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A holistic systems thinking approach to space sustainability via space debris management

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A B S T R A C T

This paper explores the concept of space sustainability and its interconnections using systems thinking approaches. This is done by highlighting the importance of multi-disciplinary perspectives when creating policies aimed at addressing the complex challenges of sustainability for space-related activities. Causal loop diagrams are employed to highlight the presence of feedback loops and causal relationships that are typically absent in space debris models and are treated as separate systems. A systems representation of the space environment is presented along with a discussion of its role in furthering research relating to the impact of large satellite constellations on factors important for holistic sustainability. This study investigated one example feedback between the space environment and the atmosphere and found that CO_2 emissions specifically emitted from launches and re-entries have no significant impact on atmospheric density below 500 km.

1. Introduction

The recent decade has seen a substantial rise in launch frequency and satellite spatial density in Low Earth Orbit (LEO) as large constellations of commercial satellites providing a range of services have entered the market. This growth has sparked concerns about the long-term sustainability of space activities, particularly regarding space debris and its potential impact on the safe operation of such a substantial and varied population in the orbital environment.

Multiple international bodies exist to provide research, polices and guidelines to address the growing concern of space debris and promote sustainable practices in space activities. One of the key challenges in space sustainability is the need for informative models and simulations to inform policy decisions regarding space debris mitigation strategies. Many current space debris models primarily focus on either broad-population collisional assessments within the orbital environment, or single-mission-specific life-cycle assessments and demise analysis. Most consider the launch and re-entry of objects to be input and exit points for the model and neglect the existence of feedback loops between environments such as the orbital and atmospheric environments and how that may impact debris assessments and other markers for sustainability. Approaches that ignore feedbacks connected to but existing outside of the space environment are limited in their ability to fully identify and capture the complex dynamics that may drive non-linear behaviour in the wider system. The significance of considering feedbacks has been demonstrated in other sustainable management scenarios such as sustainable water management [1].

To ensure the long-term sustainability of space activities, it is important to consider space debris alongside other environmental metrics. Concerns over the impact of increased space activities on the astronomical community through light pollution interference has led to numerous recent research studies focused on understanding and mitigating these impacts for both terrestrial [2-4] and orbital observatories [5]. The increase in space activities has prompted the establishment of international working groups such as the Satellite Constellation working group (SATCON) as well as international policy discussions to address this issue effectively outside of previously established communities concerned with space sustainability assessment.

Additionally, there has been an increase in research assessing the terrestrial environmental impacts of increased space activities.

