A Policy Framework for Space Debris Management: Evaluating the Feasibility of a Space Environmental Tax

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Abstract

The accumulation of space debris poses a critical challenge to the long-term sustainability of space activities. Existing mitigation strategies, such as collision avoidance and Active Debris Removal (ADR), face significant technical, economic, and regulatory barriers. In this study we explore the feasibility of implementing a Space Environmental Tax (SET) as a policy mechanism to incentivize responsible space operations and finance debris mitigation efforts. Using a system dynamics model, this study evaluates the economic implications of SET on satellite operators, the effectiveness of tax-induced behavioral changes, and its impact on orbital sustainability. Simulation results indicate that the SET can effectively reduce debris accumulation by discouraging excessive satellite launches and providing financial support for ADR. Additionally, the study highlights the role of dynamic tax rate adjustments in responding to orbital congestion levels. The findings suggest that economic incentives, coupled with technological solutions, can offer a sustainable governance framework for managing space debris. This research contributes to space policy discussions by presenting SET as a viable mechanism for integrating environmental and economic considerations into global space governance.

Keywords: Space Debris, Kessler Syndrome, Space Environmental Tax, System Dynamics, Active Debris Removal, Space Policy, Sustainability.

1. Introduction

1.1 Background

The expansion of space activities has led to a significant accumulation of space debris, which consists of non-functional satellites, spent rocket stages, and mission-related fragments that remain in orbit almost indefinitely. These objects pose a persistent risk of collision with operational spacecraft, endangering satellite operations, human spaceflight, and future space missions (Kessler & Cour-Palais, 1978). The increasing amount of space debris has emerged as a critical challenge for governmental and commercial space actors, necessitating urgent mitigation strategies to ensure the long-term sustainability of outer space (UNOOSA, 2021).

Since the beginning of space exploration in 1957, more than 7,000 spacecraft have been launched into various Earth orbits (ESA, 2023). The number of debris objects has escalated significantly in recent decades, particularly following deliberate anti-satellite (ASAT) tests and accidental satellite collisions. The 2007 Chinese ASAT test produced over 3,500 trackable debris fragments, and the 2009 Iridium-Cosmos collision further exacerbated the debris population (Secure World Foundation, 2012a; 2012b). As of 2023, estimates suggest that over 100 million pieces of debris, each larger than 1 mm, are orbiting Earth at velocities exceeding 7.5 km/s (Sky Perfect JSAT Group, 2020).

At such speeds, even millimeter-sized debris can cause severe damage to spacecraft. The risk of debris-induced fragmentation continues to grow, threatening the sustainability of space activities if effective mitigation policies are not implemented.

Figure 1 presents data on all cataloged objects in Earth's orbit as of January 9, 2025 (NASA Orbital Debris Quarterly News, 2025). These objects are classified by type and tracked by the U.S. Space Surveillance Network (SSN). The graph highlights several key trends. First, the total number of objects in Earth's orbit has been increasing steadily, largely due to the expansion of commercial satellite constellations. Second, fragmentation debris accounts for a significant portion of the objects in orbit, indicating the growing challenge of space debris mitigation. Finally, a substantial number of rocket bodies remain in orbit, contributing to long-term space congestion. Overall, the graph illustrates the increasing density of objects in Earth's orbit and the urgent need for improved space traffic management and active debris removal strategies. Ensuring the sustainability of space activities will require coordinated efforts from governments, space agencies, and commercial operators.

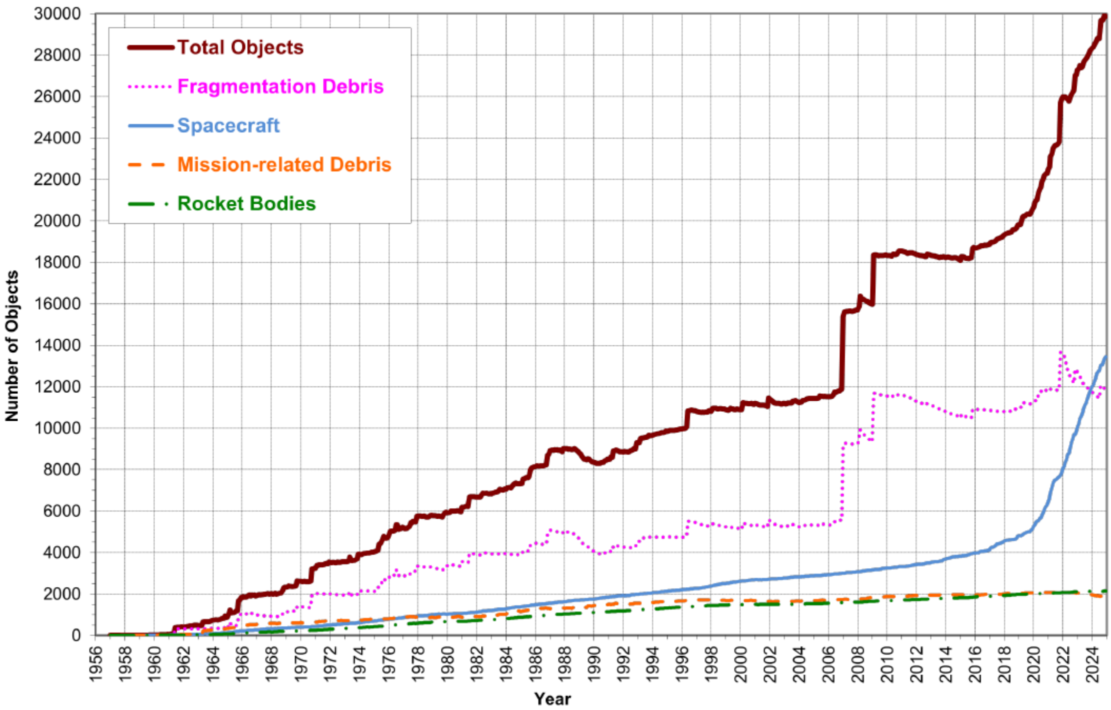

Figure 1 Number of objects in earth orbit by object type (NASA, 2025)

(Image source: NASA Orbital Debris Quarterly News, Volume 29, Issue, February 2025)

1.2 Kessler syndrome

The Kessler Syndrome, originally proposed by Kessler and Cour-Palais (Kessler & Cour-Palais, 1978), describes a scenario in which collisions between debris fragments initiate a self-sustaining cascade of fragmentation, exponentially increasing the number of debris objects in orbit. Once critical debris density is reached, certain orbital regions may become permanently hazardous or entirely unusable for future space activities.

Beyond the environmental risks, space debris imposes substantial economic costs. As the probability of collisions increases, satellite operators must invest in shielding, collision avoidance maneuvers, and debris tracking systems, significantly raising operational expenses (Liou & Johnson, 2006). The need for frequent orbital maneuvers reduces satellite lifespan and efficiency, affecting both commercial and scientific missions (Arustei and Dutta, 2024). This economic burden has been described as the Economic Kessler Syndrome, wherein rising costs deter investment and slow innovation in the space industry (Adilov et al., 2015, Adilov et al., 2020).

Traditional approaches to debris mitigation primarily rely on engineering solutions, including collision avoidance, shielding, and Active Debris Removal (ADR) (ESA, 2023). Collision avoidance involves operational satellites performing orbital maneuvers to evade potential collisions (Arustei and Dutta, 2024). However, this approach requires precise debris tracking, additional propellant reserves, and meticulous maneuver planning, all of which contribute to increased operational costs (Schaub et al., 2015).

Similarly, ADR technologies, such as robotic capture, tethered harpoons, and laser ablation, have been proposed as methods for removing existing debris from orbit (Forshaw et al., 2017). Despite their potential, ADR methods face substantial technical, legal, and economic challenges. The high costs associated with debris removal, coupled with the absence of direct economic benefits, discourage private sector involvement (Macauley, 2015). Furthermore, legal uncertainties and geopolitical concerns complicate international collaboration, as ADR activities may be perceived as military operations or unauthorized interventions (Sheer and Li, 2019).

