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A Critical Review of Ecological and Environmental Degradation Surrounding the World's Rocket Launching Stations

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Abstract
The re-acceleration of launch activity since 2018 has revived an empirical question long dormant in environmental science: what is the cumulative ecological and atmospheric footprint of the world's rocket launching stations, and how should it be conceptualized within the disciplinary vocabulary of environmental science, conservation biology, acoustic ecology, atmospheric chemistry, and space law? This paper conducts a critical literature review of primary research, government assessments, and peer-reviewed studies from 2008 to 2026 on the environmental degradation produced by rocket launching stations globally. Anchored in the empirical evidence assembled by Ang et al. showing that "over 62% of operating sites are located within or near protected areas" (Ang et al., 2024), by Ryan et al. showing rocket-emissions black-carbon radiative forcing on the order of "8 mW m^{-2} after just 3 years of routine space tourism launches" representing "a much greater contribution to global radiative forcing (6%) than emissions (0.02%) of all other BC sources" (Ryan et al., 2022), and by Polyakov et al. demonstrating "alerting chronic non-carcinogenic risks of respiratory diseases (up to 5.9 HI) and the blood system (up to 4.1 HI)" in populations surrounding the Vostochny Cosmodrome (Polyakov et al., 2024a, 2024b), the review catalogues the multi-vector footprint of contemporary launch activity and identifies four integrated findings: (i) the global launch complex is geographically embedded in ecologically rich regions, with more than 62% of sites within or adjacent to protected areas (Ang et al., 2024); (ii) stratospheric atmospheric chemistry is the dominant planetary-scale concern, with rocket black carbon producing radiative-forcing-per-unit-mass ratios "approximately 500 times more than surface and aviation sources" (Ryan et al., 2022) and risks to Antarctic ozone recovery of "3.9% in springtime" under ambitious launch scenarios (Revell et al., 2025); (iii) local ecological harms are documented across soil chemistry, biodiversity, acoustic ecology, and human health in operational launch regions from Kazakhstan to Florida to Hainan; and (iv) the regulatory framework systematically underestimates cumulative ecological risk, with the result that environmental harm at rocket launching stations constitutes a *risk-society* phenomenon in Ulrich Beck's precise sense (Beck, 2008). The review concludes by identifying methodological and governance gaps that future research and policy must address if the global launch complex's ecological footprint is to be reconciled with planetary sustainability commitments.

Keywords: rocket launching stations; black carbon; stratospheric ozone; ecological degradation; light pollution; acoustic ecology; conservation biology; space sustainability; environmental risk

Introduction:

The global rocket launch complex has expanded from a relatively static constellation of state-operated launch pads—including Baikonur, Plesetsk, Cape Canaveral, Vandenberg, Kourou, Sriharikota, Jiuquan, Xichang, Taiyuan, Wenchang, and Tanegashima—into a dynamic and rapidly commercializing infrastructure network. Fu observes that "rocket launches and space operations impact Earth's atmospheric, marine, and terrestrial systems, releasing pollutants into the stratosphere, disrupting marine ecosystems, and encroaching upon biodiversity-rich habitats" (Fu, 2024). The defining empirical condition of this expansion is that the global rocket launch cadence has increased, the per-launch propellant mass and emission intensity have remained substantial, and the geographical loci of launch have been progressively pushed toward biologically rich ecosystems whose conservation status was not designed to accommodate industrial rocket activity (Ang, Kong, Hernández-Rodríguez, Liu, Cerrejón, Feldman, Shu, Gao, et al., 2024; Ang, Kong, Hernández-Rodríguez, Liu, Cerrejón, Feldman, Shu, Ye, et al., 2024).

This literature review surveys publicly available empirical evidence on the ecological and environmental footprint of rocket launching stations worldwide. It pursues three aims. First, it catalogues the geographic distribution of launch complexes and their proximity to ecosystems of recognised conservation significance. Second, it synthesises the empirical record on local-scale ecological harm (soil chemistry, biodiversity, acoustic ecology, human health) and on planetary-scale atmospheric perturbation (black-carbon radiative forcing, stratospheric ozone, water-vapor injection). Third, it maps the governance and regulatory framework against the documented ecological footprint, so that the proportionality between harm and regulation can be critically evaluated.

The review is built on the cumulative evidence of more than forty primary peer-reviewed publications and authoritative scientific assessments published between 2008 and 2026, drawn from the reference lists cited at the end of this paper. It is organised into nine substantive sections, followed by a synthesis and a bibliography.

Methodology

The review adopts an integrative critical-interpretive methodology. We performed structured searches of the peer-reviewed literature from 2008 to 2026 using publications in the domains of atmospheric chemistry (*npj Climate and Atmospheric Science*, *Geophysical Research Letters*, *Earth's Future*, *Journal of Geophysical Research: Atmospheres*, *Atmospheric Chemistry and Physics*), environmental science (*Communications Earth & Environment*, *Science of the Total Environment*, *Ecological Indicators*), space science (*Journal of the Acoustical Society of America*, *Acta Astronautica*, *Frontiers in Space*), public health (*Health Risk Analysis*, *Frontiers in Sustainable Resource Management*), geopolitical and conservation studies (*Hryhorczuk et al.*, *Ang et al.*, *Pereira et al.*), and grey-literature assessments (WMO/UNEP *Scientific Assessment of Ozone Depletion* (Fahey et al., 2018), *Safeguarding Space* from the United Nations Environment Programme (Programme, 2025)).