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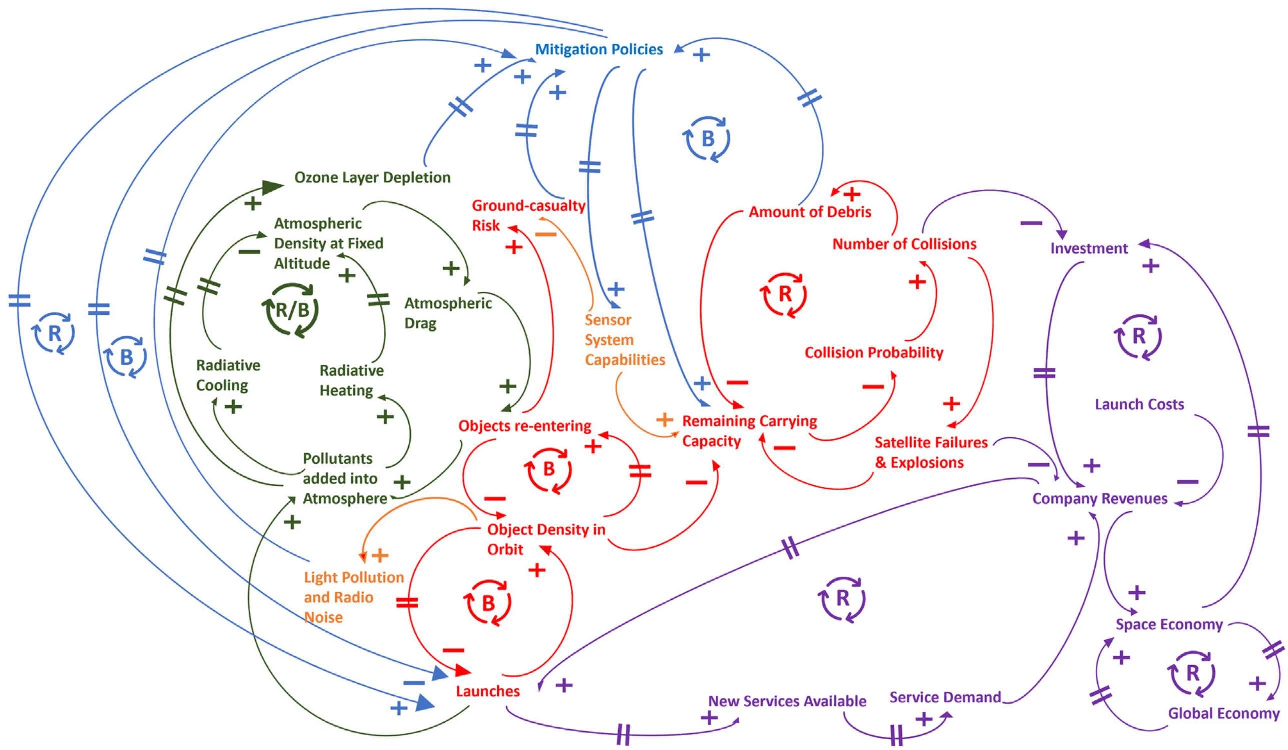

Fig. 1. Causal loop diagram outlining the connections and polarity of relationships between a wide variety of factors linked to the space environment. Colour coding in this figure signifies the predominant grouping for the connections shown. Red signifies the space environment, green signifies the atmospheric environment, purple signifies economics, blue signifies polices and orange signifies sensor systems.

Concern over the consequences of incomplete and uncontrolled object re-entry for human life [6,7], land-based ecosystems and the ocean [8,9], launch emission concerns both locally and atmospherically for disposable and reusable rockets [10,11], ionospheric recovery due to launches [12], ozone layer impacts [13,14] and impacts on stratospheric chemistry [15] have been highlighted in direct relation to the significant upscaling of space activities.

Anthropogenic activities on Earth have also been shown to impact the space environment through reduced atmospheric drag due to atmospheric contraction caused by increasing atmospheric carbon dioxide (CO_2) concentrations [16]. Following potential future increases in ground-level CO_2 due to anthropogenic CO_2 emissions, [17] reports that the resulting atmospheric density reductions will decrease the projected re-entry rate of objects in orbit. Such considerations are important for appropriate planning for post-mission disposal strategies, particularly for spacecraft employing passive decay mechanisms such as drag sails.

A comprehensive evaluation of the interconnecting elements relating to the long-term viability of the orbital environment is challenging because of the broad scope. An initial attempt to capture some of these connections is presented in Fig. 1, which shows a causal loop diagram emphasising the interdependencies amongst a selection of factors in the space sustainability system. The factors chosen in Fig. 1 aim to offer insights into the varied relationships and elements involved in a holistically sustainable space system. While not complete, it provides a baseline system framework for future expansion and analysis and highlights key feedbacks in the system. Fig. 1 illustrates various interconnected variables including space debris, launch activities, re-entry events and risks, sensor capabilities, atmospheric considerations, economics and their connections to mitigation policy formation. In this study, a specific feedback relating CO_2 emissions from launches and re-entries in the space environment to the atmospheric environment is explored using this systems thinking approach.

