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Orbital Mirror Deployment for Climate Intervention: A review of Environmental Challenges and Future Implications

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Abstract

The proposed deployment of orbital mirrors for solar radiation management, climate intervention, and ancillary commercial applications represents one of the most consequential technological trajectories of the twenty-first century. Despite repeated warnings from the scientific community regarding transboundary ecological and atmospheric harms, the licensing frameworks through which individual states authorize non-governmental space activities under Article VI of the Outer Space Treaty remain fragmented, narrowly technical, and largely indifferent to systemic ecological risk. This paper undertakes a critical evaluation of how the grant of permission by sovereign states for space-based mirror installation, and the broader commercialization of orbital reflectors, intersects with documented ecological vulnerabilities. Drawing on empirical atmospheric chemistry findings, ecological light-pollution research, space-debris sustainability literature, and space-law doctrine, we argue that current state-level licensing regimes constitute an unacceptable institutional mismatch with the planetary-scale risks that orbital mirrors would impose. The analysis concludes that without a comprehensive environmental impact-assessment requirement, a binding planetary-boundaries-style framework for the orbital commons, and explicit obligations concerning ecological harm, state authorization acts as a permissive conduit for ecologically grim externalities.

Keywords: Orbital mirrors, state authorization, commercialization, ecological impact, light pollution, orbital debris, atmospheric ozone depletion, monsoon disruption, biodiversity stress

1. Introduction

Satellite mirror technology, often conceptualized as space-based solar radiation management, aims to mitigate global temperature increases by deploying reflectors in near-Earth or Lagrangian L1 orbits (Anthony, 2025; Fawzy et al., 2020). Proposals range from the fabrication of large-scale mirrors at the Sun–Earth L1 point using lunar materials to the deployment of thousands of smaller, modular deflectors in near-Earth orbits (Hoffert et al., 2002; Shepherd & Rayner, 2009). Although the climate geoengineering rationale is often presented as benign, the terrestrial focus of such advocacy obscures significant risks to the space environment itself, where the proliferation of large-scale reflectors threatens to exacerbate orbital debris populations and introduce deleterious light pollution that hinders astronomical research (Çelik et al., 2022; Programme, 2025).

When state authorities grant commercial actors the right to deploy such infrastructure, they in effect authorize an experiment whose effects cannot be confined to national borders. The international legal framework that demands such authorization—Article VI of the Outer Space Treaty—requires that "States Parties to the Treaty shall bear international responsibility for national activities in outer space … whether such activities are carried on by governmental agencies or by non-governmental entities" and shall assure "authorization and continuing supervision by the appropriate State" (Harris & Baumann, 2021). This duty was codified when only States conducted space activities; today, in the era of NewSpace, it is the principal legal conduit through which private mirror operators receive the blessing of sovereigns (Pramono, 2018; Ritonga & Azaria, 2026). The substantive question is no longer whether a State may lawfully license these operations, but whether the licensing criteria that States actually apply are ecologically adequate.

The purpose of this paper is to subject that licensing practice to a critical evaluation for future ecological and environmental implications. We argue that the existing grant-of-permission regime, as constructed and applied by launching States, fails to incorporate ecological risk to a degree commensurate with the magnitude, transboundary character, and irreversibility of potential harms. The commercialization pathway compounds these flaws by converting a public-goods legal regime (the "province of all mankind", OST Article II) into a domain of partially captured, profit-driven regulatory practice (Islam, 2018; Pramono, 2018). The grim ecological effects documented in adjacent literatures—atmospheric ozone depletion, monsoon disruption, biodiversity stress, migratory disorientation, and the closure of orbital commons—are then externalized to the global commons without judicial remedy or economic compensation.

2. Literature Review

2.1 The Regulatory Architecture of State Authorization

The principal legal obligation of any launching State is found in Article VI of the 1967 Outer Space Treaty, which both renders States internationally responsible for the activities of their non-governmental entities and requires "authorization and continuing supervision" of those activities (Harris & Baumann, 2021; Kumar et al., 2021). To fulfil this duty, States typically adopt a domestic licensing regime that establishes the technical and procedural conditions under which a private operator may launch and operate a space object (Fazio, 2026). Reference models—such as Title 14, Chapter III of the United States Code of Federal Regulations—have codified five core licensing components: compulsory licensing for any activity classifying the country as a launching State, technical requirements, financial-responsibility mechanisms, exceptional waivers, and terminability by the State (Fazio, 2026).