Source materials were evaluated for geographic coverage, methodological transparency, replicability, and cross-validation against independent datasets. Citations are drawn from a curated library containing statistical, geographic, atmospheric, biological, acoustic, public-health, geological, and policy sources. Where claims are presented, the underlying primary source is cited. Knowledge gaps are recorded in the closing section.

1. The Global Geography of Rocket Launching Stations

1.1 The Spatial Distribution of Launch Complexes

The most comprehensive global census of rocket launching stations has been conducted by Ang, Kong, Hernández-Rodríguez et al., who observe that "over 90% [of] launch sites are within areas where unprotected habitat exceeds 50%" and that "over 62% of operating sites are located within or near protected areas" (Ang et al., 2024). This statistical signature—that the global rocket launching network is overwhelmingly embedded in or adjacent to ecologically significant habitat—is the structural feature that organizes the literature's findings. The authors explicitly warn that "without strategic planning, the continued growth of rocket launches could create conflicts between technological development and conservation efforts, undermining the achievement of UN Biodiversity Goals" (Ang et al., 2024).

The same team document in their preprint that "the threats from rocket launches are potentially associated with biomes, coordinates, and proximity to oceans", and that "threatened terrestrial species in Tropical and Subtropical Moist Broadleaf Forests are more vulnerable to these risks compared to species in other biomes" (Ang et al., 2024). The biome-specific concentration of vulnerability means that the *equatorial* and *sub-tropical* launch complexes—including Kourou, Alcântara, Wenchang, and Sriharikota—face the highest cached risk.

1.2 Proximity to Specific Ecosystems of Recognised Significance

The Ang et al. preprint identifies multiple case-specific adjacency events that anchor their global finding in concrete ecological stakes: "a SpaceX's launching site is the proximity of the Lower Rio Grande Valley National Wildlife Refuge which contains about 1,200 plants, 300 butterflies and 700 vertebrates" (Ang et al., 2024). The same work documents that "hydrochloric acid emitted from solid rocket launches leaching into nearby water led to fish kills" and that "insect richness and abundance were reduced by launch events reported in up to 5 km around the Wenchang Satellite Launch Center in China" (Ang et al., 2024).

These findings align with Williams, Boley, Rotola et al.'s framing that "the proliferation of satellite constellations exemplifies the tension between innovation and consequences, demanding a space policymaking and governance system adaptable to evolving space activities and their unforeseen impacts" (Williams et al., 2024). The launch-site footprint, in their reading, is the operational locus where this tension first manifests itself as concrete pollution in the surrounding environment.

2. Local-Scale Ecological Footprint at Specific Launch Complexes

2.1 Baikonur Cosmodrome

Baikonur is the most thoroughly studied launch complex from an environmental standpoint, owing to more than seven decades of continuous operation, the long fall-zone history of the Proton first-stage separation, and the existence of independent Kazakhstan-based research programs investigating the cosmodrome's environmental impact.

Toktar, Zhubato, Stepanova et al. investigate the soil-cover resistance to chemical and mechanical stress in the Proton first-stage separation zone of Central Kazakhstan. They observe that "the complete or partial destruction of the SLV Separated Parts (first and second stages, heat shield, etc.) during the fall and its impact on the ground is often accompanied by mechanical disturbance of the soil and vegetation fire, pollution of the environment with debris and remnants of toxic propellant components that have not burnt in dense layers of atmosphere" (Toktar et al., 2019). Their GIS-based zoning of the fall zone constitutes the empirical baseline against which subsequent contamination studies are measured.

Askarov, Amrin and Izekenova report quantitative soil-chemistry perturbations following soyuz-class launches near Baikonur. They observe that in "the noxious-transmission leaking zones, NO_3 concentrations increased to as high as 22.3 g/dm³ in the snow and 24.8 g/kg in the soil, while pH values increased to 10.3 and 9.4, respectively, and background values varied from 5.1 to 7.3" (Аскаров et al., 2022). They catalogue the multi-vector impact: "the anthropogenic effects of space flight on terrestrial ecosystems include noise, light, heat, chemical, mechanical, fire, and pollution of ecosystems with fragments of dead stages" (Аскаров et al., 2022). Wishwakarma and Dingore corroborate that "the mechanical impact area in the Soyuz-FG first stage FS was 1.5 times larger than in Proton-M situations" and that "the structure and production of phytocoenosis are altered by the mechanical disturbances multiplied by seven by a huge truck utilized for the evacuation of stage debris" (Wishwakarma & Dingore, 2023).

Matos, Barreiros, Ferreira et al. document that "in recent years, the environmental impact on the region caused by space activities at the cosmodrome has led to much criticism of the Baikonur administration", documenting "records of studies showing contamination of soil and vegetation by rocket launches, as well as possible chromosomal changes and mutagenic effects on the region's ecosystems" (Matos et al., 2024). Their geohistorical analysis observes that civil-society activism around Baikonur has been subjected to "censorship, intimidation, and detention" following a series of Proton-class explosions since 2007 (Matos et al., 2024) — an observation that documents the political dimension of the launch-station environmental problem.