1.3 Purpose

Despite technological advancements, engineering-based solutions alone are insufficient to address the growing space debris problem. A fundamental challenge is determining financial responsibility for debris removal. Unlike terrestrial environmental policies, where polluters are held accountable, space law lacks enforceable mechanisms to mandate debris mitigation (United Nations, 2022). Under the Outer Space Treaty (1967) and the Liability Convention (1972), states are responsible for objects they launch; however, there is no binding international framework to ensure compliance with debris removal obligations (UNOOSA, 2021).

The Polluter Pays Principle (PPP) has been widely adopted in environmental economics as a mechanism to internalize externalities—imposing financial responsibility on entities that contribute to pollution (Tilton, 2016). While some scholars advocate for applying PPP-based taxation to space debris, practical implementation remains challenging due to uncertainties in liability attribution and enforcement mechanisms (Macauley, 2015). To address these challenges, a market-based regulatory mechanism—such as a Space Environmental Tax (SET)—has been proposed as a policy instrument to incentivize responsible space operations while funding debris mitigation efforts (Adilov et al., 2020, Leonard and Williams, 2023).

This study investigates the feasibility of implementing a Space Environmental Tax (SET) as a policy tool for sustainable space governance. By imposing a tax on space launches, SET aims to internalize the environmental costs of debris generation and create a financial mechanism for funding debris removal.

2. Literature Review

2.1 Economic Perspectives on Space Debris Management

The issue of space debris represents a classic case of negative externalities, where the costs associated with orbital congestion, increased collision risks, and debris mitigation efforts are disproportionately borne by third parties rather than the entities generating the debris (Yoshida & Araki, 1994; Macauley, 2015; Weeden & Chow, 2012). This externality problem has resulted in free-rider behavior, wherein private and governmental actors benefit from access to space while lacking sufficient incentives to contribute to debris mitigation initiatives (Adilov et al., 2020; Adilov et al., 2022; Nozawa et al., 2023).

Historically, space development has been characterized by government-led initiatives, with funding primarily sourced from national budgets (Minato et al., 2023a). While previous research has focused on debris removal technologies (Forshaw et al., 2017) and legal frameworks for cost allocation (Macauley, 2015), relatively little attention has been given to financial resource mobilization for long-term debris mitigation (Adilov et al., 2020; Adilov et al., 2022; Zhu, 2022; Nozawa et al., 2023). As private-sector participation in space activities grows, reliance on national funding mechanisms alone is no longer adequate, necessitating a sustainable cost-sharing system (Sheer & Li, 2019; Minato et al., 2023b).

Economic models addressing these externalities have proposed several solutions. The Polluter Pays Principle (PPP), widely applied in terrestrial environmental policy, suggests that entities responsible for pollution should bear the costs of mitigation (Hardin, 1968; Tilton, 2016). While theoretically applicable to space activities, its implementation remains challenging due to difficulties in tracking debris origins and enforcing compliance across multiple jurisdictions (Macauley, 2015; Weeden, 2011; Weeden and Chow, 2012).

Market-based mechanisms have also been explored to incentivize debris mitigation, including auction-based removal contracts, performance-based subsidies, and liability-sharing schemes (Pelton., 2015; Adilov et al., 2020; Adilov et al., 2022). However, the effectiveness of such mechanisms depends heavily on global regulatory coordination, which remains fragmented due to differing national interests and regulatory frameworks (Bastida Virgili et al., 2016; Sheer & Li, 2019).

A more structured approach, the Space Environmental Tax (SET), has been proposed as a means of internalizing the costs of space debris management (Minato et al., 2023a, 2023b). Environmental taxation is widely recognized as an effective tool for managing external diseconomies, such as pollution (Beal et al., 2020; Karmaker et al., 2021). Prior research has confirmed that environmental taxes can generate financial resources (World Bank) while also inducing voluntary mitigation measures. Taxation secures dedicated funding for environmental initiatives and encourages companies to adopt sustainable practices due to increased financial obligations (Guan et al., 2025). These dual effects suggest that a space environmental tax (SET) holds strong potential for enabling autonomous space environmental conservation.

However, economic and policy challenges must be addressed. High tax rates may impede economic activities, and taxes imposed on specific industries or regions could drive companies to relocate, limiting long-term impact (Macauley, 2015). While national and regional environmental taxation models have been successfully implemented (Murray and Rivers, 2015; Anderson, 2019), global-scale applications remain rare. To support international policy discussions, the effectiveness of SET in achieving global sustainability goals must be empirically demonstrated.

2.2 Technical and Policy Challenges in Space Debris Mitigation

While economic solutions are essential for long-term sustainability, space debris mitigation efforts have traditionally been dominated by technical and policy approaches. Current strategies primarily fall into three categories: collision avoidance, passive mitigation, and active debris removal.

Collision avoidance strategies utilize ground-based tracking and onboard maneuvering to prevent spacecraft-debris collisions (Madonna, 2023). However, as the number of satellites in orbit continues to grow, such maneuvers become increasingly complex and costly, consuming significant onboard fuel resources (Schaub et al., 2015; Krag et al., 2018).

Passive mitigation techniques involve design modifications, such as low-fragmentation materials and controlled deorbiting, to reduce the probability of debris generation (Anselmo et al., 1999; Yan, 2023). However, compliance with such measures remains largely voluntary, with no binding enforcement mechanisms in place (Klinkrad, 2006).

Active Debris Removal (ADR) has been proposed as a technological solution to remove existing debris from orbit. Concepts such as robotic arms, tethered capture, and laser ablation have been explored (Liou, 2011; Forshaw et al., 2017; Svotina, 2024). Despite promising technological advancements, ADR faces significant financial and legal hurdles. The high costs associated with debris removal, coupled with uncertainties regarding liability and potential military applications, have hindered widespread adoption (Sheer & Li, 2019; NASA, 2023).

While these technical solutions mitigate immediate risks, they fail to address the underlying financial responsibility for debris management. Without a sustainable funding mechanism, large-scale debris removal remains economically unviable, underscoring the need for an economic framework that incentivizes sustainable space activities (Salter, 2016).

2.3 Legal and Regulatory Barriers to Economic Solutions

The governance of space debris is primarily dictated by international treaties such as the Outer Space Treaty (1967) and the Liability Convention (1972) (UNOOSA, 2021). However, these agreements were established before the rapid commercialization of space and lack explicit provisions regarding financial responsibility for debris mitigation (Jakhu & Pelton, 2017; Sheer & Li, 2019).

A major limitation of current space law is the absence of binding obligations for debris mitigation. While international guidelines exist, enforcement mechanisms are weak, making adherence largely voluntary (Schrogl et al., 2011; Smith et al., 2024). Additionally, unlike terrestrial environmental regulations, outer space lacks a central governing authority capable of imposing global taxation or regulatory measures (UNOOSA, 2021; Manoli, 2024).

2.4 Research Gaps and Contributions

To achieve sustainable space environmental conservation, a long-term, balanced taxation framework is essential. Without a systematic study that designs and evaluates SET, international discussions on taxation in space governance cannot advance. This study aims to determine whether a space environmental tax can simultaneously (i) support continued space development, (ii) reduce space debris, and (iii) contribute to the sustainable utilization of space.

3. Methodology

3.1 Analytical Approach

This study adopts a system dynamics (SD) modeling approach to analyze the feasibility and effectiveness of a Space Environmental Tax (SET) as a policy tool for space debris mitigation. System dynamics is a computational modeling methodology designed to examine complex, interdependent systems that exhibit feedback loops and time delays (Forrester, 1971; Sterman, 2000). Given that the space environment involves long-term interactions between satellite launches, debris generation, and policy interventions, SD provides a suitable framework for evaluating the long-term impacts of taxation on orbital sustainability.

The primary objectives of this study are threefold. First, the study aims to simulate the long-term impact of SET on orbital debris accumulation, focusing on the effectiveness of financial incentives in reducing space debris. Second, the study examines the economic effects of SET on spacefaring entities, particularly launch operators and active debris removal service providers. Third, the research investigates the dynamic interactions between taxation, debris mitigation, and the growth of the space industry, considering various taxation rates and policy scenarios.