2. Model framework

2.1. Systems models

Very few examples of systems analysis being applied to the space environment exist in the current literature. Reference [18] is one existing example that explores the use of causal loop diagrams to analyse the behaviour of the space system beyond orbital debris factors including links to policy, social and economic factors. However, [18] does not include any links to atmospheric feedbacks, light or radio pollution, or links to sensor system capabilities. This study presents an extended causal loop diagram, shown in Fig. 1, capturing further interdependencies and feedbacks within the space domain. In Fig. 1, the arrows represent causal relationships between the identified factors in the diagram. These arrows represent an equation or system of equations linking the two variables whereby the polarity symbols '+' and '-' indicate the overall connection behaviour. Connections with positive polarity identify reinforcing behaviour, whereby an increase in the leading variable will elicit an increase in the following variable, and vice versa. Closed reinforcing loops, denoted by 'R' in Fig. 1, describe an escalation of behaviour over time. In contrast, connections with negative polarity indicate that an increase in the leading variable will result in a decrease in the following variable, and vice versa. Balancing feedbacks, denoted by 'B' in Fig. 1, exist when one or many of the variables act to limit the growth of a stock within that loop and influence it to tend to a state of equilibrium. The 'R/B' loop present in the atmospheric section of the causal loop diagram indicates that connection pathways within the closed atmospheric feedback loop can either result in a balancing or reinforcing effect depending on the strength of each connection and the influence of delays in these pathways. Numerical analysis and determination of the equations that govern the behaviour within this type of loop is needed to determine the overall behaviour caused by the feed-

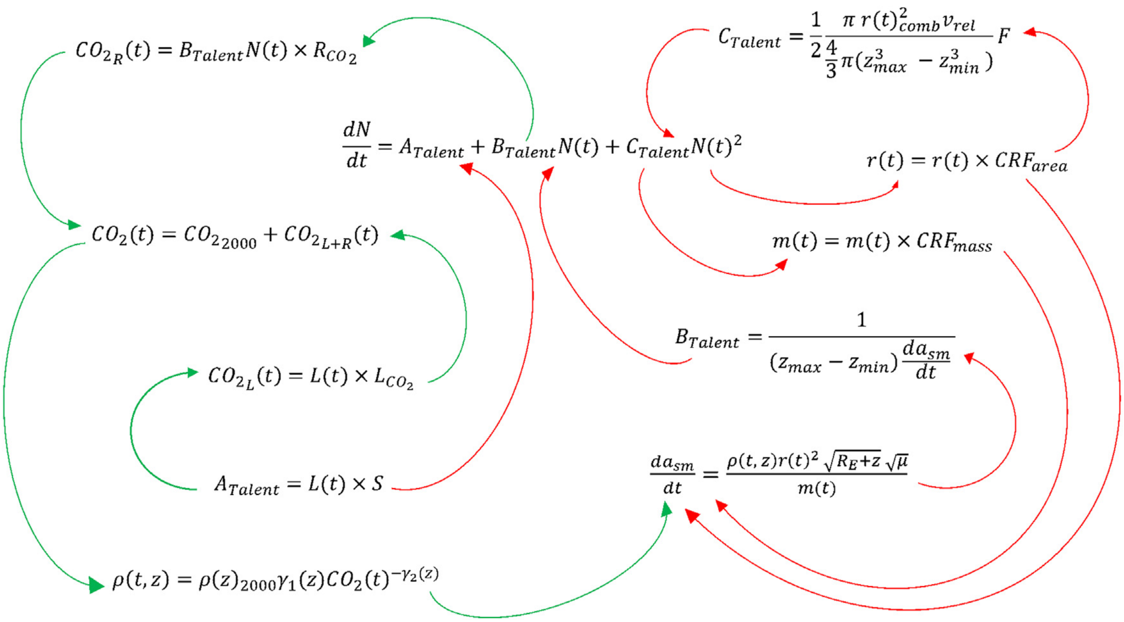

Fig. 2. Diagram displaying the space environment and atmospheric CO_2 feedback loop and the interconnecting equations.

back. This is discussed further in Section 2.2. For the analysis performed in this study focussing on the impacts of CO_2 specifically on atmospheric density, this feedback loop is assumed to be reinforcing and is represented in more detail in Fig. 2. Delays in the system are denoted by double parallel lines in Fig. 1 and indicate that there is a time delay between the occurrence in the change of a leading variable and the impact on the following variable. These delays can influence the behaviour of the system by introducing complex interactions and non-linear relationships that require numerical modelling to understand their long-term impact.