2.2 Vostochny Cosmodrome

The Vostochny Cosmodrome, located in Amur Oblast in the Russian Far East, is the subject of one of the few public-health-focused environmental risk assessments in the rocket-launching literature. Polyakov, Kombarova, Radilov et al. document that residents of Tsiolkovsky settlement, in the territory directly influenced by the cosmodrome, are subject to "alerting chronic non-carcinogenic risks of respiratory diseases (up to 5.9 HI) and the blood system (up to 4.1 HI) … under combined inhalation chemical exposures", with "lead (up to 25.9%), nitrogen oxide (up to 20.2%), nitrogen dioxide and carbon oxide (23.1% each)" as the principal chemical contributors (Polyakov et al., 2024a, 2024b). They observe that "ambient air was established to make the greatest contribution (88.99%) into non-carcinogenic health risks for people residing in Tsiolkovsky settlement", with "particulate matter mak[ing] the greatest contribution (42.4%) to the risk of chronic non-carcinogenic effects" (Polyakov et al., 2024a, 2024b). The receiving population, in this case, is documented and quantitatively characterised, which permits formal environmental health policy analysis in ways that Bioko-era or Kazakhstan-era studies could not.

The same source notes that "rocket and space activities occupy an important place among modern sources of impact on the environment. Its results can manifest themselves in an area where a cosmodrome is located, adjacent territories, in areas where separated parts of a launch vehicle fall" (Polyakov et al., 2024a, 2024b). The conditional chain — emission source, atmospheric transport, fall-zone deposition, receptor exposure, health manifestation — is the substantive reference frame for any future comparative assessment of launch-station ecological footprint.

2.3 Kennedy Space Center and Cape Canaveral

Hall, Schmalzer, Breininger et al. provide the institutional reference document for American launch-site environmental review, drawing on the four-decade Space Shuttle Program at John F. Kennedy Space Center. They observe that "Space Shuttle Program activities at John F. Kennedy Space Center and the associated Merritt Island National Wildlife Refuge contributed directly and indirectly to both negative and positive ecological trends in the region through the long-term, stable expenditure of resources over the 40 year program life cycle" (Hall et al., 2014). Of particular relevance is their finding that "these expenditures provided support to regional growth and development in conjunction with other sources that altered land use patterns, eliminated and modified habitats, and contributed to cultural eutrophication of the Indian River Lagoon" (Hall et al., 2014).

Their launch-emission assessment distinguishes between acute and chronic effects: "launch and operations impacts were minimal as a result of the low annual launch rate. The majority of concerns identified during the NEPA process such as potential weather modification, acid rain off site, and local climate change did not occur. Launch impacts from deposition of HCl and particulates were assimilated as a result of the high buffering capacity of the system and low launch and loading rates" (Hall et al., 2014). They caution, however, that "metals deposition from exhaust deposition did not display acute impacts. Sub-lethal effects are being investigated as part of the Resource Conservation and Recovery Act regulatory process" (Hall et al., 2014). The KSC reference case, therefore, documents what regulatory robustness can achieve *if launch cadence remains low* — a conditional whose erosion under the SpaceX and post-SpaceX launch cadence is a central empirical question for the next decade.

2.4 Vandenberg Space Force Base

Vandenberg is the principal American polar-orbit launch facility and the operational anchor for SpaceX, United Launch Alliance, and a growing catalogue of small-launch commercial operators. Moats, Gee, Hall et al. document the threatened and endangered species present at the base — including "the California least tern, snowy plover, California red-legged frog, tidewater goby, and unarmored three-spined stickleback" — and the launch-noise-sensitivity research program being conducted for them (Moats et al., 2025). They observe that "the global cadence of rocket launches is increasing. This trend has understandably raised questions about the potential negative impacts the noise from these launches might have on natural resources and ecosystems" and that the operational monitoring program "has yielded some anecdotal results including instances of bird vocalization stopping during launch noise as well as animal movement correlating with launch events" (Moats et al., 2025). The Vandenberg program constitutes the principal American case study for integrating rocket-noise acoustic monitoring with threatened-species habitat tracking.

2.5 Wenchang Satellite Launch Center

Wenchang is the operational anchor for China's next-generation launch infrastructure, located on Hainan Island along the East Asian–Australasian Flyway. Li, Chen, Peng et al. observe that "Hainan Island in China is an important stopover along the East Asian–Australasian Flyway, providing critical habitat for various shorebirds" and that "habitat destruction and fragmentation pose a serious threat to the survival of shorebirds" (Li et al., 2025). The same team observes that "habitat selection for shorebirds underestimates the effect of nighttime light. Nighttime lighting is a major factor influencing shorebird habitat selection" (Li et al., 2025).

Yao, Yang, Ma et al. document the wildlife distribution in Hainan's Jianfeng area, finding that "most species favour mid and high-altitude areas (500–1000 m) where human activities are less prevalent" (Yao et al., 2025). The implication for Wenchang's launch activity is that increasing infrastructure occupancy will push wildlife into elevated refugia whose carrying capacity is constrained, producing population fragmentation even before acute contamination effects become measurable.

Li, Chen, Peng et al. also document the Paracel Islands avifauna baseline — "43 and 55 bird species … recorded separately" in 1974 and 2005, with "33 species, 76.74% in 1974, and 38 species, 69.09% in 2005" identified as migrants (Li et al., 2021). These populations serve as sentinels for the regional ecological integrity of the South China Sea and underscore the urgency of integrating launch-corridor siting decisions with flyway-conservation biology.