To achieve these objectives, the study follows a three-phase methodological approach. In the first phase, a conceptual system model is developed to represent the key interactions between space activities, debris accumulation, and taxation mechanisms. In the second phase, a quantitative SD model is constructed using stock-flow diagrams and mathematical equations to capture system behaviors over time. Finally, in the third phase, simulation experiments and sensitivity analyses are conducted to assess the effectiveness of SET under different policy conditions and taxation rates.

3.2 Dynamic Hypothesis (Causal Loop Analysis)

The core dynamics of orbital debris can be understood through the lens of system feedback, as illustrated in the causal loop diagram (Figure 2). We can conceptualize the system through a set of interacting balancing loops. Voluntary Launch Control (B1) loop suggests that as orbital congestion increases, operators should reduce launches due to the higher risk and cost. Similarly, Voluntary Debris Removal (B2) loop assumes that as debris levels rise, cleanup activities will naturally increase.

However, a critical point is that these two loops rely on voluntary actions, which are often insufficient due to the lack of economic incentives. In this study, we focus on two policy-based balancing loops. 'Launch Demand Decline' (B3) loop introduces the Space Environmental Tax, which increases launch costs and consequently reduces launch demand. 'Debris Removal Acceleration' (B4) loop uses the tax revenue to subsidize debris removal, reducing its cost barrier. Together, these two loops form a dynamic framework where SET internalize the environmental costs of space activities.

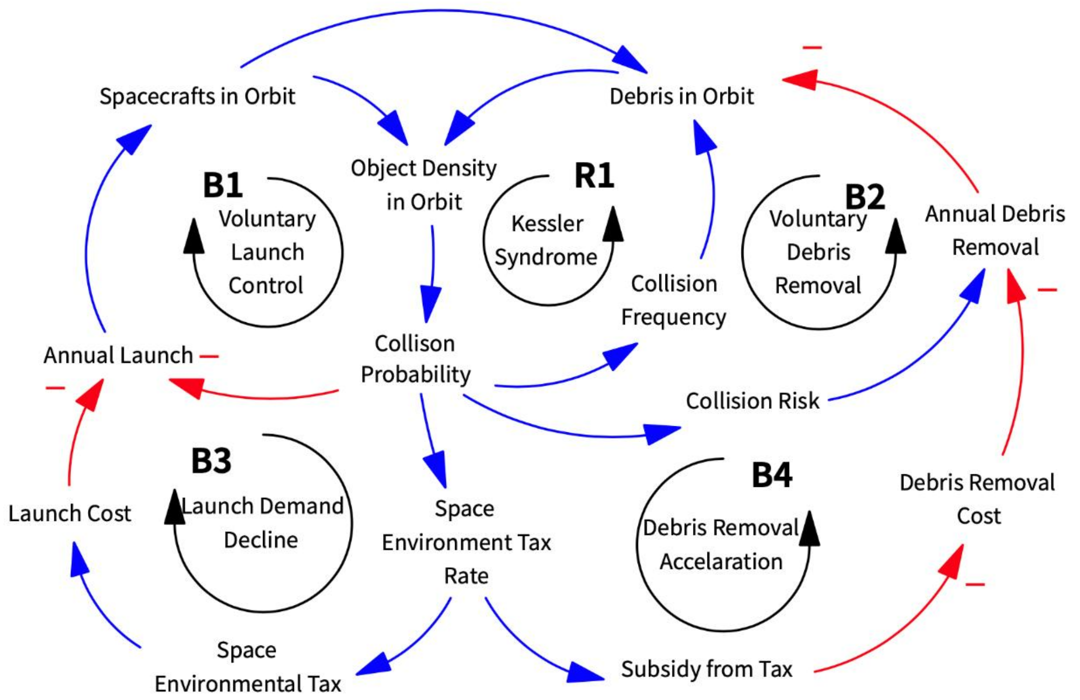

Figure 2 Balancing Feedback Loops (B3 and B4) introduced by SET Policy

Finally, it is crucial to acknowledge the latent self-reinforcing (R1) loop in the system. The most dangerous one is the debris generation due to cascading collisions. Without strong, proactive policy-based feedback control mechanisms (whether voluntary or policy-based), this reinforcing feedback loop may dominate the system over time, leading to exponential growth of debris and eventual loss of orbital usability (the Kessler Syndrome).

In this study we hypothesize that, in the absence of proactive policy, the orbital environment is susceptible to a reinforcing dynamic where growing collisions lead to further debris generation, thereby creating a self-reinforcing loop of orbital degradation. To explore this hypothesis, the following sections develop a system dynamics model incorporating launch taxation and debris removal subsidies, simulate policy scenarios, and assess their impact on long-term debris population.

3.3 Model Design

3.3.1 Stock variables in the model

The stock-flow structure of the system dynamics model (Figure 4) is developed to replicate the process of spacecraft launches, debris generation, debris mitigation, and taxation-based interventions. The model comprises four key stock variables (Table 1), which capture fundamental dynamics of the orbital environment.

Table 1 Stock variables in the model

Name of variable	Notation	Explanation	Unit
Number of Spacecraft	S	Represents the total number of active satellites in orbit. This stock increases as new satellites are launched and decreases when satellites are either retired or actively removed from orbit.	Object
Number of Space Debris	D	Represents the cumulative number of debris in orbit. This stock increases as new debris fragments are generated through launch, satellite fragmentation and collisions, and decreases as debris is removed from orbit through natural decay or ADR operations.	Object
Space Environmental Tax Fund	T	Represents the financial resources collected through the SET mechanism. The tax revenue is collected from launch operators and is partially allocated to subsidies for debris removal services.	Million Dollar
Space Environmental Tax Rate	τ	Represents the tax imposed on each launch. This tax rate is dynamically adjusted based on debris accumulation levels, ensuring that higher debris densities lead to increased taxation.	Dimensionless (Dmnl)

3.3.2 Expected dynamics in the model

Once launched, spacecraft remain in orbit for a certain period, and if post-mission disposal (PMD) is not properly conducted at the end of their operational lifespan, they ultimately become orbital debris. While debris in low Earth orbit (LEO) can gradually decay due to atmospheric drag, this process is exceedingly slow and insufficient for resolving short-term orbital congestion. In this regard, ADR services are expected to play an increasingly important role as a complementary measure. The debris removed through ADR is subtracted from the total orbital debris count, thereby directly contributing to the improvement of the orbital environment.

The model also includes a mechanism in which a portion of the SET revenue paid by space companies is redistributed as subsidies to offset debris removal costs. These subsidies reduce the financial burden of ADR services, incentivizing service providers to expand their debris removal operations. As a result, the pace of debris removal accelerates, leading to a reduction in the overall number of orbital debris. This mechanism enhances the effectiveness of debris mitigation efforts while maintaining a balance between space development activities and space environmental conservation.

Furthermore, the model incorporates a function to calculate the generation of new debris resulting from collisions between orbital objects based on the number of spacecraft and debris present in orbit. An increase in collision risks leads to additional debris formation, which in turn heightens the demand for debris removal, prompting adjustments in the space environmental tax rate. The tax rate is dynamically modified in response to changes in the amount of debris, thereby influencing the expansion or contraction of space development programs through launch costs. This tax adjustment mechanism serves as a crucial policy instrument for maintaining orbital sustainability while ensuring that the growth of the space industry is not excessively constrained.

To ensure a realistic simulation, the model accounts for significant historical orbital events that have had a substantial impact on the space environment. Specifically, the 2007 Chinese anti-satellite (ASAT) test and the 2009 Iridium-Cosmos satellite collision were incorporated into the scenario. These events significantly increased the number of orbital debris and have been widely recognized as severe threats to the sustainability of the space environment (Secure World Foundation, 2012a; 2012b). To accurately replicate these abrupt events, the PULSE function was utilized within the model to replicate the sudden surge in the number of debris caused by these catastrophic collisions. The PULSE function enables the introduction of large-scale, transient changes at specific time points, effectively simulating the sudden surge in debris generation observed in 2007 and 2009. This approach allows for a detailed analysis of how unexpected debris-generating incidents impact the total debris count, tax rates, and the financial reserves allocated for debris removal, providing valuable insights into the long-term implications of space environmental management policies.