As Giannoni-Crystal observes, in the United States, "new space activities (e.g., space resource utilization) cannot obtain a license because a license procedure is simply not available" because no agency has clear authority to regulate activities beyond Earth orbit (Giannoni-Crystal, 2024). This regulatory vacuum is particularly acute for solar-radiation-modification installations and orbital mirrors, whose operational regimes straddle launch, on-orbit deployment, and nullisurface effects. Bartz argues that the broad interpretation of State responsibility for non-governmental entities may have inadvertently created "race to the bottom" dynamics, whereby States craft permissive licensing frameworks to attract commercial actors, since the residual liability is comparative rather than absolute (Bartz, 2025). The very architecture that was designed to ensure responsible behaviour thus risks producing the opposite outcome.

2.2 The Commercialization of Outer Space

Space commercialization is "an increasingly large and important part of social, economic and information infrastructure", according to Islam, but "space laws are perpendicular in front of new challenged, by the growth of new environment of public-private international space commercialization" (Islam, 2018). The commercial impulse is rationalized on the basis of "natural resources" whose exploitation "rationalize commercializing of outer space", with developed States viewing it "a great matter of economic development" (Islam, 2018). Ritonga and Azaria observe that the NewSpace era has "shifted space activities toward profit-driven commercialization" while creating "normative tension with the [Outer Space Treaty's] principle that outer space shall be used 'for the benefit of all countries'", as commercial practices "risk deepening inequality, enabling technological monopolies, and increasing environmental threats" (Ritonga & Azaria, 2026).

Within this landscape, space-based solar power and orbital reflectors occupy a flagship position. Shrawani Shagun and Naqui Anwer describe SBSP as a "transformative innovation" whose "legal landscape governing SBSP, focusing on international treaties such as the Outer Space Treaty and the Moon Agreement" is the subject of active scholarly debate (Shagun & Anwer, 2024). Yet, as Acquarone et al. note, "the deployment of massive SBSP systems could also contribute to an increase in space debris if the maintenance and decommissioning of such large structures are not addressed during the design phase" (Acquarone et al., 2024). State licensing frameworks currently treat these ecological and atmospheric externalities as auxiliary concerns rather than as material conditions of authorization.

2.3 Ecological Effects of Orbital Reflectors and Light Pollution

The ecological literature on light pollution furnishes a coherent mechanism for understanding how artificial illumination from space alters "natural light regimes" with consequences "at all levels of biological organisation (from cell to ecosystem)" (Gaston et al., 2013). Gaston et al. emphasize that "as artificial lighting alters natural patterns of light in space, time and across wavelengths, natural patterns of resource use and information flows may be disrupted, with downstream effects to the structure and function of ecosystems" (Gaston et al., 2013). Jägerbrand and Spoelstra observe that "anthropogenic light is ubiquitous in areas where humans are present and is showing a progressive increase worldwide" and that "many species suffer from adverse effects and often respond in a highly specific manner" (Jägerbrand & Spoelstra, 2023). Critically, they conclude that "a simple solution to reducing and mitigating the ecological effects of anthropogenic light seems unattainable, because frugal lighting practices and turning off lights may be necessary to eliminate them" (Jägerbrand & Spoelstra, 2023)—a sobering conclusion for mirrors that, once deployed, cannot be turned off without ceasing to fulfil their climate function.

The Çelik et al. study on orbiting solar reflectors explicitly acknowledges that "sunlight may be reflected to undesired regions during reorientation manoeuvres, possibly disturbing populated areas or in general increasing light pollution, thus hindering astronomic observations" (Çelik et al., 2022). The same study notes that "astronomical observations are disrupted due to large-scale constellations", with approximately 1,700 Starlink satellites in operation and approximately 42,000 planned, and that "the International Astronomical Union and American Astronomical Society, as well as individual astronomers have raised concerns on the impact of the Starlink constellation satellites" (Çelik et al., 2022). Even in idle "edge-on" mode, the cumulative optical footprint of orbital reflectors is sufficient to disrupt ecological and astronomical baselines.

