DEEP TIME ANALYSIS OF SPACE DEBRIS AND SPACE SUSTAINABILITY

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ABSTRACT

A number of initiatives for quantifying the environmental impact of space missions, the sustainability of space activities and the so-called "carrying capacity" of Earth orbital regions, have emerged in the last few years. Most initiatives lack an awareness of the deep time issues that arise from the enduring nature of the space debris problem. We lack appropriate frames of reference or tools from our conventional modelling approaches for tackling multimillennial timescales of debris hazard. Consequently, we use this paper to explore how the space debris population will grow and to introduce model-based approaches that work across deep time. These sit within a framework that integrates all of the elements needed to support a deep time analysis of space debris and space sustainability.

1 INTRODUCTION

In June 2019, the United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS) adopted 21 guidelines on the long-term sustainability (LTS) of outer space activities and, as part of the preamble, the following definition of space sustainability [1]:

"*The long-term sustainability of outer space activities is defined as the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations*."

The Secure World Foundation (SWF) use a similar definition of space sustainability [2]:

"*Space sustainability is ensuring that all humanity can continue to use outer space for peaceful purposes and socioeconomic benefit now and in the long term*."

As reported by [3], some delegations to COPUOS are in the process of implementing the LTS guidelines through changes to domestic legislation, development and application of national space policies, and enhancements to national space situational awareness capabilities, amongst other actions. In parallel, some initiatives for quantifying the environmental impact of space missions, the sustainability of space activities and the so-called "carrying capacity" of Earth orbital regions, are also being developed. These initiatives tend to employ simple indicators or indices that are intended to represent the status of efforts to achieve space sustainability or to address the space debris problem. Working Group 2 of the Inter-Agency Space Debris Coordination Committee (IADC) recently completed a review of some initiatives (based in part on a previous review by Colombo et al. [4]), highlighting their commonalities, advantages and limitations. The approaches studied by the IADC used simple analytical expressions, complex models, or a mix of the two but featured a diverse range of environmental- or mission-related inputs to derive their indicators, with aspects related to collision risk and adherence to mitigation measures as the most common.

One key initiative is the Space Sustainability Rating (SSR), which was enabled through the World Economic Forum's Global Future Council on Space Technologies [5]. The SSR is a composite indicator of the environmental 'footprint' represented by a space mission, which – like those considered in the IADC review – is based in part on measurement of collision risk and planned adherence to some of the COPUOS LTS Guidelines and IADC Space Debris Mitigation Guidelines [6].

The SSR and other initiatives aiming to quantify space sustainability are still nascent but even in the near-term they are likely to disrupt how the community understands and communicates issues related to space debris and space sustainability. For example, the objective of the SSR [5] is to provide an incentive for space industry "*to design missions compatible with sustainable and responsible operations, and operate missions considering potential harm to the orbital environment and impact on other operators in addition to mission objectives and service quality.*" Yet most of the initiatives, including the SSR, do not genuinely measure the qualities expressed in the UN COPUOS or SWF definitions of space sustainability. They lack an awareness of the deep time issues that arise from the phrases "*indefinitely into the future*" or "*the long term*" that appear in the definitions of space sustainability. They do not truly account for the enduring nature of the space debris problem or for the essentially unknowable use of space by future generations. We lack appropriate frames of reference or tools from our conventional modelling

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approaches for tackling multimillennial timescales of debris hazard. Instead, 'space sustainability' is measured in terms of risks to our current use of space [7] – essentially as a proxy for the use of space by future generations of humanity – and in terms of the potential reduction in those risks arising from compliance with existing debris mitigation measures.

1.1 Deep time thinking

The Long Time Project provides a valuable way of thinking about the type of deep time thinking and behaviour we want to encourage in relation to space sustainability [8]:

"*Long time behaviour seeks to cultivate an attitude of care for the future, however near or far off it might be, so that we change our behaviour to take responsibility for it in the present*."

Krznaric also provides a slightly different view, based around the idea of being a 'good ancestor' [9]:

"W*e want to be good ancestors and be remembered well by the generations who follow us*."

Whilst an understanding of the risks associated with a present-day space mission and the adherence to space debris mitigation guidelines can be important to incentivise good behaviour, this is not the same as having empathy for all future generations, valuing their freedom to use space as they wish, or using this thinking to create responsible behaviour in the present.

As a starting point, we need to gain an understanding of the *inheritance* that the present generation will leave for all future generations of humanity. In this context, there is no consensus on how our current behaviour in the space environment will influence the future state or the activities of future generations. There is an infinite number of possible scenarios for the future that would need to be considered before we could gain such insight, something beyond even the most powerful computer. As such, we must take a different perspective: we don't want to understand what the future use of space might look like to us, but rather we want to understand what our present use of space will mean for future generations. Rather than trying to predict the future, we must instead empathise with the future generations of space users and look back with that new awareness.