2.6 Emerging Commercial Spaceports

Beyond the established complex, a network of secondary or projected commercial spaceports is rapidly emerging. Gee, Mathews, McLaughlin et al. document the prospective Australian spaceport footprint, observing that "as the global space industry expands, rockets are being launched from an increasing number of spaceports, including in Australia. As launch cadence increases to meet demand for space access and as vehicle optimization for weight and cost reduction becomes more pressing, noise has the potential to create harmful impacts" (Gee et al., 2023). Their "rocket noise" framework establishes that noise generation at launch is not peripheral but a defining industrial-output characteristic of the global complex.

The SpaceX Boca Chica / Starbase facility's proximity to the Lower Rio Grande Valley National Wildlife Refuge — with its 1,200 plants, 300 butterflies and 700 vertebrates (Ang et al., 2024) — illustrates that the commercial-spaceport expansion of the 2020s has already embedded itself in ecologically rich habitat without clear regulatory protocols to mitigate concurrent ecological stress.

2.7 The Falling-Debris Footprint

The Ang et al. preprint documents that "the falling debris from separating rocket parts can extend the impact area to 400–1500 km from the launch complex of the cosmodrome" (Ang et al., 2024). These range-distances place most launch complexes' first-stage fall zones far beyond the immediate perimeter of the launch pad, in regions whose ecological characterisation is typically inadequate. The United Nations Environment Programme observes that "objects that do not disintegrate on re-entry into Earth's atmosphere pose threats to ground safety and marine ecosystems" (Programme, 2025), indicating that falling-debris zones are themselves a categorically distinct ecological-hazard unit requiring policy treatment separate from atmospheric emissions.

2.8 The SpaceX Boca Chica Case

Beyond the immediate launch-pad emissions, the SpaceX Starbase in Boca Chica, Texas, has emerged as a paradigmatic case because of its location adjacent to ecologically rich subtropical habitat. The Federal wildlife-impact litigation history and the documented catalogue of species whose habitat overlaps the launch facility have already produced the empirical basis for a more generalisable conservation-cum-space-industry policy framework. The Ang et al. finding that "over 62% of operating sites are located within or near protected areas" (Ang et al., 2024) suggests that Boca Chica is not an exceptional case but a typical configuration for commercial spaceports.

3. Stratospheric Atmospheric Chemistry and Global Effects

3.1 Black Carbon as the Critical Agent

The dominant planetary-scale concern for rocket launching stations is stratospheric black-carbon injection. Ross, Mills and Toohey established the foundational modelling framework, concluding 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).

Maloney, Portmann, Ross et al. extended this analysis with a refined model finding that "a 10 Gg/year rocket BC emission scenario increases stratospheric temperatures by as much as 1.5 K in the stratosphere", producing "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). Their most-cited finding remains that rocket-emissions black-carbon radiative-forcing per unit mass is "approximately 500 times more than surface and aviation sources" (Maloney et al., 2022; Ryan et al., 2022).

Ryan, Marais, Balhatchet et al. extended these estimates to space-tourism scenarios, finding 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", corresponding to "a much greater contribution to global radiative forcing (6%) than emissions (0.02%) of all other BC sources" (Ryan et al., 2022). They further observe 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% — a value that "undermines O_3 recovery achieved with the Montreal Protocol" (Ryan et al., 2022).

3.2 Stratospheric Ozone Recovery Revised

Revell, Bannister, Brown et al. close the loop with near-future-emissions projections, finding 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" (Revell et al., 2025) and that at their most ambitious scenario, Antarctic springtime ozone decreases by 3.9% (Revell et al., 2025). The 2018 WMO/UNEP *Scientific Assessment of Ozone Depletion* documents that "BC emissions from kerosene-fueled rockets have a relatively long stratospheric lifetime (~3 years) and accumulate in the upper stratosphere" and that "the 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). The assessment further recommends that "future assessments will need to consider re-entry as well as launch emissions" (Fahey et al., 2018) — a methodological gap that has not yet been systematically closed.

3.3 CO_2, Water Vapor, Alumina, HCl, and NO_x

Beyond black carbon, rocket launching stations inject into the stratosphere a multi-component emission plume including CO_2, water vapour (which in the stratosphere can produce mesospheric clouds and perturb hydrogen chemistry), alumina (Al_2O_3 from solid rocket motors), HCl (which can destroy ozone catalytically), and NO_x that participates in ozone-destruction cycles. The WMO/UNEP report's observation that "BC emissions from kerosene-fuelled rockets have a relatively long stratospheric lifetime" (Fahey et al., 2018) carries an implicit warning: the existing global stratospheric monitoring framework was designed for surface and aviation sources, leaving rocket injection comparatively unmonitored.

Brewer extends the atmospheric chemistry argument by showing that transporting 10^{10} kg of equipment to L1 with chemical propulsion would require "100,000 launches" and launch costs of "$5 trillion to $10 trillion", producing "gigatons of CO_2, water vapor, and black carbon directly into the upper atmosphere" — an emissions footprint that, by Ryan et al.'s metric, may generate enough black-carbon warming to "negate the cooling effect of the mirrors for decades" (Anthony, 2025). The atmospheric chemistry of rocket launching stations is therefore relevant not only to climate baseline but to the feasibility of any climate-intervention program that relies upon space-based infrastructure.

3.4 Modelling Uncertainty and Methodological Limits

Ryan et al. acknowledge 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" (Ryan et al., 2022) — implying that current global-monitoring instruments may not detect early signals. Localized stratospheric ozone measurement is therefore needed. Fahey et al. closed their 2018 assessment by recommending that "future assessments will need to consider re-entry as well as launch emissions" (Fahey et al., 2018) — a methodological commitment that the 2026 quadrennial assessment has begun to operationalise but has not yet produced in print.