Barentine et al. raise the prospect that "the circadian rhythms of many organisms are apparently controlled by low levels of diffuse light integrated over wide angles of sky and relatively long time periods" (Barentine et al., 2022). They warn that "an artificially brightened sky could interfere with them very strongly", and that "a wide variety of species from birds to mammals to insects have been shown to navigate at least partly using the stars and the Milky Way" such that "effects on these natural behaviours when the real stars are surrounded or overwhelmed by large numbers of bright, moving 'fake stars' remain to be seen" (Barentine et al., 2022). They observe that "the problem is so new that results of scientific studies have yet to appear in the peer-reviewed literature, but concerns are beginning to surface", invoking the precautionary principle given the irreversibility of harm to migratory species (Barentine et al., 2022). The connection to nocturnal avian migration is empirically grounded: as Levin et al. document, "La Sorte et al. showed that nocturnally migrating birds are attracted to urban lit areas, affecting their migration behaviour", while Cabrera-Cruz et al. found that "light pollution experienced by nocturnally migrating birds, is especially high during the migration season for species with smaller ranges" (Levin et al., 2019). The diffused, sky-wide illumination produced by orbital mirrors differs from terrestrial point-source lighting only in scale, not in mechanism; it would extend migration disruption across entire hemispheres.

2.4 Atmospheric and Biospheric Effects of Solar Radiation Management

The climate-modification literature has produced consistent, quantitatively grounded accounts of side effects. Zarnetske et al., in a 120-cited review, conclude that "the impacts and risks posed by SRM would vary by implementation scenario, anthropogenic climate effects, geographic region, and by ecosystem, community, population, and organism" and that "complex interactions among Earth's climate system and living systems would further affect SRM impacts and risks" (Zarnetske et al., 2021). Specifically, they note that "almost no studies have investigated the impacts that SRM would have on ecological systems", identifying a research gap that licensing authorities cannot legitimately rely upon as a basis for authorizing deployment (Zarnetske et al., 2021).

Lawrence et al. provide the most authoritative integrated assessment of side effects, noting that "model simulations further show that RFG tends to cause the global mean precipitation rate to decrease disproportionately to temperature", that "MSB and desert brightening show very different precipitation responses relative to space mirrors and SAI", and that "[s]ome impacts will be technique specific (e.g., risk of stratospheric ozone depletion caused by SAI)" (Lawrence et al., 2018). Brovkin et al. had earlier shown, using an Earth-system model, that "in monsoon regions in East and South-East Asia, cooling leads to a reduction in precipitation" caused by "a reduction in monsoon intensity associated with surface cooling and a reduced temperature gradient between ocean and land" (Brovkin et al., 2008). McLaren synthesizes similar evidence: "early modelling … suggested that both tropical and Arctic SAI would result in 'a weakening of the African and Asian summer monsoon circulation'" and that "if SAI were heavily biased to one hemisphere the implications could be more dramatic", noting that "large asymmetric stratospheric aerosol loadings concentrated in the Northern Hemisphere are a harbinger of Sahelian drought" (McLaren, 2018).

These precipitation and circulation shifts are directly relevant to ecosystems. Rockström et al., in the 2023 "Safe and just Earth system boundaries" paper, observe that "an increased concentration of reflecting aerosols in one hemisphere leads to precipitation decreasing in the same hemisphere's tropical monsoon regions while increasing in the opposite hemisphere", with empirical volcano-derived AOD differences of 0.07–0.08 already producing measurable precipitation shifts (Rockström et al., 2023). The implication is that even a partial deployment of orbital mirrors, by redistributing incoming solar radiation, may push already-stressed biomes past critical thresholds.

Harper et al. observe that SAI would "delay the recovery of the ozone layer" by altering UV-B radiation, and that "[e]ffects on hydrological systems would be regionally diverse and uncertain due to potential changes in non-linear variables including surface runoff, evapotranspiration, rainfall levels, and distribution", which "could then affect vegetation" such that "[p]lant communities could transform their structure, traits, and geographical range, particularly under larger swifter SAI deployments" (Harper et al., 2026). Xia et al. similarly show that "stratospheric sulfate geoengineering could enhance the terrestrial photosynthesis rate" but only via the diffuse-radiation fertilization effect, with model-simulated net primary productivity response varying widely such that "even the sign of global mean change is uncertain" (Xia et al., 2016). The IPCC's 2023 assessment confirms that "[t]he change in the absolute amount of direct and diffuse radiation could also depend on the height of the additional sulphate aerosol layer" and that "SRM-induced cooling would decrease NPP at high latitudes" ((IPCC), 2023).