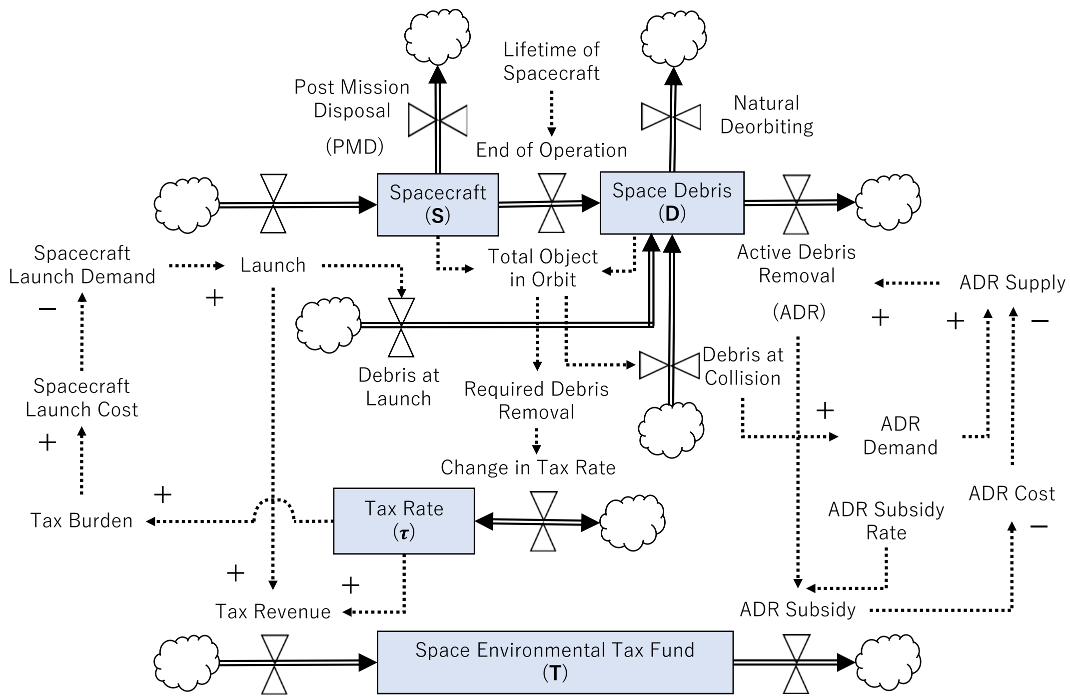

Figure 3 Model overview

3.3.3 Mathematical Representation of the Model

The dynamic behavior of the system is expressed through a set of differential equations, which model the accumulation of spacecraft and debris, tax revenue collection, and tax rate adjustments.

The accumulation of spacecraft in orbit is defined by the following equation:

$$S_t = S_{t-1} + L_t - R_t \tag{1}$$

where S_t represents the number of active spacecrafts at time t, L_t denotes the number of new satellite launches, and R_t corresponds to the number of retired or deorbited satellites.

Similarly, debris accumulation is modeled as follows:

$$D_t = D_{t-1} + F_t - R_d \tag{2}$$

where D_t represents the number of debris objects at time t, F_t is the number of new debris fragments generated, and R_d is the number of debris objects removed through ADR or natural decay.

The total tax fund at any given time is computed as follows:

$$T_t = T_{t-1} + \tau \cdot L_t - S_d \tag{3}$$

where is the space environmental tax rate, and S_d represents the subsidy allocation for debris removal services.

The tax rate is dynamically adjusted based on the level of debris in orbit, ensuring that tax rates rise as debris accumulation increases. The adjustment follows:

$$\tau_t = \tau_{t-1} + \alpha\left(D_t - D_{target}\right) \tag{4}$$

where α is the policy adjustment parameter, and D_{target} represents the target debris level required for sustainable space operations.

Debris Removal Dynamics

The Debris Removal per Year is calculated using Equation (5), which accounts for changes in removal costs due to subsidies and the price elasticity of debris removal.

$$\begin{aligned} &Debris\ Removal\ per\ Year \\ &\quad = Annual\ Debris\ Removal\ Target \\ &\quad \times \left(1 + \frac{Subsidy\ for\ Removal}{Average\ Price\ of\ Debris\ Removal}\right) \\ &\quad \times Price\ Elasticity\ of\ Debris\ Removal\ Demand \end{aligned} \tag{5}$$

The Annual Debris Removal Target is determined by dividing the total number of debris objects by the target period for complete debris disposal (Equation 6). This approach assumes that the number of debris removed annually depends on the desired timeline for achieving a fully clean orbital environment.

$$Annual\ Debris\ Removal\ Target = \frac{Number\ of\ Space\ Debris}{Target\ Period\ of\ Total\ Debris\ Disposal} \tag{6}$$

Taxation Framework

The Required Tax Rate is derived using Equation (7), which establishes a proportional relationship between debris removal costs and launch costs. The model assumes that tax revenues should fully offset the cost of debris removal over the long term. A policy lever (switch) is introduced to control tax activation: when activated, its value is set to 1; otherwise, it remains at 0.

$$Required\ Tax\ Rate = \frac{Average\ Price\ of\ Debris\ Removal\ \times Expected\ Debris\ Removal\ per\ Year}{Average\ Price\ of\ Launch\ \times Expected\ Launch\ Demand} \times Policy\ Lever \quad (7)$$

To avoid sudden fluctuations, the Space Environmental Tax Rate is adjusted gradually using a Tax Rate Change function, which modulates inflow and outflow to maintain consistency with the required tax rate. A Time to Adjust Tax Rate parameter ensures smooth transitions.

Tax Fund Management

The Space Environmental Tax Fund is a stock variable that accumulates tax revenue (inflow) and is depleted by tax expenditures (outflow). Tax Revenue is computed based on the number of launches and the tax per launch, which is determined by multiplying the Average Price of Launch by the Space Environmental Tax Rate. Tax Expenditure covers the cost of debris removal subsidies and is withdrawn from the fund accordingly. If the fund balance is insufficient, expenditures are capped at the remaining tax fund balance. Decision rules governing fund allocation and tax expenditures are implemented using the IF-THEN-ELSE function.

Launch Demand Adjustments

The Actual Price of Launch is determined by adding the baseline launch price and the tax per launch. The subsequent change in launch demand is calculated using Equation (8), which accounts for the effect of tax-induced price fluctuations and the price elasticity of launch demand.

$$Change\ in\ Launch\ Demand = \left(\frac{Actual\ Price\ of\ Launch}{Average\ Price\ of\ Launch} - 1\right) \times Price\ Elasticity\ of\ Launch\ Demand \quad (8)$$

To prevent abrupt demand fluctuations, the Expected Launch Demand is smoothed over time using Equation (9).

$$Expected\ Launch\ Demand = SMOOTH\ (Average\ Launch\ Demand\ \times (1 - Change\ in\ Launch\ Demand, Launch\ Demand\ Adjstment\ Time) \quad (9)$$

4. Simulation Design and Assumptions

To evaluate the long-term effectiveness of a Space Environmental Tax (SET) in mitigating orbital debris, a system dynamics simulation model is developed using VENSIM 10 (Figure 4). The simulation period spanned 66 years, from 1957 to 2022, and validation data were sourced from NASA's Orbital Debris Charts (March 2023). The time unit (t) of the model is set in years in this simulation. The model incorporates both a baseline scenario (Without SET) and a policy intervention scenario (With SET) to compare the effects of taxation on space debris accumulation and industry sustainability. Additionally, sensitivity analyses are conducted to assess the robustness of the findings under varying tax rates, subsidy levels, and debris removal adoption rates.