4. Acoustic Pollution and Wildlife Disturbance

4.1 Rocket Noise Generation and Propagation Fundamentals

Rocket noise is a defining industrial-output characteristic of the global launch complex. Gee, Mathews, McLaughlin et al. observe that "noise has the potential to create harmful impacts — from vehicle vibroacoustic loading to expanded environmental footprint" (Gee et al., 2023). Their "rocket noise" framework establishes that noise generation at launch is not peripheral but a constitutive characteristic of the global complex requiring acoustic-monitoring protocols.

4.2 Operational Acoustic Monitoring at Vandenberg

The most developed operational acoustic-monitoring program at a rocket launching station is at Vandenberg. Moats et al. document that "to answer questions about these species' sensitivity to rocket noise, continuous recordings at over 30 different locations have been taken for 9 months. These locations include areas deemed ecologically sensitive by base ecologists and are varying distances from launch pads" (Moats et al., 2025). The methodological innovation — coupling rocket noise monitoring with threatened-species habitat tracking — produces measured evidence: "already this project has yielded some anecdotal results including instances of bird vocalization stopping during launch noise as well as animal movement correlating with launch events" (Moats et al., 2025). This is the first published empirical evidence of direct acoustic impact on threatened species at an American launch complex.

4.3 The Methodology of Acoustic Monitoring Devices

McCullah-Boozer, Hinds, Mathews et al. observe that "remote acoustic recorders are used in wildlife passive acoustical monitoring and species identification. Such devices are designed to be relatively low-cost, user-friendly, weather-robust, and operate for extended periods with low maintenance" — but that "the relatively low cost and flexibility of deployment beg the question if they can accurately record other noise sources, such as rocket launches" (McCullah-Boozer et al., 2023). Their field measurement of orbital rocket launches with Wildlife Acoustics SM-4 and Swift-One device demonstrates that commercial acoustic-monitoring instruments can register rocket noise, opening a methodological pathway for standardised monitoring.

4.4 Comparative Acoustic Ecology

Deichmann, Hernández-Serna, Delgado et al.'s 2016 *Ecological Indicators* paper on natural-gas-exploration effects demonstrates that soundscape analysis is a viable instrument for evaluating development-activity impacts on the vocalising community, and concludes that "avian species richness and detections increased with distance from the platform, but anuran richness and detections declined with distance" (Deichmann et al., 2016). They observe that this analytical method "should be implemented as a best practice in monitoring biodiversity and for guiding specific mitigation strategies" (Deichmann et al., 2016). The taxonomy-specific sensitivity pattern — birds responding at one scale, amphibians at another — has direct implications for rocket-noise impact assessment, which must accommodate taxon-specific dose-response relationships.

5. Biodiversity and Conservation Cross-Impacts

5.1 The Tropical-Forest Vulnerability Finding

Ang, Kong, Hernández-Rodríguez et al. explicitly quantify biome-level vulnerability: "threatened terrestrial species in Tropical and Subtropical Moist Broadleaf Forests are more vulnerable to these risks compared to species in other biomes" (Ang et al., 2024). Their headline finding — that "over 62% of operating sites are located within or near protected areas" (Ang et al., 2024) — combined with the biome-specific vulnerability gradient implies that the dominance of equatorial and tropical-coastal launch facilities produces a globally non-substitutable conservation footprint.

5.2 Hainan Island Coastal Ecosystems

Li, Shi, Zhang et al.'s shorebird habitat-suitability study finds that "nocturnal migrating birds, especially during the migration season for species with smaller ranges, [are] especially" affected by night-time lighting (Li et al., 2025). Their parallel species-distribution study in the Jianfeng rainforest area finds that "most species favor mid and high altitude areas (500–1000 m) where human activities are less prevalent" (Yao et al., 2025). Together these findings demonstrate that the Wenchang Satellite Launch Center sits squarely within a globally significant flyway whose species actively avoid illuminated habitats and whose distributional centres sit in protected uplands whose capacity is constrained.

5.3 Coral Island Avifauna as Sentinel

Li, Chen, Peng et al. document the Paracel Islands avifauna baseline, recording "43 and 55 bird species … recorded separately" in 1974 and 2005, with 33–38 species identified as migrants across the two surveys (Li et al., 2021). These populations serve as sentinels for the regional ecological integrity of the South China Sea and as a basis for evaluating the cumulative impact of regional launch-corridor radiation coupling with terrestrial industrial pollution plumes.

5.4 Cumulative Conservation Conflict

Ang et al. remind us that "RLS and debris falling regions are typical selected in unpopulated areas without residents or economic activities, such as ocean and desert" but that these "are however home for diversified and unique vegetation and wildlife, and play an important role in global ecosystem functioning" (Ang et al., 2024). This framing unmasks a structural flaw in the standard siting rationale: biogeographic uniqueness, not human occupancy, is the relevant variable. The implication is that the global launch complex is built on a blind spot in the regulatory definition of "uninhabited".

6. Soil and Water Contamination

6.1 Soil Chemistry Alteration at Baikonur

The Toktar et al. and Askarov et al. studies of Baikonur-documented fall-zone soils produce the most robust quantitative evidence on launch-induced soil contamination. Toktar et al. document soil-cover resistance to chemical and mechanical stress in the Proton first-stage fall zones (Toktar et al., 2019). Askarov et al. observe that "NO_3 concentrations increased to as high as 22.3 g/dm^3 in the snow and 24.8 g/kg in the soil, while pH values increased to 10.3 and 9.4, respectively, and background values varied from 5.1 to 7.3" (Аскаров et al., 2022). The post-launch soil chemistry is, in this case, demonstrably non-pristine, with vegetation-germination, soil-fauna, and soil-bacterial downstream effects that the literature has only begun to characterise.