Fig. 1 can be used as an initial framework to build a systems analysis model to investigate complex and non-linear behaviour due to feedbacks and delays that are not currently included in existing models. An example model and discussion of the methodology used to formulate this model from a section of the causal loop diagram is shown in Section 2.2, with the findings presented in Section 3.

2.2. Implementation

The numerical framework for this model analysis is derived from the connections identified in Fig. 1. An equivalent equation-based version of the atmospheric-orbital environment subset for CO_2 emissions is presented in Fig. 2. In Fig. 2, each connection represents a differential equation showing a stock's change over time, which has been used to simulate the behaviour of the system in accordance with orbital propagation techniques outlined by [19]. The model in [19] provided the foundation for the implementation of the systems dynamics modelling approach in this study.

In Fig. 2, A_{Talent}, B_{Talent} and C_{Talent} are the coefficients from the model in [19], $L(t)$ represents the launch function and is described in Eq. (1), and $\rho(z, t)$ is the function for atmospheric density and is outlined in Eqs. (2-4), with parameter t representing time, z representing altitude, and γ_1 and γ_2 representing integers. $N(t)$ represents the number of objects in orbit, $m(t)$ the average mass of all objects in orbit, $r(t)$ the average radius of all objects in orbit, $r(t)_{comb}$ is the combined radii of the colliding objects, $CO_{2_R}(t)$ and $CO_{2_L}(t)$ are the CO_2 contributions from re-entries and launches respectively, $CO_2(t)$ is the ground-level CO_2 concentration, and a_{sm} is the semi-major axis of a representative object in the model. Constants in Fig. 2 are R_E for the radius of the Earth, μ is the Earth's gravitational constant, $CO_{2_{2000}}$ is the ground-level CO_2 concentration in the year 2000 (taken to be 370 parts per million in this study), R_{CO_2} is the amount of CO_2 released per object re-entry, L_{CO_2} is the amount of CO_2 released per launch, v_{rel} is the relative velocity of objects in orbit (taken to be 10 kms^{-1} in this study), F is the number of fragments generated from a collision (taken to be 10 in this study), CRF_{mass} and CRF_{area} are the collision reduction factors for the mass and area of objects due to collisions respectively, and S is the average number of satellites delivered to orbit per launch. Variables z_{max} and z_{min} represent the maximum and minimum altitudes in the altitude band under consideration.

To implement the systems dynamics modelling approach, a representative population of orbiting objects and launch characteristics was used to simulate the population of a single constellation of satellites in LEO. All objects were given an average area and mass of 30 m^2 and 300 kg respectively to approximate SpaceX's V1.5 satellites [20] operating at around 500 km, with 200 km acting as the limiting object re-entry altitude. The launch vehicles used in each simulation case were given a fixed average number of satellites per launch of 45, based on historical SpaceX launch data between May 2019 to October 2023.[1] These launch vehicles each released a fixed amount of CO_2 per launch matching emissions reported from SpaceX's Falcon 9 rocket[2] and Starship rocket with all 6 engines.[3] Specific values for CO_2 outputs per launch from each rocket vary in the literature. However, this study aims to evaluate trends on an order of magnitude level, so this variation does not impact the final conclusions. It was also assumed that launchers only deposit satellites into the environment and discarded rocket bodies were not considered in this model. This is because, as discussed later in this section, data relating to CO_2 inputs into the atmosphere due to re-entries was derived from studies assessing

[1] Jonathan McDowell's Space Pages, https://planet4589.org/space/con/star/stats.html, accessed 30 October 2023.

[2] https://championtraveler.com/news/one-spacex-rocket-launch-produces-the-equivalent-of-395-transatlantic-flights-worth-of-co2-emissions/, accessed 30 October 2023.

