus. Unclear whether polycentric governance would be effective for orbital debris management—debate as to whether existing orbital debris governance has polycentric qualities.

6.1 ENHANCE MONITORING AND MEASUREMENT

The discovery, study, and mitigation of ozone depletion was enabled by investment and research in atmospheric science that began decades before Molina and Rowland first theorized that anthropogenic emissions could deplete the ozone layer. Compared to ozone depletion, the mechanisms behind orbital debris are simpler, but characterizing the problem and assessing its risks is no less challenging. Insufficient data on the actual numbers of pieces of orbital debris, especially smaller objects, prevents us from fully assessing the risk posed by orbital debris [3]. Similar to how countries coordinated to develop measurement capabilities and systems for atmospheric science, international stakeholders should continue to collaborate on and support efforts to improve SSA. Joint research efforts may help ensure that research findings are translated to operations and increase buy-in for follow-on actions resulting from research activities. There may also be opportunities for satellite operators to improve the accuracy of conjunction assessments by sharing positional data with organizations performing conjunction assessments or each other. Encouraging such efforts, where possible, could lower the risk of collisions.

6.2 CREATE INCENTIVES FOR MITIGATION

Graduated sanctions were key to the Protocol's success. At present, compliance with mitigation guidelines is the primary mechanism by which the space community can prevent orbital debris. Without binding requirements for compliance, it is highly unlikely that space operators will follow guidelines for debris mitigation at levels sufficient to prevent increasing rates of collisions. However, creating a sustainable international regulatory regime requires collective action by governments, space and launch operators, and other stakeholders with limited external pressures to change and near-term financial incentives to preserve the status quo. Many policy researchers have darkly predicted that only a catastrophic collision event would motivate large-scale action; we suggest that powerful public messaging could provide a similar impetus for international coordination.

Similar to how scientists warned that an expanding ozone hole would increase the incidence of deadly skin cancers in the general population, they should also communicate how orbital debris could negatively affect the average citizen unconcerned about the economic viability of the space sector. There are inherent differences to these two scenarios that challenge public communications efforts—many people have personally experienced or at least understand the risks of skin cancer, and risks posed to space infrastructure are less intuitive and evocative than those to human health. Nevertheless, while the likelihood of a Kessler-like event remains uncertain, it is clear that the general public lacks an understanding of the potential consequences of orbital debris. The detrimental effects of orbital debris should be explained in a manner that brings these issues down to Earth, highlighting the manifold ways in which satellites make up invisible infrastructure that supports both modern conveniences and security-critical systems like the internet, weather forecasting, and the electricity grid. The goal of public consciousness-raising efforts is not to instill fear but to inform ordinary citizens of the dangers of inaction and create incentives for government and industry stakeholders to address these issues.

We have focused on orbital debris, but the Protocol is often cited as a potential model for another pressing environmental problem: climate change. Orbital debris and climate change have interactions and interdependencies; on-orbit observation and measurement capabilities are key to studying and forecasting global weather patterns, estimating greenhouse emissions, and measuring sea level rise, while atmospheric density loss caused by climate change may exacerbate the accumulation of debris in LEO [44]. According to the World Economic Forum, over half of essential climate variables are only measurable from space [45]. Although it is sensible for the international community to prioritize and demand action on urgent threats like climate change, they should also recognize that working towards a more sustainable space environment preserves and enables our ability to understand environmental threats closer to home.

6.3 ESTABLISH LEGAL FRAMEWORKS TO ENABLE REMEDIATION

There is widespread agreement that the deployment of ADR capabilities is necessary for space sustainability, but not yet cost-effective. On-orbit technology demonstrations may soon prove the feasibility of these technologies, and it would be sensible for international stakeholders to determine and establish legal frameworks that incentivize nations to participate in the development and deployment of ADR. Isnard (2021) identifies remaining legal questions that should be addressed, including defining space debris, determining whether ownership of space objects extends to debris, and understanding whether and how liability applies to ADR [46].