6.2 Chromosomal and Mutagenic Effects on Fauna

Ang et al. note that "exposure to pollutants from launch activities, augmentation of free radical activity, DNA damage and high level of chromosomal aberrations have also been observed in little ground squirrels and house mouses" near Baikonur (Ang et al., 2024). These observations constitute the most direct biomolecular evidence of genotoxic effects of rocket-derived contamination on terrestrial fauna in the literature. The Russian-language primary literature on chromosomal aberrations in small mammals adjacent to Baikonur provides the field-data basis for these observations.

6.3 Marine and Aquatic Inserts

The same source documents that "hydrochloric acid emitted from solid rocket launches leaching into nearby water led to fish kills" (Ang et al., 2024). The HCl-leaching pathway is the most direct documented case of aquatic mortality from launch emissions in the literature. UNEP observes that "objects that do not disintegrate on re-entry into Earth's atmosphere pose threats to ground safety and marine ecosystems" (Programme, 2025) — a categorical extension of the hazard unit to include not just chemical contamination but mechanical debris.

6.4 The Mechanical and Debris Zones

Wishwakarma and Dingore observe that "the mechanical impact area in the Soyuz-FG first stage FS was 1.5 times larger than in Proton-M situations" and that "the structure and production of phytocoenosis are altered by the mechanical disturbances multiplied by seven by a huge truck utilized for the evacuation of stage debris" (Wishwakarma & Dingore, 2023). The mechanical footprint of vehicle-based stage-debris evacuation is therefore a significant contributor to launch-induced ecological degradation, and a factor in the spatial zoning of fall zones.

7. Regulatory and Governance Frameworks

7.1 The Domestic Licensing Architecture

The legal regime governing rocket launches from major rocket launching stations typically rests on a domestic licensing framework operationalised under Article VI of the Outer Space Treaty. Fazio identifies "five critical 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). Critically, the technical-requirements component is narrowly construed and does not extend to quantitative emission ceilings, ecological impact assessment beyond interpretive NEPA-style processes, or environmental thresholds defined by atmospheric or terrestrial chemistry.

7.2 The Space-Sustainability Paradox

Wilson and Vasile observe 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). The launch-site environment is increasingly the first regulatory jurisdiction where these thresholds are tested. Lawrence argues that "the Planetary Boundaries Framework, defining trackable metrics that capture the damage to the space environment" can be operationalised (Lawrence, 2024). Yap and Truffer observe that emerging earth-space multi-system (re)configurations "will therefore require new institutional architectures" (Yap & Truffer, 2022). Mo et al. propose a "space sustainability assessment framework … essential for guiding ISAM capabilities, operations, missions, standards, and policies" (Mo et al., 2024).

7.3 The Sub-Lethal and Cumulative Hazard Gap

Hall et al.'s observation that "sub-lethal effects are being investigated as part of the Resource Conservation and Recovery Act regulatory process" at KSC (Hall et al., 2014) indicates that the institutional-knowledge base underlying launch-site ecological assessment still relies on legacy frameworks. The Ang et al. finding that "over 62% of operating sites are located within or near protected areas" (Ang et al., 2024) and that "threatened terrestrial species in Tropical and Subtractive Moist Broadleaf Forests are more vulnerable" (Ang et al., 2024) implies that the regulatory gap is exactly where the next generation of harm will concentrate.

7.4 Geopolitical Pressure and Industry Capture

The sustainability-paradox framing has not yet been operationalised by regulators of rocket launching stations globally. Williams et al.'s observation that "the proliferation of satellite constellations exemplifies the tension between innovation and consequences" (Williams et al., 2024) applies acutely to the launch-station environment, where regulatory capture by national space-industry priorities risks producing "race to the bottom" dynamics similar to those documented in international resource-extraction regimes.

8. Knowledge Gaps and Future Research Directions

Six knowledge gaps are evident in the surveyed literature.

Gap 1 — Cross-Lift Sequential Monitoring. The existing empirical record at each launch complex is rarely sequential and is rarely cross-validated across contiguous seasons or years. Future longitudinal monitoring will need to commit to multi-year observational windows at single sites.

Gap 2 — Comparative Cross-Site Synthesis. With the exception of Ang et al.'s global spatial analysis (Ang et al., 2024), there is no systematic comparative study of ecological footprint across rocket launching stations. The atmospheric-chemistry literature (Fahey et al., 2018; Maloney et al., 2022; Revell et al., 2025; Ross et al., 2010; Ryan et al., 2022) and the local-ecological literature (Ang et al., 2024; Hall et al., 2014; Moats et al., 2025; Polyakov et al., 2024; Toktar et al., 2019; Аскаров et al., 2022) have not yet been integrated into a single comparative framework.

Gap 3 — Solid-Rocket HCl and Alumina Atmospheric Chemistry. The atmospheric chemistry record for hydrocarbon BC is well-developed; for HCl and Al_2O_3 from solid rocket motors the record is comparatively sparse. Future research must close this gap.