2.5 Rocket Emissions from the Launch Phase

The orbital mirror enterprise is bookended by rocket launches. Ryan et al., examining 2019 emissions and a speculative space-tourism scenario, find that "rocket emissions of black carbon produce substantial global mean radiative forcing of 8 mW m^{-2} after just 3 years of routine space tourism launches", which is "a much greater contribution to global radiative forcing (6%) than emissions (0.02%) of all other BC sources, as radiative forcing per unit mass emitted is ~500 times more than surface and aviation sources" (Ryan et al., 2022). They also find that "decline in global stratospheric O_3 is small (0.01%), but reaches 0.15% in the upper stratosphere (~5 hPa, 40 km) in spring at 60–90°N after a decade of sustained 5.6% a^{-1} growth in 2019 launches and re-entries", with the higher space-tourism scenario reaching 0.24%—"undermining O_3 recovery achieved with the Montreal Protocol" (Ryan et al., 2022).

Maloney et al. estimate that a 10 Gg/year rocket BC emission scenario "increases stratospheric temperatures by as much as 1.5 K in the stratosphere" and produces "a 10%–20% weakening of the overturning circulation … in the northern hemisphere during multiple seasons" with "ozone reduction in the northern hemisphere by as much as 16 DU in some months" (Maloney et al., 2022). Revell et al. confirm that "near-future rocket launches could slow ozone recovery", with their "ambitious" scenario (2,040 launches/year) yielding "−0.29% depletion in annual-mean, near-global total column ozone in 2030" and "Antarctic springtime ozone decreases by 3.9%" (Revell et al., 2025). Ross et al., in the foundational 2010 analysis, noted that "after one decade of continuous launches, globally averaged radiative forcing from the black carbon would exceed the forcing from the emitted CO_2 by a factor of about 10^5 and would be comparable to the radiative forcing estimated from current subsonic aviation" (Ross et al., 2010). Fahey et al., in the 2018 Scientific Assessment of Ozone Depletion, observe that "BC emissions from kerosene-fuelled rockets have a relatively long stratospheric lifetime (~3 years) and accumulate in the upper stratosphere" and that "[t]he fraction of global launches using propellants that have a relatively large BC emission index (mainly kerosene) has trended upward in recent years, increasing the steady-state BC accumulation" (Fahey et al., 2018). For a state licensing an orbital mirror constellation, the launch-phase carbon paradox is therefore not theoretical but measurable.

2.6 The Orbital Commons and Sustainable-Paradox Literature

The orbital commons themselves are increasingly characterized in ecological terms. Wilson and Vasile observe that "since spaceflight began, we have been contributing to the problem at a faster rate than our orbits can self-regulate, making space operations more dangerous" and that "we must learn to use space in a more sustainable way, respecting the ecological thresholds of both Earth and our orbital environment" (Wilson & Vasile, 2023). Lawrence argues for "the Planetary Boundaries Framework, defining trackable metrics that capture the damage to the space environment", noting that the "key metric is simply the number of Anthropogenic Space Objects", whose reflectivity "is currently doubling every 1.7 years; we are heading towards degree scale separation" (Lawrence, 2024). Trozzi et al. observe that "the orbits around Earth in which satellites reside are a limited natural resource", analogous to "the Earth's non-renewable resources (i.e., minerals and fossil fuels)", and that "their regeneration involves the passage of many years" (Trozzi et al., 2021). Öz frames the issue as a "super-wicked problem" in which "a certain carrying capacity in the orbital medium exists", and exceeding it produces "an environmental tragedy … in the form of cascading collisions" (Öz, 2021).

Given the above, the literature reveals three converging concerns:

1. The licensing architecture is technically narrow and obligational permissive.
2. The ecological, atmospheric, and biospheric harms are documented, large-scale, and largely irreversible at the technological scale contemplated.
3. The commercial incentives driving deployment structurally externalize those harms.
   The literature also indicates that the legal regimes designed to police these risks—the Outer Space Treaty's Article VI and Article II provisions, the Liability Convention, and national licensing regimes—are operating well below the threshold required by the science.

3. Methodology

This study employs a qualitative, integrative critical review methodology using the doctrinal–juridical and ecological-analytical traditions of space-law and environmental-impact assessment literature. The methodological framework comprises four interlocking components.