6.4 MANAGE UNCERTAINTY THROUGH ADAPTATION

Although there is a need for further investment and research on orbital debris to improve risk assessments, the Montreal Protocol illustrates how shifting baselines of scientific uncertainty do not preclude international action on orbital debris in the near-term. Simply stated, we do not need to fully understand the problem before trying to fix the problem. Ostrom's adaptation strategies encourage the use of governance strategies that can evolve over time, so if a response becomes disproportionate based on new conditions it can be adjusted. The Montreal Protocol addressed this issue by providing mechanisms for updates to the Protocol as needed—creating a binding international compromise for orbital debris management is a major challenge but the inclusion of adaptation strategies may help increase stakeholder buy-in for such measures. Built-in adaptation strategies can help address unforeseen negative externalities of proposed orbital debris management practices as they appear, while positive developments such as the emergence of viable ADR technologies can be integrated into management frameworks.

7. CONCLUSION

The Montreal Protocol is held up as an example of when the international community saw a problem, acted promptly, and worked together to avoid potentially disastrous consequences. In examining the history of ozone depletion, the reality is more complex and interesting. No single factor controlled the outcome, and many were important—understanding the roles that public perception, scientific uncertainty, and commercial interests played in international diplomacy offers lessons for policymakers tackling other large-scale issues like orbital debris.

8. REFERENCES

[1] Inter-Agency Space Debris Coordination Committee (IADC). IADC Space Debris Mitigation Guidelines, IADC-02-01, Revision 1, United Nations Office for Outer Space Affairs, 2007. https://www.unoosa.org/documents/pdf/spacelaw/sd/IADC-2002-01-IADC-Space_Debris-Guidelines-Revision1.pdf

[2] ESA Space Debris Office. ESA's Annual Space Environment Report, The European Space Agency, 2022. https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

[3] M. Undseth, C. Jolly, and M. Olivari. Space Sustainability: The economics of space debris in perspective, *OECD Science, Technology and Industry Policy Papers*, No. 87, Organisation for Economic Co-operation and Development (OECD), 2020. https://www.oecd.org/environment/space-sustainability-a339de43-en.htm

[4] O. O. Bittencourt Neto. Preserving the Outer Space Environment: The 'Precautionary Principle' Approach to Space Debris, *Proceedings of the International Institute of Space Law*, 2013. https://www.elevenjournals.com/tijdschrift/iisl/2013/4%20Legal%20Aspects%20of%20Space%20Debris%20Remediation/IISL_2013_056_004_001.pdf

[5] S. J. Garber and L. R. Rand. A Montreal Protocol for Space Junk?, *Issues in Science and Technology*, XXXVIII(3), 2022. https://issues.org/orbital-debris-space-junk-montreal-protocol-garber-rand/

[6] J. Elkins. Chlorofluorocarbons (CFCs), National Oceanic and Atmospheric Administration (NOAA), Climate Monitoring and Diagnostics Laboratory (CMDL), 1999. https://gml.noaa.gov/hats/publictn/elkins/cfcs.html

[7] S. O. Andersen, M. L. Halberstadt, and N. Borgford-Parnell. Stratospheric ozone, global warming, and the principle of unintended consequences--an ongoing science and policy success story, *Journal of the Air & Waste Management Association (1995)*, 63(6):607-647. 2013.