[3] https://www.theecoexperts.co.uk/blog/elon-musk-rocket-emitted-358-tonnes-of-co2#:~:text=Elon%20Musk's%20SpaceX%20Starship%20SN15,the%20Office%20for%20National%20Statistics, accessed 30 October 2023.

satellite re-entries only. Additionally, it was assumed that objects are inserted directly into their operational altitude after launch, with no orbit-raising phase as is typical of current constellation operations. The population of objects at the start of the simulation was assumed to be zero to allow for clearer analysis of the impact of the constellation of objects only. This study aimed to illustrate the impact of atmospheric feedbacks on modelled results, rather than making precise predictions about future population trends. As such, this simplified and averaged population and launch treatment was deemed appropriate for this analysis. Furthermore, the use of population and launch characteristics resembling SpaceX's vehicles was solely driven by data availability.

The A coefficient in [19]'s model represents a launch rate. In this study, the Gompertz function represents this variable launch rate. This mathematical function, known for its sigmoid shape, is frequently employed for modelling population growth dynamics, especially when considering the presence of a maximum growth capacity. The generalised Gompertz function is described in Eq. (1),

$$L(t) = d + \left(a - d\right)e^{-be^{ct}} \quad (1)$$

where a is the asymptote, b is the displacement in time, c is the growth rate of the profile, d is the initial baseline value and t is time. The Gompertz function has also been used by SpaceWorks Enterprises when making predictions of trends in the small satellite market [21]. In this context, a sigmoid launch profile represents a launch company's ability to optimise their launch frequency up to a limiting maximum number for a given launch vehicle. The maximum launch rate used for this study was 144 launches per year, which was based on SpaceX's projected launch numbers for the year 2024,[4] representing an average of approximately one launch every 2.5 days. As such, to approximate the launch profile seen by SpaceX up until present day, the coefficients used were $a = 144$, $b = 0.9$, $c = 1.1$, $d = 0$, with the growth profile most variable between 2018 and 2024. The coefficients b and c can be varied without significant influence on the overall model. This is because the simulation timescale is much larger than the profile growth period. Therefore, the most influential coefficient is the peak launch rate, as it remains at its maximum value for a majority of the time during a 100-year simulation.

The coefficient B in [19]'s model is the inverse of an object's orbital lifetime and represents the perturbing effects that decrease its semi-major axis. In this study, the only perturbing effect acting on the orbiting objects is atmospheric drag from Earth's atmosphere. The calculation of atmospheric density variability did not consider solar cycle or geomagnetic variability. Any variability in the atmospheric density was due to CO_2 inputted into the model from launches or re-entries. Atmospheric density variation trends with altitude at 100 km intervals were derived from [16] and are outlined in Eqs. (2-4). Although this model does not account for solar cycle or geomagnetic variability, the results in [16] were obtained from models that accounted for low solar activity $F_{10.7} = 70$ sfu and $K_P = 0.33$ geomagnetic conditions when deriving trends of atmospheric density variability. As such, to remain consistent and ensure that any variations in the modelled population numbers were the result of CO_2 variations from launches and re-entries, baseline atmospheric density values for low solar activity from the MSISE-90 model [22][5] were used. To calculate the lifetime of an object across the full orbital region, the region was split into 100 km bands and the time for an object to decay through each of these bands was calculated. For each band, the mid-altitude atmospheric density value was used as an approximation. For the baseline population case, this atmospheric density was considered constant for each band throughout the simulation. However, for the CO_2 variable case, a reduction factor (described through Eqs. (2-4)) was applied to scale the atmospheric density for each band. An atmospheric contraction factor corresponding to the maximum band altitude was used, which resulted in an overestimation of the atmospheric reduction of the mid-altitude density for each band. The orbital lifetimes for each band were then summed and the inverse was taken to obtain the coefficient B.

$$\rho_{500km} = \rho_{500km_{2000}}\ 202875\ CO_2(t)^{-2.063} \quad (2)$$

$$\rho_{400km} = \rho_{400km_{2000}} 56937 CO_2(t)^{-1.842} \quad (3)$$

$$\rho_{300km} = \rho_{300km_{2000}}\ 7220.9 CO_2(t)^{-1.492} \quad (4)$$

No active lifetime delay was applied so any object added into the environment began to decay immediately. This removal of the delay due to an object's active lifetime allowed for the investigation of the most extreme impact of re-entering objects on the atmosphere, which was the objective of this study. In reality, this delay would have an impact on the system.