1. Doctrinal legal analysis:

Primary international space instruments (the 1967 Outer Space Treaty, the 1972 Liability Convention, national licensing frameworks), supplemented by State practice and interpretive scholarship, are analysed to determine the scope of the State's authorization obligation under Article VI and to identify the criteria actually applied by licensing authorities. Particular attention is given to the doctrinal writings of Harris and Baumann (Harris & Baumann, 2021), Ritonga and Azaria (Ritonga & Azaria, 2026), Islam (Islam, 2018, 2019), Bartz (Bartz, 2025), Kumar et al. (Kumar et al., 2021), Yusliwidaka and Roisah (Yusliwidaka & Roisah, 2025), and Neef (Neef, 2025) on the applicability of space law to SRM and orbital reflectors.

2. Orbital-commons sustainability synthesis:

Space-debris and orbital-commons scholarship is reviewed for state-of-the-art understanding of carrying capacity, with particular reference to Wilson and Vasile (Wilson & Vasile, 2023), Lawrence (Lawrence, 2024), Trozzi et al. (Trozzi et al., 2021), and Öz (Öz, 2021).

3. Comparative regulatory and equity analysis:

The granting of permission and commercialization pathways are evaluated against the principles of equitable benefit sharing (Deplano (Deplano, 2023), Butkevičienė and Rabitz (Butkevičienė & Rabitz, 2022), Saunders (Saunders, 2019)) and against sustainable-development governance frameworks (Mo et al. (Mo et al., 2024), Yap and Truffer (Yap & Truffer, 2022), Ruddigkeit et al. (Ruddigkeit et al., 2025), Williams et al. (Williams et al., 2024), Bahlmann et al. (Bahlmann et al., 2025)).

The critical-evaluation criterion employed is the proportionality test: a regulatory regime is judged adequate only if the substantive criteria of authorization reflect the magnitude, geographic reach, and irreversibility of the ecological and atmospheric externalities documented in the empirical literature. Where the licensing regime omits or materially underweights such externalities, the regime is judged inadequate as a matter of institutional design.

4. Results

The synthesis yields eight principal findings, each of which supports the central thesis that current state authorization practices for space-based mirror installation and its commercialization fail the proportionality test and this will culminate in to eco-environmental challenges in the coming future.

4.1 The Licensing Architecture is Technically Narrow and Procedurally Fragmented

The five critical licensing components identified by Fazio—mandatory licensing, technical requirements, financial-responsibility mechanisms, exceptional waivers, and terminability (Fazio, 2026)—are entirely silent on the ecological and atmospheric externalities documented in the climate-engineering and atmospheric-chemistry literatures. The mandatory "technical requirements" component is interpreted narrowly to cover launch safety, frequency coordination, and orbital debris mitigation during the operational phase; it does not extend to atmospheric emissions from the launch fleet, biospheric consequences of optical operations, or the precipitation-circulation effects of solar-radiation modification. As Giannoni-Crystal records concerning U.S. practice, "regulatory agencies may not prohibit a U.S. national from conducting an activity in space unless Congress required federal oversight", with the consequence that "Article VI (which is not self-executing) would not require regulation of any particular activities of U.S. citizens in outer space" (Giannoni-Crystal, 2024). This doctrinal posture effectively fragments authorization across discrete national regimes, none of which is competent to evaluate the planetary-scale ecological risk of an operational mirror constellation.

4.2 The Rocket-Emission Externalities Inherent in Mirror Deployment Subvert the Climate Rationale

The most arresting finding concerns the carbon paradox. The Ryan et al. estimate that "radiative forcing per unit mass emitted is ~500 times more than surface and aviation sources" for rocket-emitted black carbon (Ryan et al., 2022)—a finding that calls into question the very techno-economic premise on which mirror-based SRM is being licensed. The Tsiolkovsky rocket equation (used by Brewer to estimate that transporting 10^{10} kg to L1 with chemical propulsion would require "100,000 launches" and launch costs of "$5 trillion to $10 trillion" (Anthony, 2025)) implies a launch-phase emissions footprint that, by Ryan's metric, may generate "gigatons of CO_2, water vapor, and black carbon directly into the upper atmosphere", potentially "negat[ing] the cooling effect of the mirrors for decades" (Anthony, 2025). License conditions that do not require disclosure of the launch-phase radiative-forcing budget thus conceal an externality that may large-ly cancel the claimed benefit.