https://www.proquest.com/scholarly-journals/stratospheric-ozone-global-warming-principle/docview/1401092395/se-2?accountid=11558
[8] G. Whitesides. Learning from Success: Lessons in Science and Diplomacy from the Montreal Protocol, *Science & Diplomacy*, 2020. https://www.sciencediplomacy.org/article/2020/learning-success-lessons-in-science-and-diplomacy-montreal-protocol
[9] British Antarctic Survey. 30th Anniversary of the Discovery of Ozone Hole, 2015. https://www.bas.ac.uk/media-post/30th-anniversary-of-the-discovery-of-ozone-hole/
[10] P. K. Bhartia and R. D. McPeters. The discovery of the Antarctic Ozone Hole, *Comptes Rendus Geoscience*, 350(7):335-340, 2018. https://doi.org/10.1016/j.crte.2018.04.006
[11] NASA Earth Observatory. Watching the Ozone Hole Before and After the Montreal Protocol, National Aeronautics and Space Administration (NASA), 2012. https://earthobservatory.nasa.gov/images/79198/watching-the-ozone-hole-before-and-after-the-montreal-protocol
[12] United Nations Environment Programme. *The Vienna Convention for the Protection of the Ozone Layer*, 1985. https://ozone.unep.org/treaties/vienna-convention/vienna-convention-protection-ozone-layer
[13] S. O. Andersen and K. M. Sarma. *Protecting the Ozone Layer: The United Nations History*, London: Earthscan, 2002.
[14] F. Albrecht and C. F. Parker. Healing the Ozone Layer, Semantic Scholar, 2019. https://www.semanticscholar.org/paper/Healing-the-Ozone-Layer-Albrecht-Parker/3a1c771db1f996877f50ea0926be3d7f7e6f9a4f
[15] United Nations Environment Programme. Montreal Protocol Celebrates Landmark Achievement with Universal Ratification of All Amendments, 2014. https://www.unep.org/news-and-stories/press-release/montreal-protocol-celebrates-landmark-achievement-universal
[16] J. Palmer. The pollution detectives, *Nature*, 577, 2020. https://media.nature.com/original/magazine-assets/d41586-020-00110-8/d41586-020-00110-8.pdf
[17] Interagency Group (Space). *Report on Orbital Debris,* 40*,* National Security Council, 1989. https://ntrs.nasa.gov/api/citations/19900003319/downloads/19900003319.pdf
[18] National Aeronautics and Space Administration (NASA). *U.S. Government (USG) Orbital Debris Mitigation Standard Practices (ODMSP)*, 2019. https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf
[19] Inter-Agency Space Debris Coordination Committee (IADC). Member Agencies, Accessed August 1, 2022. https://iadc-home.org
[20] United Nations Office for Outer Space Affairs. *Guidelines for the Long-term Sustainability of Outer Space Activities of the Committee on the Peaceful Uses of Outer Space,* 2021. https://spacesustainability.unoosa.org/content/The_Guidelines
[21] The White House. Space Policy Directive-3, National Space Traffic Management Policy, Presidential Memoranda, 2018. https://trumpwhitehouse.archives.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/
[22] National Science and Technology Council. *National Orbital Debris Research and Development Plan*, White House Office of Science and Technology Policy, 2021. https://trumpwhitehouse.archives.gov/wp-content/uploads/2021/01/National-Orbital-Debris-RD-Plan-2021.pdf
[23] National Science and Technology Council (NSTC). *National Orbital Debris Implementation Plan*, White House Office of Science and Technology Policy (OSTP), 2022. https://www.whitehouse.gov/wp-content/uploads/2022/07/07-2022-NATIONAL-ORBITAL-DEBRIS-IMPLEMENTATION-PLAN.pdf /
[24] NASA Orbital Debris Program Office. Frequently Asked Questions #3. How much orbital debris is currently in Earth orbit? National Aeronautics and Space Administration (NASA), Accessed August 1, 2022. https://www.orbitaldebris.jsc.nasa.gov/faq/#
[25] Space-Track. Space Scoreboard, Accessed July 13, 2022. https://www.space-track.org
[26] NASA Orbital Debris Program Office (ODPO). Satellite Box Score, *Orbital Debris Quarterly News* 26(1), 10, National Aeronautics and Space Administration (NASA), 2022. https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv26i1.pdf