To consider a contribution of CO_2 for re-entries, results from the Atmospheric *Re*-entry Assessment (ARA) study [23] were used. This study used nominal and worst-case simulation scenarios, with the worst-case scenario using a population of constellation satellites. As such, data from this worst-case scenario was selected as it better represents the scenario used in this study. From [23], a value of 1100 kg of CO_2 per re-entry event was identified. The characteristics of the satellites used in this study and in [23] differ, likely leading to an overestimate of CO_2 per re-entry for this study. Further analysis is required to determine the specific contribution of CO_2 from re-entering spacecraft into the atmosphere. However, the value of 1100 kg of CO_2 per re-entry was used to illustrate the concept in this study.

The coefficient C represents the collisions that occur within the orbital environment. The equations driving this collisional assessment come from a simplistic Particles In a Box (PIB) evaluation whereby objects with similar characteristics are treated similarly to gas particles colliding in an enclosed space.

The atmospheric drag and number of collisions within the population are also influenced by the objects' masses and cross-sectional areas. As such, changes in these characteristics due to collisional events were considered by implementing weighted averages throughout the population. For each collision event it was assumed that a fixed number of 10 fragments were produced and that each fragment was 10 % of the mass and cross-sectional area of the original objects. This method produces fragments with the same area-to-mass ratio as the original objects, which is unlikely in reality, but is sufficient for the analysis in this study. The weighted average scaling was calculated using the number of new objects introduced with the original characteristics, the number of decayed objects with reduced characteristics and the number of new collisional fragments with reduced characteristics for each time step. The new weighted average mass and area values were then used to calculate the coefficients C and B in the next time iteration.

3. Results and discussion

3.1. Case 1 – Single constellation launch scenario

The population of objects and launch profile in this simulation adhere to those described in Section 2.2, with 336,552 kg of CO_2 emitted per launch (representative of SpaceX's Falcon 9 launch vehicle). In Case 1, a single launch profile is active with a maximum

[4] https://arstechnica-com.cdn.ampproject.org/c/s/arstechnica.com/space/2023/10/next-year-spacex-aims-to-average-one-launch-every-2-5-days/amp/, accessed 30 October 2023.

[5] http://www.braeunig.us/space/atmos.htm, accessed 30 October 2023.

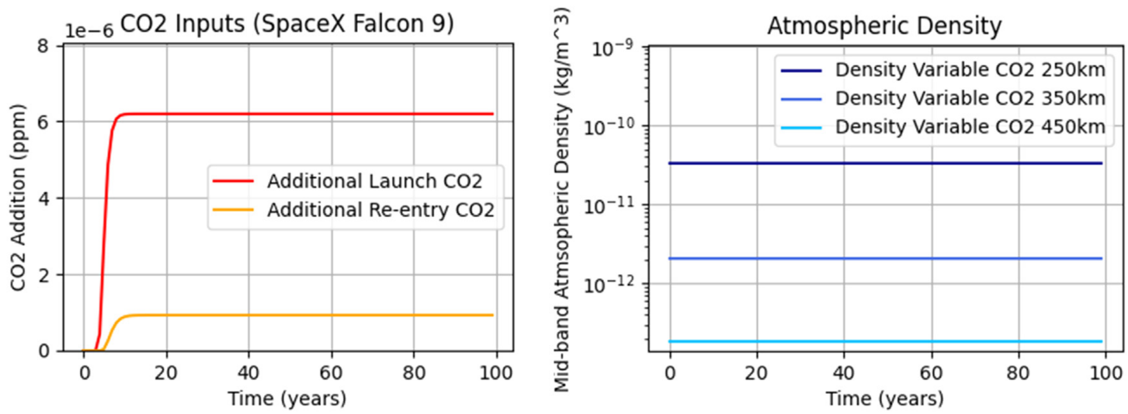

Fig. 3. (Left) CO_2 inputs from launches with SpaceX Falcon 9 rocket populating 1 constellation of satellites and the re-entry CO_2 contributions from these re-entering satellites over time. (Right) Atmospheric density at various altitudes with variable CO_2 concentrations considered over time.