4.3 Stratospheric Ozone Recovery Will Be Materially Delayed by a Robust Mirror Launch Cadence

The Revell et al. findings are dispositive: at a 2,040-launch-per-year scenario, "Antarctic springtime ozone decreases by 3.9%" by 2030 (Revell et al., 2025). Because Antarctic stratospheric ozone is the principal UV-B shield for Southern Hemisphere ecosystems, this delay would translate into concrete biospheric harm—especially to phytoplankton, which underpins the marine food web. Fahey et al., in the 2018 WMO/UNEP Scientific Assessment of Ozone Depletion, observe that the "steady-state BC accumulation" is "trending upward" as "the fraction of global launches using propellants that have a relatively large BC emission index (mainly kerosene) … has trended upward in recent years" (Fahey et al., 2018). Authorization frameworks that omit a quantitative emission ceiling implicitly accept this trajectory.

4.4 Habitat Illumination Produces Documented Cross-Taxon Ecological Stress

The light-pollution literature, as catalogued by Gaston et al. (Gaston et al., 2013), Jägerbrand and Spoelstra (Jägerbrand & Spoelstra, 2023), Barentine et al. (Barentine et al., 2022), and Çelik et al. (Çelik et al., 2022), establishes that artificial light functions not merely as an ecological nuisance but as a cross-taxa disruptor of "natural patterns of resource use and information flows" with "downstream effects to the structure and function of ecosystems" (Gaston et al., 2013). Migratory birds, mammals, and insects are documented to navigate using stellar cues (Barentine et al., 2022); nocturnal migratory species are documented to be attracted to lit areas and experience disruption particularly during migration seasons (Levin et al., 2019). Orbital mirrors producing even diffuse, sky-wide illumination would, in the mechanism identified by these studies, disrupt navigation in entire hemispheres. Çelik et al. candidly observe that for reflectors, "potential adverse effects would be more likely in case of full-time illumination", and that "this risk is clearly augmented in a constellation with multiple reflectors" (Çelik et al., 2022).

4.5 Precipitation and Biome Shifts Are Quantitatively Anticipated

Brovkin et al. document that "in monsoon regions in East and South-East Asia, cooling leads to a reduction in precipitation" and that "[i]n southern Europe and subtropical North America, summer aridity is increased as well" (Brovkin et al., 2008). McLaren catalogues that "if SAI were heavily biased to one hemisphere the implications could be more dramatic", producing outcomes such as "large asymmetric stratospheric aerosol loadings concentrated in the Northern Hemisphere are a harbinger of Sahelian drought" (McLaren, 2018). Rockström et al. connect these dynamics directly to "safe and just Earth system boundaries", documenting that "model-simulated AOD differences of 0.1 and approximately 0.2 lead to declining precipitation in tropical monsoon regions" (Rockström et al., 2023). Mirror-based SRM, which redistributes solar input in spatially non-uniform patterns, would produce analogous precipitation shifts. Keller et al. caution that termination itself is dangerous: "SRM cannot be discontinued without causing rapid global change" because the carbon stored during deployment is "released rapidly once temperatures increase" (Keller et al., 2014). Any license that fails to require a binding termination protocol thereby accepts the risk of abrupt climatic and ecological destabilization.

4.6 The Orbital Commons is Approaching Carrying-Capacity Limits Independent of Mirrors

The proliferation of objects in orbit threatens to compound mirror-induced risks without any further authorization. Lawrence observes that the number of anthropogenic space objects' reflectivity "is currently doubling every 1.7 years; we are heading towards degree scale separation" (Lawrence, 2024). Wilson and Vasile observe that "from an environmental perspective, the most sustainable option would actually be to end space operations altogether and allow space debris to re-enter naturally" (Wilson & Vasile, 2023). The post-mission disposal regime of any reflective structure must therefore be evaluated under conditions where "objects that do not disintegrate on re-entry into Earth's atmosphere pose threats to ground safety and marine ecosystems", as the United Nations Environment Programme records (Programme, 2025). The licence-authorizing State's evaluation of cumulative in-orbit environmental load is, under current practice, not required for any individual mirror deployment.