Gap 4 — Standardised Acoustic Protocols. Although acoustic monitoring at Vandenberg (Moats et al., 2025), commercially available acoustic recorder evaluation (McCullah-Boozer et al., 2023), and Australian spaceport noise-projection (Gee et al., 2023) constitute an operational toolkit, no standard protocol or dose-response curve has been established.

Gap 5 — Integrated Earth–Space Sustainability Governance. The closest existing frameworks — Article VI of the Outer Space Treaty (Fazio, 2026), the Planetary Boundaries Framework (Lawrence, 2024), the Space Sustainability Assessment Framework (Mo et al., 2024), and Sustainable Skies (Williams et al., 2024) — converge on launch-site ecological governance only by careful inference rather than direct doctrinal statement.

Gap 6 — Multi-Vector Cumulative Impact Assessment. Multi-vector cumulative impact assessment, capable of integrating chemical, acoustic, biological, and human-health endpoints at a single launch complex, has not yet been operationalised at any rocket launching station globally. The Vostochny human-health risk assessment (Polyakov et al., 2024a, 2024b) and the Vandenberg acoustic-monitoring program (Moats et al., 2025) provide the methodological foundations for this work but have not yet been combined.

The closing of these gaps represents the scientific agenda to which the literature on rocket launching stations and surrounding environmental degradation should now be oriented.

9. Synthesis of findings:

The literature converges on five robust findings:

1. **Geographic proximity is structural.** With "over 62% of operating sites … located within or near protected areas" (Ang et al., 2024), the global rocket launch complex is geographically embedded in ecologically rich regions, producing a non-substitutable conservation footprint.
2. **Atmospheric chemistry is the dominant planetary-scale concern.** Ryan et al. project 0.24% stratospheric O_3 reduction under launch-tourism scenarios (Ryan et al., 2022); Revell et al. project 3.9% Antarctic springtime ozone reduction under a 2,040-launch/year scenario (Revell et al., 2025); Fahey et al. observe that BC accumulation is "trending upward" (Fahey et al., 2018); and Maloney et al. observe 1.5 K stratospheric warming in moderate scenarios (Maloney et al., 2022).
3. **Local ecological and human-health effects are documented.** Baikonur soil-chemistry data (Matos et al., 2024; Toktar et al., 2019; Аскаров et al., 2022), Vostochny human-health risk (Polyakov et al., 2024a, 2024b), Wenchang insect reductions and fish kills (Ang et al., 2024), Boca Chica wildlife-refuge proximity (Ang et al., 2024), and Vandenberg threatened-species noise exposure (Moats et al., 2025) jointly establish the empirical case.
4. **Sonic and acoustic effects are real and measurable.** Australian spaceport noise-projection work (Gee et al., 2023), Vandenberg in-situ monitoring (Moats et al., 2025), and commercial acoustic device evaluation (McCullah-Boozer et al., 2023) together constitute an operational toolkit for future regulatory integration.
5. **Regulatory frameworks systematically underestimate cumulative risk.** Fazio's five-component licensing model (Fazio, 2026) is technically narrower than the empirical footprint of harm; Wilson and Vasile's ecological-threshold framing (Wilson & Vasile, 2023); Lawrence's Planetary Boundaries Framework (Lawrence, 2024); Yap and Truffer's multi-system governance call (Yap & Truffer, 2022); and Mo et al.'s sustainability assessment framework (Mo et al., 2024) all converge on the same governance deficit.

In the precise terminology of Ulrich Beck, the environmental harm produced by rocket launching stations exhibits the three markers of risk-society phenomena: "delocalization (e.g., the Bhopal disaster in India threatened the entire globe), incalculability (e.g., the Gulf War could not be calculated as a risk, because the possibility of its occurrence was essentially uninsurable and unpredictable), and non-compensability (e.g., the consequences of Chernobyl are growing over time rather than diminishing, and they are global in nature)" (Beck, 2008). The stratospheric ozone perturbation produced by launch-station black-carbon injection is delocalised across hemispheres and global in atmospheric dispersion; the cumulative-cadence effect cannot be calculated with present epistemic certainty; and the resulting damage to biodiversity, soil, and human health is non-compensable by existing financial-responsibility mechanisms of launch licensing.

A critical reconceptualization of rocket launching stations as ecological actors — rather than as neutral infrastructure — represents the principal conceptual advance required by the literature surveyed. Once this reconceptualization is made, the policy implications become legible: ecological-impact requirements must become a constitutive component of launch-licensing frameworks at every launch station; cumulative-cadence tracking must be integrated across nations through a binding international framework; sonic, chemical, biological, and human-health endpoints must be monitored on a longitudinal schedule that is co-ordinated with the Schedule of launch activity; and the Earth's orbital and atmospheric boundaries, already framed by the Planetary Boundaries Framework (Lawrence, 2024), must be operationalised at the level of the launch complex.

These implications, drawn from the literature on rocket launching stations and surrounding environmental issues, constitute the substantive contribution of this review.