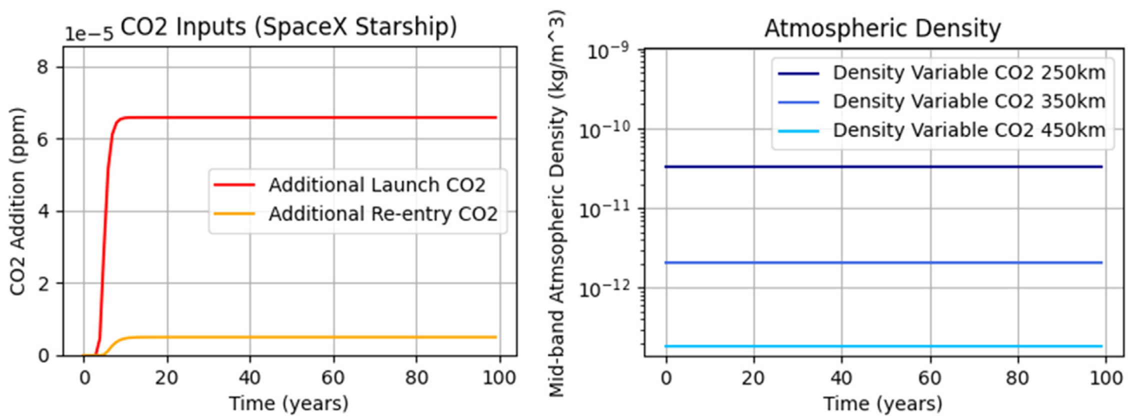

Fig. 4. (Left) CO_2 inputs from launches with SpaceX Starship rocket populating 5 constellations of satellites and the re-entry CO_2 contributions from these re-entering satellites over time. (Right) Atmospheric density at various altitudes with variable CO_2 concentrations considered over time.

launch rate of 144 launches per year, each delivering 45 satellites per launch. The simulation period spanned 100 years and the CO_2 contributions in parts per million (ppm) and influence on the atmospheric densities are shown in Fig. 3.

Fig. 3 shows that this population and launch scenario has no significant impact on ground-level CO_2 concentrations, with overall additions on the order of 1×10^{-6} ppm (contributing to an overall CO_2 concentration change over 100 years for this scenario on the order of 1×10^{-4} ppm). This also has a negligible impact on the atmospheric density at all mid-altitude bands considered below 500 km.

3.2. Case 2 – Extreme launch scenario

The population characteristics for Case 2 match Case 1 except for the modification of the number of active launch profiles and the launch vehicle emissions. In this simulation case, 5 identical constellations are launched to 500 km altitude and are populated simultaneously (i.e. 5 identical launch profiles are active at the same time). Additionally, each launch emits the same amount of CO_2 as SpaceX's Starship (716,000 kg). This vehicle still only delivers 45 satellites into orbit per launch. Whilst many other large satellite constellations have been planned, SpaceX is currently the only launch provider with such high launch rate capabilities, with many other satellite companies using SpaceX's launch services to populate their own constellations. As such, 5 companies launching at the same rate as SpaceX was taken as a reasonable but extreme launch scenario.

Even in this extreme launch case scenario, as shown in Fig. 4, CO_2 inputs from launches and re-entries are small on the order of 1×10^{-5} ppm (contributing to an overall CO_2 concentration change over 100 years of this scenario on the order of 1×10^{-3} ppm). This also has a negligible impact on the atmospheric density at all mid-altitude bands below 500 km and a negligible impact on the number of objects in orbit compared to the constant CO_2 concentration case.

With this implementation of a PIB collision calculation and a CO_2 per re-entry, the CO_2 contribution from re-entries is likely an overestimate. This is because the PIB calculation overestimates the collision rate by assuming random movement of objects within the volume, no collision avoidance abilities, that every collision results in the fragmentation of 10 new fragments and that these relatively large satellites are all populating a 300 km band of space (particularly dense in the extreme launch case scenario). This leads to an overestimated increase in the number of objects in the model which, due to a fixed assignment of CO_2 per object, each contribute the same amount of CO_2 upon re-entry despite their differences in mass. Studies investigating the CO_2 contribution per unit mass would help to reduce this overestimate, but this was outside the scope of the current work.