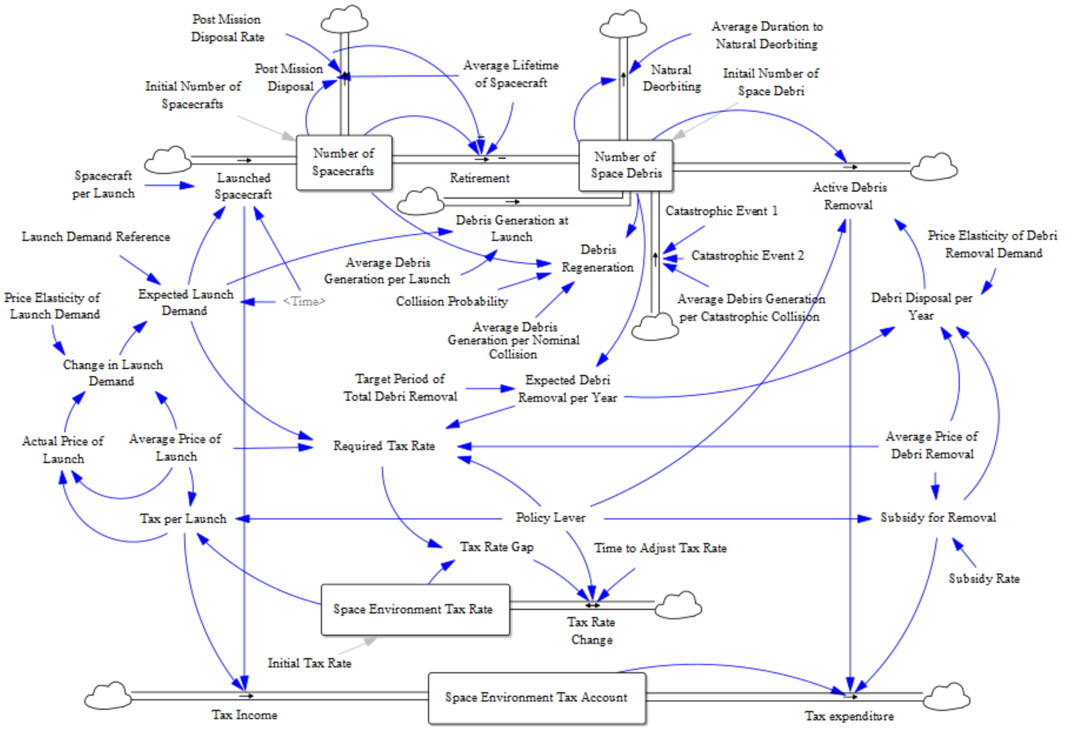

Figure 4 Stock and flow diagram (developed with VENSIM 10)

4.1 Baseline Scenario (Without SET)

In the baseline scenario, it is assumed that no taxation mechanism is introduced, and space debris continues to accumulate following historical trends. This scenario reflects the status quo in which space operators face no direct financial incentives to implement debris mitigation measures. The key assumptions for this scenario are as follows:

- Launch Rates: The annual number of satellite launches is determined based on historical data from NASA and other space agencies, following current industry trends.

- Debris Generation: The probability of collision-induced debris formation is estimated to be low while the number of debris objects is escalated by the deliberate anti-satellite tests and accidental satellite collisions, which are replicated using the PULSE function.
- Debris Removal: The adoption of Active Debris Removal (ADR) remains low, as there are no financial incentives for operators to engage in voluntary debris mitigation efforts.
- Economic Factors: Space development continues without additional regulatory constraints, meaning that launch operators are primarily concerned with cost efficiency rather than environmental sustainability.

Under this scenario, space debris accumulation is expected to follow historical growth patterns, potentially leading to increased collision risks and a worsening of the Kessler Syndrome, wherein collisions generate further debris, making certain orbital regions unsuitable for future operations.

4.2 Policy Intervention Scenario (With SET)

In contrast, the policy intervention scenario introduces the Space Environmental Tax (SET) to internalize the costs of debris generation and provide financial incentives for debris mitigation. In this scenario, launch operators are required to pay a tax proportional to their projected contribution to space debris, and the revenue generated is partially allocated to subsidies for ADR services. The key assumptions for this scenario are as follows:

- Dynamic Tax Rate: The tax rate is adjusted based on debris accumulation levels, increasing when orbital congestion rises and decreasing when mitigation efforts successfully reduce debris levels.
- Revenue Allocation: 50% of tax revenues are allocated to subsidizing ADR operations, lowering the cost barrier for companies engaged in active debris removal.
- Launch Demand Elasticity: The model accounts for changes in launch demand in response to increased launch costs due to taxation, ensuring that the economic impact on space development is considered.

The introduction of SET is expected to lead to a reduction in debris accumulation, as economic incentives encourage responsible space operations while also funding large-scale debris removal efforts. By dynamically adjusting tax rates in response to debris levels, SET serves as a regulatory mechanism to balance economic growth with orbital sustainability.

5. Model Validation

The baseline parameter settings for the model are summarized in Table 2. The initial values for both the number of spacecraft and the number of orbital debris were set to zero, corresponding to conditions in 1957. The demand for rocket launches was determined based on historical data, specifically the global number of rockets launches to orbital space from 1957 to 2022.

The price elasticity for both launch demand and debris removal demand was set at 0.9. Price elasticity quantifies the sensitivity of demand fluctuations in response to price variations. In this context, it represents the extent to which increased tax burdens influence launch costs and how subsidies affect debris removal costs and subsequent changes in demand.

The space environmental tax (SET) was computed based on launch costs and the tax rate, with the assumption that the financial burden would be borne by launch operators. The baseline subsidy rate for ADR was set at 0.5, indicating that 50% of ADR operation costs would be covered by revenue generated from space environmental tax. This subsidy structure directly impacts the supply of ADR services, incentivizing debris removal efforts and contributing to the overall sustainability of the orbital environment.

Table 2 Baseline model parameter settings

Name of variable	Value	Unit
Initial Number of Spacecrafts	0	Object
Initial Number of Space Debris	0	Object
Average Years of Operation	20	Year
Average Duration to Natural Deorbiting	30	Year
Target Period of Total Debris Removal	50	Year
Average Price of Launch	100	Million Dollar
Average Price of Debris Removal	10	Million Dollar
Collision Probability	0.0000001	Dmnl
Average Debris Generation per Launch	3.2	Objects/Launch
Average Debris Generation per Nominal Collision	10	Objects/Collision
Average Debris Generation per Catastrophic Collision	3500	Objects/Collision
Post Mission Disposal Rate	0.3	Dmnl
ADR Subsidy Rate	0.5	Dmnl
Price Elasticity of Launch Demand	0.9	Dmnl
Price Elasticity of Debris Removal Demand	0.9	Dmnl

To assess the validity of the constructed model, a trial simulation was conducted using the baseline parameter values specified in Table 2, which are either drawn from the previous study (Minato et al., 2023), selected for simplification to isolate the effects of policy interventions, or calibrated to align the model behavior with reference data. The simulation period spanned 66 years, from 1957 to 2022, and validation data were sourced from NASA's Orbital Debris Charts (NASA, 2025).