4.7 The Commercialization Pathway Concentrates Externalities While Diffusing Benefit

Ritonga and Azaria document the structural tension: "commercial practices risk deepening inequality, enabling technological monopolies, and increasing environmental threats, particularly space debris" (Ritonga & Azaria, 2026). The model of "Space Sovereignty" developed by Smith argues that "traditional property-based governance models are inadequate for managing the unique characteristics of the orbital commons", and proposes "a multi-layered 'firewall' approach grounded in ecological systems thinking, stewardship principles, and intergenerational equity" (Smith & HATI, 2026). Under the conventional licensing regime, by contrast, "the deployment of massive SBSP systems could also contribute to an increase in space debris if the maintenance and decommissioning of such large structures are not addressed during the design phase" (Acquarone et al., 2024). The financial-responsibility mechanism of Fazio's licence model addresses compensation after-the-fact, not prevention ex ante; and as Deplano cautions, "the possibility of new market forces establishing themselves on a first-come, first-served basis runs the risk of widening the economic gap between the countries possessing financial and technological capabilities to perform space activities and those without" (Deplano, 2023). The ecological harm is thus inflicted on a global common from which the benefit is extracted privately.

4.8 The Sustainable-Development Frameworks That Exist Are Not Incorporated into Authorization

Multiple frameworks—United Nations Sustainable Development Goals, the European Space Agency's Environmental Impact Indicators for space systems, the Planetary Boundaries Framework, and the Space Sustainability Assessment Framework proposed by Mo et al. (Mo et al., 2024)—provide template criteria for evaluating space infrastructure against ecological thresholds. Bahlmann et al. developed "18 Sunshade Development Criteria, a framework for sustainable development" specifically for geoengineering sunshades, which they argue is necessary because "the required industry on Earth should align with broader sustainability goals" (Bahlmann et al., 2025). Andrzej Yap and Truffer observe that "[e]merging earth-space multi-system (re)configurations will therefore require new institutional architectures that will be built from a complex mix of governance approaches" (Yap & Truffer, 2022). Ruddigkeit et al.'s analysis of SRM governance demonstrates that "the existing web of international obligations offers a foundational framework that addresses many of the potential impacts associated with deployment of solar geoengineering" (Ruddigkeit et al., 2025)—but the analysis is of obligations, not of licensing practice. Licensing authorities therefore have available frameworks whose adoption would rebalance the proportionality test, but whose actual incorporation into national grant-of-permission practice is at best sporadic.

5. Discussion

5.1 The Inadequacy of the Doctrinal Frame: From "Use" to "Re-Oriented Authorization"

The Outer Space Treaty's Article I provides that the exploration and use of outer space "shall be carried out for the benefit and in the interests of all countries, irrespective of their economic or scientific development, and shall be the province of all mankind". Ritonga and Azaria show that "the current interpretation of 'use' is inadequate for regulating multi-actor commercial activities" and call for "an ius constituendum … to redefine and limit 'use' through fair benefit-sharing, proportional responsibility, and sustainable protection of the outer space environment" (Ritonga & Azaria, 2026). Bartz argues that the authorization-and-supervision requirement is "independent of carrying out activities 'in conformity with the provisions set forth in the [OST]'" (Bartz, 2025)—a positivist reading that, if widely adopted, would contract the ecological content of authorization to near-zero. The doctrinal fragility of ecological-proportional authorization thus becomes a primary object of critique.

Islam observes that the "existing legal protection towards the peaceful and sustainable uses of space is not well-organized and competent" and that "particularly, the issues of commercialization of space not been fully agreed upon" (Islam, 2019). The political economy of this incompleteness is consonant with Pramono's finding that "[s]tates with advanced space technologicaly support are always at the center of advancing and protecting their national interests in various international forums to continue the 'commercialization' of outer space" (Pramono, 2018). Licensing outcomes therefore tilt, structurally, towards permission rather than refusal. Yusliwidaka and Roisah confirm: "Only technologically developed countries are capable of going on missions and exploiting outer space … This indicates developed countries' domination over outer space", a domination that "challenges developed and developing countries to collaborate" (Yusliwidaka & Roisah, 2025).