This study only assesses the impacts on atmospheric density levels below 500 km. Reference [16] demonstrated that the impacts of atmospheric contraction due to CO_2 concentration increases with altitude, with higher altitudes experiencing more contraction for the same change in CO_2 concentration. Given that many future constellations are planned above 500 km, extension of this study to higher altitudes may provide additional useful insights into whether launch and re-entry CO_2 emissions may impact the modelling of these higher altitude constellations.

This study also only estimates the atmospheric contraction due to CO_2 contributions from launches and re-entering objects. This is just one example of a feedback outlined in Fig. 1 that is linked to the overall sustainability and environmental impacts of future large satellite constellation related activities. Many other emissions of substances from launches and re-entries have been identified as requiring further research by the existing literature. By using frameworks that consider launches as entry points and re-entries as exit points, existing models cannot be used to investigate the potential impacts of these other substances.

A further limitation in this study was the simplification of the altitude insertion of CO_2 emissions from launches and re-entries. The model directly inputted any released CO_2 into the ground-level concentration during the 1-year timestep, which does not accurately represent realistic mechanisms. Future studies should consider the varied injection height of substances associated with launches and re-entries, as this can have an impact on the atmospheric dynamics at different altitudes [11].

4. Conclusions

Consideration should be given to this systems approach for future assessment of the sustainability of space activities. The use of systems thinking models allows for the identification of feedbacks that may exist outside of the boundaries of current debris models and introduces pathways to address questions that existing models are unable to investigate. The literature indicates that achieving sustainability in space goes beyond space debris management alone. Developing models to assess the interdependencies and feedbacks between currently isolated domains would allow for a more holistic evaluation of the overall sustainability of space activities. With this work, there is an opportunity to connect with broader efforts to tackle emissions, to reach net zero, and work towards developing a circular economy.

This study found that, even in the extreme launch scenario where 5 identical constellations were being populated simultaneously, with a CO_2 release per launch of 716,000 kg and a CO_2 input of 1100 kg per object re-entry, no significant influence due to these factors on atmospheric density or total number of satellites in orbit below 500 km was identified.

Further work to reduce the limitations present in this study and to further validate these results is needed. Further research to quantify the impact of CO_2 from object re-entries on the atmosphere compared to launches should include the identification of CO_2 input per unit of re-entry mass. The data used to inform the re-entry CO_2 contribution in this study were limited to CO_2 per re-entry, which likely resulted in an overestimate in the specific CO_2 contribution of re-entries. Nevertheless, the contribution of CO_2 from re-entries is still expected to be significantly smaller than the emissions from launches. Furthermore, this study did not investigate the potential effects of other environmentally harmful substances that are released during launch or upon re-entry into the atmosphere. As highlighted in the existing literature, substances such as black carbon and aluminium oxide have the potential to impact stratospheric chemistry, the ozone layer, and atmospheric radiative forcing. Additionally, this study only considered altitudes up to 500 km. Previous studies have identified that as altitude increases, the atmospheric reduction caused by ground-level CO_2 concentration becomes more significant. Conducting further research in this area would contribute towards a more comprehensive understanding of the holistic environmental impacts associated with rocket launches and satellite re-entries during the age of large satellite constellations. This improved understanding will allow for further quantification of the holistic impacts on Earth's environment and aid in addressing long-term sustainability aims for space activities.

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Declaration of competing interest

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CRediT authorship contribution statement

Megan E. Perks: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Hugh G. Lewis:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Nina Vaidya:** Writing – review & editing, Supervision.

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During the preparation of this work the first author used JenniAI in order to make minor language and grammar edits only. After using this tool/service, the first author reviewed and edited the content as needed and takes full responsibility for the content of the publication. The scientific content and results of the paper are the authors' original ideas and work.

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