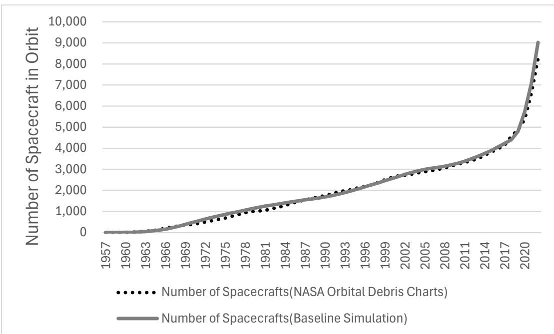

Figure 5a Spacecraft in orbit

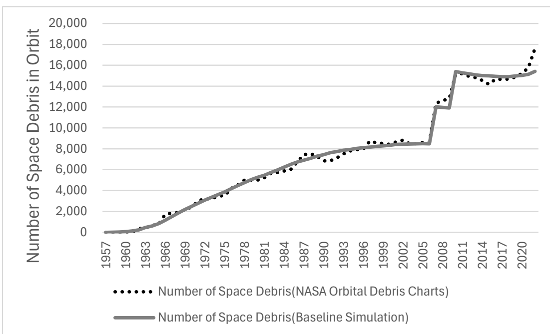

Figure 5b Debris in orbit

A comparison between the model's baseline simulation outputs and empirical data published by NASA is presented in Figure 5a (spacecraft) and Figure 5b (debris). Note that the surge in the number of spacecrafts observed in Figure 5a reflects the trend in launch demand, as the model incorporates reference data to reproduce historical launch activities. These results indicate that the model's stock variables, namely the number of spacecraft and orbital debris, accurately reproduce the time-series trends observed in the validation dataset. Moreover, the coefficient of determination (R^2) was calculated as 0.995 for the number of spacecraft and 0.993 for the number of orbital debris, thereby confirming the robustness and behavioral validity of the proposed model.

6. Results and Discussions

This section presents the findings from the 66-year simulation (1957–2022) conducted to evaluate the impact of the Space Environmental Tax (SET) on space activities and orbital debris mitigation. The analysis compares the Without SET scenario (baseline) and the With SET scenario (policy intervention) to assess the effectiveness of taxation in regulating satellite launches, reducing orbital debris, and incentivizing active debris removal (ADR). The discussion also explores the dynamic nature of tax rate adjustments and their implications for long-term space governance.

6.1 Impact of SET on Spacecraft Accumulation

The simulation results indicate a clear difference in spacecraft accumulation trends between the two scenarios (Figure 6). In the Without SET scenario (red solid line), no external interventions are imposed, resulting in a steady and unrestricted increase in the number of spacecrafts in orbit. This trend follows historical growth patterns, reflecting the continued expansion of global space activities driven by increasing commercial and governmental satellite deployments.

By contrast, in the With SET scenario (blue dotted line), the number of spacecrafts in orbit exhibits a downward deviation from the baseline trend over time. This shift is primarily attributed to higher launch costs imposed by the environmental tax, which leads to a moderation of new launch activities. The financial burden associated with taxation discourages excessive satellite deployments, compelling operators to optimize their launch strategies by extending satellite lifetimes, improving end-of-life disposal, and adopting alternative mission architectures.

However, an important observation is that the introduction of SET does not entirely suppress space industry growth. Despite the reduction in launch frequencies, the overall number of spacecrafts continues to increase over time, albeit at a more controlled rate. This suggests that, within the current simulation parameters, the tax burden is appropriately calibrated, allowing for sustained industry growth while promoting more responsible space operations.

The results highlight the potential of SET as an effective economic tool to regulate the pace of spacecraft accumulation without imposing severe restrictions on space industry development. Policymakers should consider implementing a flexible taxation model that adjusts based on real-time space traffic congestion levels, ensuring a balance between economic growth and environmental sustainability.

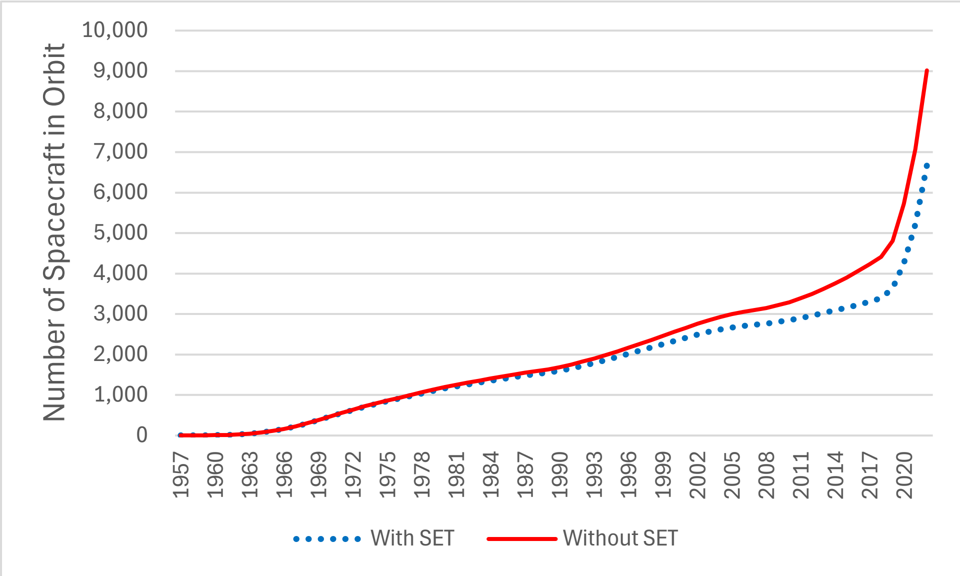

Figure 6 Impact of SET on Spacecraft Accumulation

6.2 Impact of SET on Orbital Debris Accumulation

The findings also reveal a substantial reduction in orbital debris accumulation in the With SET scenario, compared to the baseline (Figure 7). In the Without SET scenario (red solid line), debris continues to grow exponentially, driven by increasing satellite launches and frequent collision events. As the density of objects in orbit rises, the probability of debris-debris collisions increases, accelerating the onset of the Kessler Syndrome, where fragmentation events trigger an uncontrollable cascade of additional debris generation.

In contrast, the With SET scenario (blue dotted line) exhibits a notable decline in orbital debris over time. The taxation mechanism helps mitigate debris accumulation through two key pathways:

- Reduction in debris generation – By discouraging excessive launches, SET reduces the rate of new debris production, preventing unnecessary congestion in orbital regions.
- Increase in active debris removal (ADR) – A portion of tax revenues is allocated to subsidies for ADR services, enabling more frequent removal of large debris objects that pose a high risk of fragmentation.

The combined effect of lower debris generation and enhanced mitigation efforts leads to a stabilization of the orbital environment, improving the overall sustainability of space activities. The results emphasize the importance of integrating economic policies into space governance. While traditional technology-driven approaches (e.g., debris shielding and passive deorbiting) have struggled to address long-term debris proliferation, SET provides a viable financial mechanism that promotes self-sustaining debris mitigation efforts.

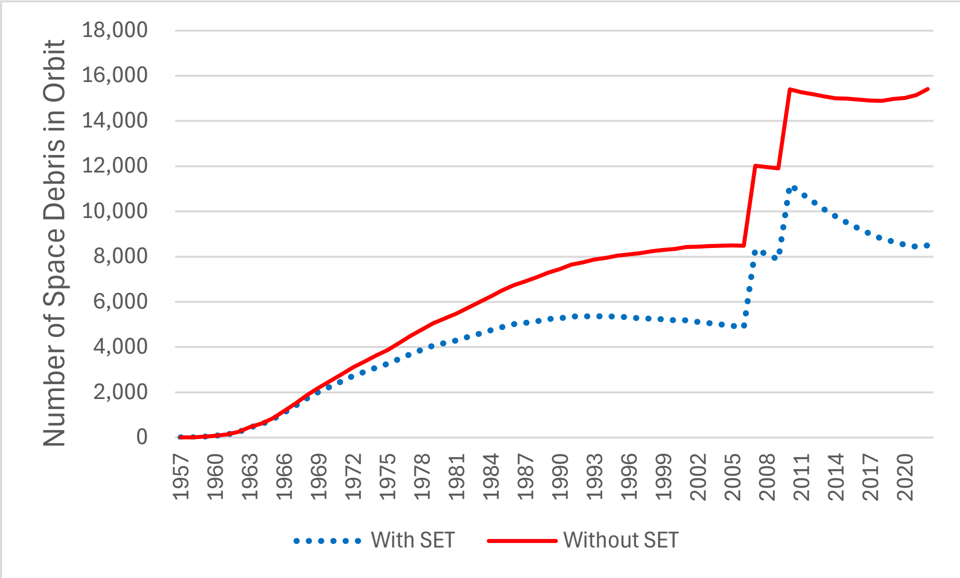

Figure 7 Impact of SET on Orbital Debris Accumulation

6.3 Influence of SET on Active Debris Removal (ADR)

A critical insight from the simulation is the role of SET in stimulating the adoption of Active Debris Removal (ADR) services (Figure 8). In the Without SET scenario (red solid line), ADR remains financially unviable, as debris removal operations incur high costs without direct economic returns. As a result, commercial ADR efforts remain underdeveloped, leading to limited improvements in debris mitigation.