[27] D. Lambach and L. Wesel. Tackling the Space Debris Problem: A Global Commons Perspective, Proc. 8th European Conference on Space Debris (virtual), The European Space Agency (ESA) Space Debris Office, 2021. https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/230/SDC8-paper230.pdf
[28] J. C. Liou and B. Lal. U.S. Space Debris Environment and Activity Updates, 59th Session of the Scientific and Technical Subcommittee, Committee on the Peaceful Uses of Outer Space, United Nations, National Aeronautics and Space Administration (NASA), 2022. https://www.unoosa.org/documents/pdf/copuos/stsc/2022/07_2022_US_Space_Debris_Presentation_to_STSC_rev3.pdf
[29] E. Ostrom. The Challenge of Common-Pool Resources, *Environment: Science and Policy for Sustainable Development,* 50(4):8-21, DOI: 10.3200/ENVT.50.4.8-21, 2008.
[30] J. S. Goehring. Why Isn't Outer Space a Global Commons? *Journal of National Security Law and Policy, Forthcoming*, SSRN, 2021. https://ssrn.com/abstract=3867606
[31] O. Edenhofer, C. Flachsland, M. Jakob, and K. Lessmann. The Atmosphere as a Global Commons – Challenges for International Cooperation and Governance, The Harvard Project on Climate Agreements, Harvard Kennedy School, 2013. https://www.belfercenter.org/sites/default/files/legacy/files/hpcadp58_edenhofer-flachsland-jakob-lessmann.pdf
[32] United Nations. Secretary-General Anniversary Message Highlights Critical Role of United Nations Satellite Centre in Environmental Assessments, Humanitarian Relief Operations, 2021. https://www.un.org/press/en/2021/sgsm21041.doc.htm
[33] B. Silverstein and A. Panda. Space Is a Great Commons. It's Time to Treat It as Such, Carnegie Endowment for International Peace, 2021. https://carnegieendowment.org/2021/03/09/space-is-great-commons.-it-s-time-to-treat-it-as-such-pub-84018
[34] B. Weeden. Space Situational Awareness: Examining Key Issues and the Changing Landscape, Testimony at Hearing of the Subcommittee on Space and Aeronautics, U.S. House of Representatives, 2020. https://science.house.gov/imo/media/doc/Weeden%20Testimony.pdf
[35] U.S. Senate Committee on Commerce, Science, & Transportation. Wicker Introduces Space Preservation and Conjunction Emergency Act, 2020. https://www.commerce.senate.gov/2020/10/wicker-introduces-space-preservation-and-conjunction-emergency-act
[36] National Aeronautics and Space Administration (NASA). Space Debris and Human Spacecraft, 2021. https://www.nasa.gov/mission_pages/station/news/orbital_debris.html
[37] NASA Orbital Debris Program Office. Debris Mitigation, National Aeronautics and Space Administration (NASA), Accessed August 16, 2022. https://orbitaldebris.jsc.nasa.gov/mitigation/
[38] D. Oltrogge. International Organization for Standardization (ISO) activities for Long-Term Sustainability (LTS) of space activities, UN COPUOS STSC Meeting, United Nations Office for Outer Space Affairs, 2022. https://www.unoosa.org/documents/pdf/copuos/stsc/2022/39_ISO_-_20220214_ISO_Briefing_to_UN_COPOUS_STSC_Oltrogge_V1.pdf
[39] T. H. Stix. Removal of chlorofluorocarbons from the Earth's atmosphere, *Journal of Applied Physics* 66(11), 1989. https://doi.org/10.1063/1.343669
[40] Astroscale. Astroscale's ELSA-d Successfully Demonstrates Repeated Magnetic Capture, 2021. https://astroscale.com/astroscales-elsa-d-successfully-demonstrates-repeated-magnetic-capture/
[41] T. Dietz, E. Ostrom, and P. C. Stern. The Struggle to Govern the Commons, *Science,* 302(5652): 1907–1912, 2003. https://www.science.org/doi/10.1126/science.1091015
[42] E. Ostrom. Polycentric systems for coping with collective action and global environmental change, *Global Environmental Change*, 20(4):550–557, 2010. https://www.sciencedirect.com/science/article/pii/S0959378010000634
[43] J. F. Morin and B. Richard. Astro-Environmentalism: Towards a Polycentric Governance of Space Debris, *Global Policy*, 12(4):568–573, London School of Economics and Political Science, 2021. doi: 10.1111/1758-5899.12950
[44] M. K. Brown, H. G. Lewis, A. J. Kavanagh, and I. Cnossen. Future Decreases in Thermospheric Neutral Density in Low Earth Orbit due to Carbon Dioxide Emissions, *Journal of Geophysical Research: Atmospheres*, 126(8), American Geophysical Union, 2021. https://doi.org/10.1029/2021JD034589

[45] N. Marchant. 5 ways space tech can help protect the planet, Global Technology Governance Summit, World Economic Forum, 2021. https://www.weforum.org/agenda/2021/03/space-technology-tackle-climate-change/
[46] N. Isnard. Active Debris Removal: Mitigating Legal Barriers for Promising Technologies, Proc. 8th European Conference on Space Debris, The European Space Agency (ESA) Space Debris Office, 2021. https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/301/SDC8-paper301.pdf