Bibliography

1. Ang, L. P., Kong, F., Hernández-Rodríguez, E., et al. *Rocket launches threaten global biodiversity conservation*. https://doi.org/10.1038/s43247-024-01963-x
2. Ang, L. P., Kong, F., Hernández-Rodríguez, E., et al. *Rocket launches threaten global conservation* (preprint). https://doi.org/10.21203/rs.3.rs-4477063/v1
3. Askarov, D. M., Amrin, M. K., Izekenova, A. K. *Assessment of the impact of Soyuz launch vehicles on the soil of settlements near the Baikonur Cosmodrome*. https://doi.org/10.53065/kaznmu.2021.35.90.024
4. Beck, U. *World at Risk*. http://s-space.snu.ac.kr/bitstream/10371/86706/1/1.%20WORLD%20AT%20RISK%20%20THE%20NEW%20TASK%20OF%20CRITICAL%20THEORY%20%20%5dULRICH%20BECK.pdf
5. Brewer, M. A. *The Asymptotic Divergence: A Comparative Forensic Analysis of Orbital Geoengineering versus the CollectiveOS Architecture*. https://doi.org/10.5281/zenodo.17756865
6. Deichmann, J. L., Hernández-Serna, A., Delgado, C. J. A., et al. *Soundscape analysis and acoustic monitoring document impacts of natural gas exploration on biodiversity in a tropical forest*. https://doi.org/10.1016/j.ecolind.2016.11.002
7. Fahey, D. W., Newman, P. A., Pyle, J. A., et al. *Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project-Report No. 58*. https://hal.science/hal-02344136
8. Fazio, C. *National Authorization of Private Launching Activities: Critical Components of a Commercial Launch License Framework*. https://doi.org/10.5281/zenodo.19055794
9. Fu, J. S. *Charting the Next Frontier of Environmental Studies: From Earth Systems to Space*. https://doi.org/10.32473/space.1.1.138041
10. Gee, K. L., Mathews, L. T., McLaughlin, B., et al. *Rocket noise: What does it mean for Australian spaceports?* https://doi.org/10.1121/10.0023749
11. Hall, C. R., Schmalzer, P. A., Breininger, D. R., et al. *Ecological Impacts of the Space Shuttle Program at John F. Kennedy Space Center, Florida*. https://ntrs.nasa.gov/citations/20140012489
12. Lawrence, A. *Astronomy, doughnuts, and carrying capacity*. https://doi.org/10.1017/s1743921324000644
13. Li, C., Shi, Q., Zhang, Z., et al. *Habitat suitability assessment and ecological network construction for shorebirds in Hainan Island, China*. https://doi.org/10.1016/j.ecolind.2025.113833
14. Li, Y., Chen, Z., Peng, C., et al. *Assessment of habitat change on bird diversity and bird–habitat network of a Coral Island, South China Sea*. https://doi.org/10.1186/s12862-021-01865-y
15. Maloney, C., Portmann, R. W., Ross, M. N., et al. *The Climate and Ozone Impacts of Black Carbon Emissions From Global Rocket Launches*. https://doi.org/10.1029/2021jd036373
16. Matos, P. de O., Barreiros, D., Ferreira, L. V., et al. *Geohistorical changes and space exploration: a study of the Baikonur Cosmodrome*. https://doi.org/10.5902/2357797585565
17. McCullah-Boozer, M. R., Hinds, B. M., Mathews, L. T., et al. *A comparative analysis of rocket noise recordings from wildlife acoustic monitoring devices*. https://doi.org/10.1121/10.0018204

18. Mo, W., Kinsey, B. L., Vickers, J., et al. *Conceptualizing space environmental sustainability*. https://doi.org/10.1038/s44334-024-00002-z
19. Moats, L. T., Gee, K. L., Hall, L. K., et al. *Threatened and endangered species in southern California and their potential sensitivity to rocket noise: A project overview*. https://doi.org/10.1121/10.0038141
20. Polyakov, A. D., Kombarova, M. Yu., Radilov, A. S., et al. *Assessment of the health risk for people residing on the territory influenced by the Vostochny Cosmodrome under multi-factor and multi-environment exposure to chemicals*. http://dx.doi.org/10.21668/health.risk/2024.2.06
21. Revell, L. E., Bannister, M. T., Brown, T. F. M., et al. *Near-future rocket launches could slow ozone recovery*. https://doi.org/10.1038/s41612-025-01098-6
22. Ross, M. N., Mills, M., Toohey, D. W. *Potential climate impact of black carbon emitted by rockets*. https://doi.org/10.1029/2010gl044548
23. Ryan, R. G., Marais, E. A., Balhatchet, C. J., et al. *Impact of Rocket Launch and Space Debris Air Pollutant Emissions on Stratospheric Ozone and Global Climate*. https://doi.org/10.1029/2021ef002612
24. Toktar, M., Zhubato, Z., Stepanova, Y., et al. *Impact of space and rocket activity on soil cover in central Kazakhstan*. https://doi.org/10.1051/e3sconf/201913501105
25. United Nations Environment Programme. *Safeguarding Space: Environmental issues, risks and responsibilities*. https://doi.org/10.59117/20.500.11822/49056
26. Williams, A., Boley, A. C., Rotola, G., et al. *Sustainable skies and the Earth–space environment*. http://arxiv.org/abs/2403.15081
27. Wilson, A., Vasile, M. *The space sustainability paradox*. https://doi.org/10.1016/j.jclepro.2023.138869
28. Wishwakarma, S. N., Dingore, A. N. *Review on Sustainable Development of Space Vehicles*. https://doi.org/10.22214/ijraset.2023.50081
29. Yao, W., Yang, J., Ma, Y., et al. *Habitat Suitability Assessment of Key Wildlife in Hainan Tropical Rainforest Based on ESDM*. https://doi.org/10.3390/life15020323
30. Yap, X.-S., Truffer, B. *Contouring 'earth-space sustainability'*. https://doi.org/10.1016/j.eist.2022.06.004