In the With SET scenario (blue dotted line), however, the introduction of tax-funded subsidies significantly enhances ADR adoption rates. Financial support from tax revenues reduces the cost burden on ADR providers, encouraging private-sector investment in debris removal technologies. This creates a positive feedback loop, where increased ADR activity leads to further debris reduction, lowering the risk of future collisions and enhancing orbital safety.

These findings underscore the necessity of integrating market-driven mechanisms to incentivize private-sector participation in debris removal. Policymakers should design subsidy frameworks that ensure predictable revenue streams for ADR providers, thereby stimulating investment in next-generation debris mitigation technologies.

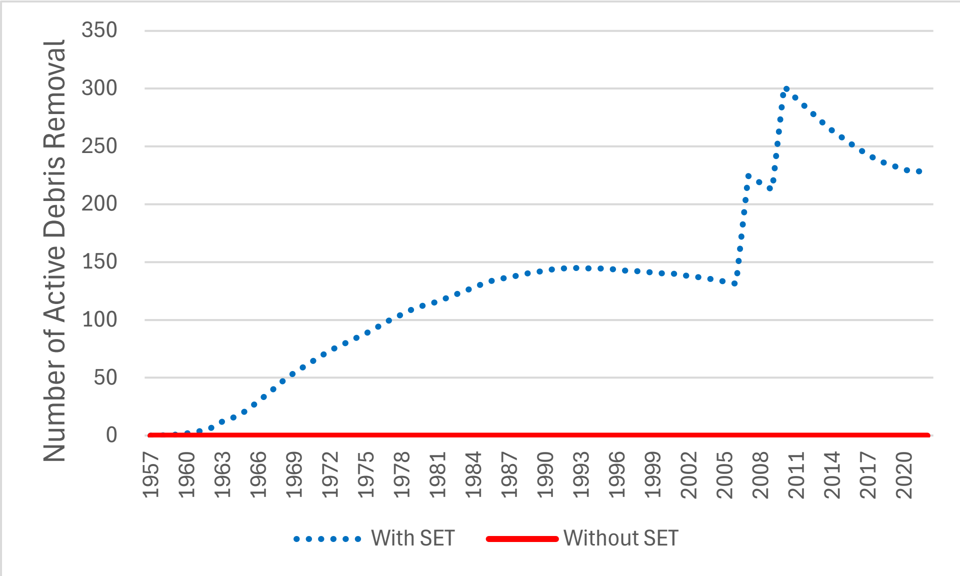

Figure 8 Influence of SET on Active Debris Removal (ADR)

6.4 Dynamic Tax Rate Adjustment Mechanism

One of the most significant findings of the study is the dynamic adjustment function of the space environmental tax rate, embedded within the SET framework. The simulation results, illustrated in Figure 9, indicate that the tax rate remains relatively low during the initial phase of space activities when orbital capacity is abundant. However, as space operations intensify and the number of debris objects increases, the environmental risks associated with space debris escalate, necessitating a gradual increase in the tax rate to secure additional funding for debris mitigation measures.

A particularly notable observation is the sharp increase in the tax rate following major debris-generating events, such as:

- The 2007 Chinese anti-satellite (ASAT) test, which resulted in the fragmentation of a defunct satellite, creating over 3,000 trackable debris fragments (Secure World Foundation, 2012a).
- The 2009 Iridium–Cosmos collision, which generated thousands of additional debris fragments, significantly worsening orbital congestion (Secure World Foundation, 2012b).

Following these events, the space environmental tax rate doubled from its previous level, exceeding 40%, allowing for the rapid mobilization of financial resources to expedite debris removal efforts. As debris removal activities succeeded in reducing orbital congestion, the tax rate was gradually reduced, demonstrating the effectiveness of a dynamically adaptive taxation model.

These findings suggest that a responsive tax structure—which increases in response to environmental crises and decreases following mitigation success—can provide a flexible regulatory tool to manage orbital sustainability. International space governance bodies should explore policy frameworks that integrate dynamic taxation models, ensuring that tax rates remain proportional to real-time space environmental risks.

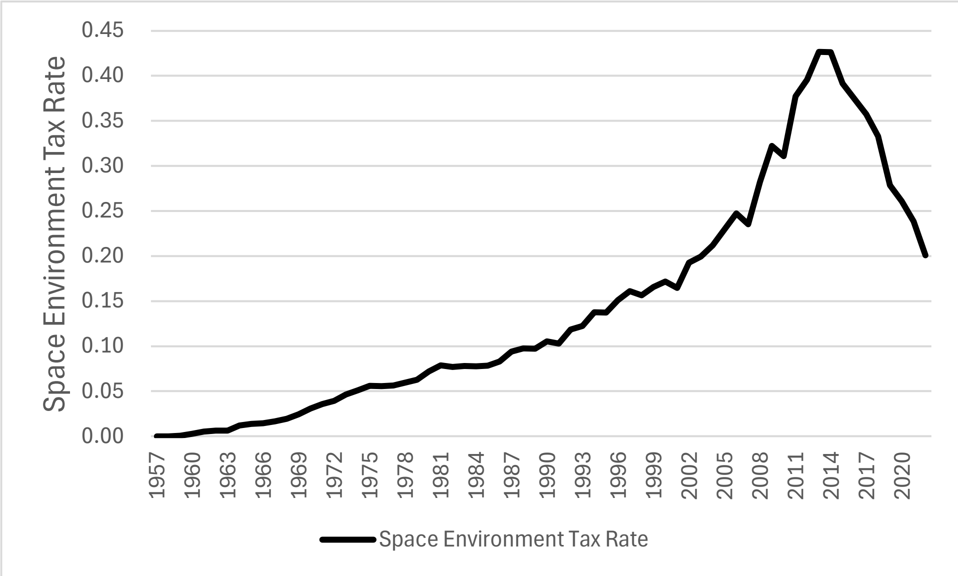

Fig. 9 Tax Rate Adjustment

6.5 Sensitivity Analysis

To ensure the robustness of the findings, a sensitivity analysis was conducted to assess the impact of subsidy rates on the number of spacecraft and space debris in orbit. The analysis explored subsidy levels ranging from 0% to 100%, where 0% indicates no financial support for debris removal, and 100% signifies full coverage of removal costs through the tax revenue. This approach provided insights into how different subsidy levels influence the balance between space development and environmental preservation. The baseline simulation was based on a 50% subsidy rate (Table 2).

Across all tested scenarios (Figure 10), a consistent trend emerged: a gradual decline in the number of spacecrafts in orbit. This finding suggests that the implementation of SET leads to a reduction in the number of operational spacecrafts, regardless of the subsidy level.

The most pronounced effect was observed when the subsidy rate was set to 0%. In this scenario, the absence of subsidies for debris removal reduced incentives for debris mitigation, resulting in a continuous increase in orbital density. The increased congestion led to a rise in the space environmental tax rate, which further elevated launch costs and eventually curbed launch demand.

Interestingly, even in scenarios where debris removal was fully subsidized (100% subsidy rate), a slight decline in the number of spacecrafts was still observed. This outcome underscores the moderating effect of SET on space development activities, illustrating that the tax policy influences industry growth, irrespective of the level of subsidy provided.

The results of the sensitivity analysis on space debris revealed variable behavior when the subsidy rate was set to 0%. Initially, a slight increase in the number of debris was observed, followed by a gradual decline, returning it to its previous level. This pattern suggests that the introduction of SET alone can contribute to stabilizing the space environment, even in the absence of subsidies. However, it is important to note that this apparent stabilization is primarily driven by suppressed launch demand, caused by the increased launch costs associated with SET (as shown in Figure 10).