5.2 Failed Principles and Unmet Promises

The composite picture is one of doctrinal overpromise and operational underdelivery. Article VI promises authorization and continuing supervision, but States lack the technical criteria, ecological thresholds, and binding instruments to operationalize both phrases. Article II declares the province of all mankind, but the commercial licensing regime, as Ritonga and Azaria show, converts the commons into a vehicle for "deepening inequality" (Ritonga & Azaria, 2026). Article IX requires due regard and avoidance of harmful contamination, but harm-to-ecology thresholds are not defined, and contamination from light pollution, atmospheric BC loading, and biome-scale precipitation shifts falls outside the conventional contamination frame (Fazio, 2026).

The Hargreaves-classic point made by the Planetary Boundaries Framework—now operationalized in the Rockström et al. analysis of "safe and just Earth system boundaries" (Rockström et al., 2023)—is that Earth-system regulation is a matter of regime design as well as science. Applying this insight to orbital mirrors forces the conclusion that the State's grant of permission is, in effect, an act of regime-design-by-default: every licence issued under the present narrow architecture entrenches a regime that fails to satisfy its own implicit proportionality requirement.

6. Conclusion

This critical evaluation yields a clear and sobering conclusion: the grant of permission by States for space-based mirror installation, and the commercialization pathway on which such installations depend, constitutes a regulatory practice that is profoundly misaligned with the magnitude, geographic scope, and irreversibility of its ecological and atmospheric consequences.

The doctoral finding is that current licensing regimes, as constructed under Article VI of the Outer Space Treaty and operationalized through domestic frameworks such as the U.S. Title 14 licensing regime or its analogues, are technically narrow and procedurally fragmented. They address launch safety, frequency coordination, and limited post-mission disposal—but they do not require quantitative accounting of launch-phase black-carbon radiative forcing (which Ryan et al. demonstrate can produce "global mean radiative forcing of 8 mW m^{-2} after just 3 years of routine space tourism launches" (Ryan et al., 2022)), stratospheric ozone impact (where the Revell et al. "ambitious" scenario produces "Antarctic springtime ozone decreases by 3.9%" (Revell et al., 2025)), biome-scale precipitation redistribution (where Brovkin et al. document direct reductions in Asian monsoon precipitation (Brovkin et al., 2008)), cross-taxa light-pollution stress (where Gaston et al. document ecosystem-wide disruption of resource and information flows (Gaston et al., 2013)), or orbital commons' carrying-capacity load (where Lawrence documents doubling of orbital-object footprint "every 1.7 years" (Lawrence, 2024)).

The grim ecological effects are not speculative. They are documented across at least four distinct empirical literatures: atmospheric chemistry, biospheric interventions, ecological light pollution, and orbital-debris sustainability. Their common signature is that they are transboundary, partially irreversible, and concentrated on populations that do not benefit from the commercial mirror enterprise—in particular, monsoon-dependent communities, nocturnal migratory species, marine phytoplankton, and Southern Hemisphere ozone-protected ecosystems.

The commercialization pathway aggravates these effects by concentrating benefits privately while externalizing harms communally. The "first-come, first-served" pattern identified by Deplano (Deplano,

2023) and the structural inequities identified by Yusliwidaka and Roisah (Yusliwidaka & Roisah, 2025) operate as reinforcing mechanisms. Without an equitable benefit-sharing doctrine, a binding termination protocol, and ecology-aware licensing criteria, the regime cannot satisfy even the proportionality test at the core of due regulation.

We therefore conclude that a comprehensive reform of the state's grant-of-permission regime for space-based mirror installation is necessary on three dimensions simultaneously: (i) substantive ecological criteria must be incorporated into the mandatory technical-requirements component of the licence, drawing on the Planetary Boundaries Framework, the Sunshade Development Criteria (Bahlmann et al., 2025), and the Space Sustainability Assessment Framework (Mo et al., 2024); (ii) the equitable-benefit-sharing obligation of OST Article I must be operationalized as a back-end condition of the licence, as Butkevičienė and Rabitz (Butkevičienė & Rabitz, 2022), Saunders (Saunders, 2019), and Deplano (Deplano, 2023) recommend; and (iii) the financial-responsibility mechanism must be calibrated to genuine planetary-scale harm, not merely to launch-incident liability, with the precautionary principle applied to the deployment threshold itself.

Pending these reforms, the State's grant of permission is best characterized not as an act of responsible stewardship of the orbital commons, but as an act of permissive delegation that externalizes grim ecological and atmospheric effects to the global commons.

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