As a result, adopting a 0% subsidy rate is not an optimal solution for achieving a balance between space environmental conservation and space development. Conversely, all other tested scenarios (20%–100% subsidy rates) exhibited a declining trend in space debris levels.

Notably, at a 100% subsidy rate, the amount of space debris was reduced to nearly half of its initial value. This result suggests that implementing an appropriately structured subsidy mechanism for debris removal can significantly decrease space debris accumulation while simultaneously supporting the continuation of space development.

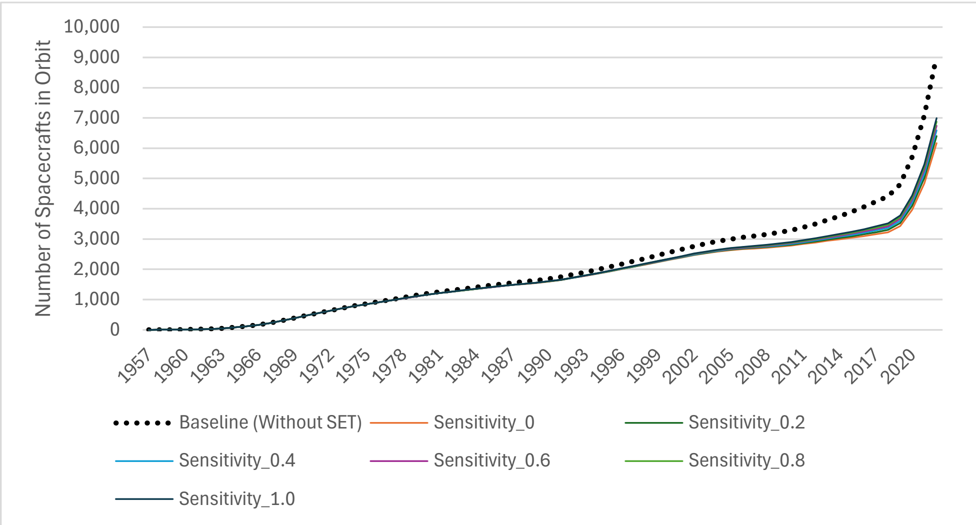

Figure 10 Sensitivity analysis of Subsidy Rate on Number of Spacecraft

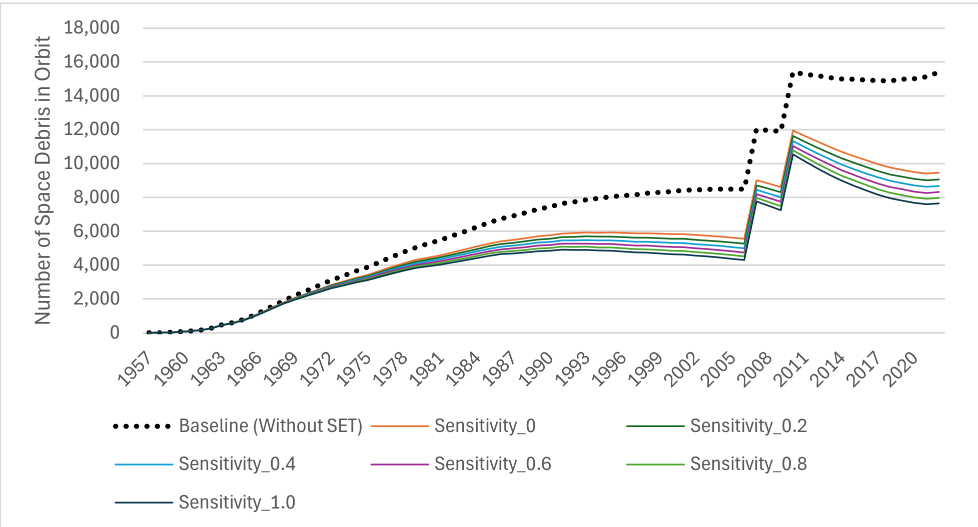

Figure 11 Sensitivity analysis of Subsidy Rate on Number of Space Debris

7. Conclusion

This study investigates the feasibility and effectiveness of implementing a Space Environmental Tax (SET) as an economic mechanism to mitigate orbital debris accumulation and ensure the long-term sustainability of space activities. By integrating taxation and reinvestment mechanisms through system dynamics simulations, this research proposes a novel cost-sharing model that funds Active Debris Removal (ADR) initiatives while simultaneously regulating the growth of satellite launches.

The findings demonstrate that SET effectively reduces the rate of spacecraft accumulation and significantly curbs the proliferation of space debris. The taxation framework increases the cost of satellite launches, leading to a more controlled expansion of space activities, while financial incentives for debris removal encourage commercial investment in ADR services. The results suggest that market-driven policy interventions such as SET can complement traditional technology-based approaches to space debris mitigation, offering a more sustainable governance model for orbital resource management.

A key academic contribution of this study is the introduction of a reinvestment mechanism for tax revenues, which enhances the long-term effectiveness of space environmental taxation. While previous studies (e.g., Macauley, 2015; Adilov et al., 2020; Adilov et al., 2022) have explored theoretical aspects of space taxation, they primarily focused on direct tax effects on debris reduction or the complexity of designing equitable tax systems. In contrast, this study integrates a dynamic reinvestment framework, where tax revenues are strategically allocated to ADR subsidies, creating a self-sustaining economic model for space debris mitigation. Furthermore, by shifting the focus from purely technological solutions to policy-driven economic mechanisms, this research contributes to the broader field of space sustainability governance and provides insights into the role of financial incentives in managing space as a shared global resource.

7.1 Limitations and Future Research

Despite its contributions, this study has several limitations. First, many of the parameter values in the simulation model were estimated based on NASA datasets and historical launch records. While this approach provides a reasonable approximation of real-world trends, it does not fully capture the evolving dynamics of space development and economic fluctuations. Future research should incorporate comprehensive national debris databases and detailed satellite launch records to enhance the model's predictive accuracy.

Second, the methodology for assessing collision risks requires further refinement. The current simulation assumes a uniform and fixed probability of satellite-debris collisions; however, in reality, collision risks vary based on spacecraft size, orbital altitude, spatial density, and temporal fluctuations in debris distribution. To improve the accuracy of risk assessment, future studies should develop dynamic collision probability models that incorporate real-time debris monitoring data from sources such as the U.S. Space Surveillance Network and European Space Agency tracking systems.

Third, legal and regulatory challenges surrounding space taxation and international governance remain unaddressed. According to Article 2 of the Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, outer space is not subject to national appropriation by any means, raising questions about the legitimacy of international taxation on space activities. The implementation of SET would likely require multilateral agreements among spacefaring nations and the establishment of an international regulatory body to oversee tax collection and revenue distribution. Future studies should engage experts in space law, international tax law, and public policy to explore the legal frameworks necessary to enforce space taxation on a global scale.

7.2 Policy Recommendations

The practical implications of this study are significant for international organizations, space policymakers, and private sector stakeholders. With global space activities increasing rapidly, the Inter-Agency Space Debris Coordination Committee (IADC) and United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) are actively debating strategies for space debris mitigation and long-term sustainability. However, the lack of a clear cost-sharing mechanism has been a major barrier to the adoption of global debris removal initiatives. This study proposes that SET can serve as a viable policy instrument by providing a structured financial model that ensures both fair cost distribution and long-term funding stability for debris mitigation programs.

The results suggest that international space governance frameworks should consider integrating environmental taxation policies to complement existing debris mitigation guidelines. Specifically, policymakers should explore:

1. A tiered taxation system – where tax rates vary based on satellite mass, orbital altitude, and mission lifespan, ensuring that larger and riskier satellites contribute more to debris mitigation efforts.
2. A revenue allocation model – where tax revenues are transparently reinvested into ADR programs, incentivizing private sector participation in commercial debris removal services.
3. A global taxation framework – requiring collaborative agreements among spacefaring nations, potentially under the oversight of UNCOPUOS, the IADC, or the OECD to ensure tax compliance and equitable revenue distribution.

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