This is a subtle change in perspective, perhaps, and objectively might lead to an approach similar to ones that already exist. Yet it is powerful because it is built on the principles encapsulated within the definition of space sustainability. Nonetheless, it is a challenging prospect because we need to predict what knowledge associated with our present use of space will have meaning for the future, regardless of how space is being used in that time. The knowledge needed is an understanding – and ideally a quantification – of how space activities might be affected. So, it appears that some prediction is needed after all! However, we have the benefit of hindsight to aid us in this process; we can look back to earlier years of the space age and ask ourselves what knowledge was available in our history that could have informed us about the impending consequences for our present-day use of space.

In hindsight, we can see that an awareness of the historical status and use of the space environment would be useful and important, but not sufficient to inform us about how our present-day space activities would be subsequently impacted. Such awareness is something that arguably we have (e.g. [10]) but knowing only that the catalogued orbital population contained 8,738 objects in February 1999 would not have offered too many clues about how the use of space in the year 2021 would be affected. Consequently, we might also want to know something about the dynamics – how the space debris population is growing – as this is something more closely linked to the future state. Of course, knowing how the population is growing might enable us to make predictions of the future, but this is not where the value lies (and we do not want to fall into the trap of believing that we can predict the unknowable future).

This was ostensibly the purpose of the stability model developed by Kessler and Anz-Meador and presented in 2001 [11]. The simple physics-based model, parameterised using data from the prevailing satellite catalogue, provided an indication of how the space debris population might respond to increases or decreases in size. It did so through a comparison of the catalogued population with the critical number of intact objects producing runaway population growth (Fig. 1). The conclusions offered in [11] are illustrative of the knowledge we might want to know about the impact of the present on the future.

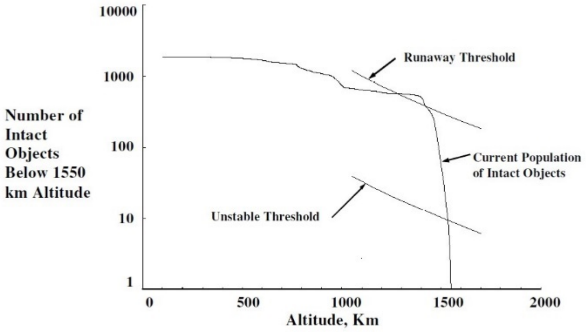

Figure 1. Regions of instability below 1550 km (February 1999 catalogue) from [11].

There are likely other features of the space environment and space debris population that are available to us in the present, which might inform us about "*the ability to maintain the conduct of space activities indefinitely into the future*," [1] but they will all tend to be representative of three fundamental elements requiring integration within a deep time framework:

1. An awareness of the current environmental status
2. An understanding of how the space debris population will grow
3. An understanding of the potential impacts on the use of space

Tackling any of these elements is not trivial, but (1) is based on concepts of space situational and domain awareness so it might be argued that it represents a technical, rather than a deep time, challenge. A more philosophical challenge lies in the need to address (2) and (3) across deep time – potentially multimillennial timescales – as this demands new thinking and possibly substantial technical innovation if reliable and meaningful assessments of space sustainability are to be made.

We use this paper to explore potential solutions to (2), introducing model-based population growth models that will ideally work across deep time, with insights drawn from ecology and epidemiology.

2 POPULATION GROWTH MODELS

In this section, simple population growth models from ecology (with concepts primarily adopted from [12]) are introduced and used to explain how the space debris population might grow. The objective is to be able to extract simple quantities – model parameters - that characterise the underlying rules governing the growth of the present-day space debris population. These quantities, although illustrative at this stage of the research, will ultimately form part of the deep time framework described above to quantify space sustainability.

2.1 Growth models for natural populations

Simple growth models tend to represent populations of single-celled organisms such as bacteria. In these populations, the individuals divide at specific intervals. If the division rate is R then the population growth can be described using the exponential equation [12]:

$$N(t) = R^t N(0) \tag{1}$$

where $N(0)$ is the number of individuals in the initial population and $N(t)$ is the number of individuals at some later time, t. R is generally referred to as the finite rate of population increase (for bacteria the finite rate of population increase is the division rate). An alternative representation is that it is the contribution of an individual to the total population size. This quantity has similarities with the reproduction number used to characterise the growth of infections in disease transmission, which is also called 'R'. Eq. 1 is a standard model describing the growth of a single population. We can write Eq. 1 as:

$$N(t) = N(0)e^{rt} \tag{2}$$

where $r = ln(R)$ is the intrinsic rate of natural increase. Again, an alternative representation is that r is the contribution of an individual to the rate of change in population size. The intrinsic rate of growth r depends on the birth rate, b, and death rate, d, in the population:

$$r = b - d \tag{3}$$

If the birth rate is greater than the death rate then $r > 0$, $R > 1$ and the population is growing. Conversely, if the birth rate is less than the death rate then $r < 0$, $R < 1$ and the population is declining.

A population that increases with a rate proportional to its current size will grow exponentially (see Fig. 2). This means that as the population increases so does the rate at which it grows. Hence, another way of writing the exponential equation is as a differential equation, where the rate of change of N is proportional to r:

$$\frac{dN}{dt} = (b - d)N = rN \tag{4}$$

For convenience, the reference to time has been dropped.

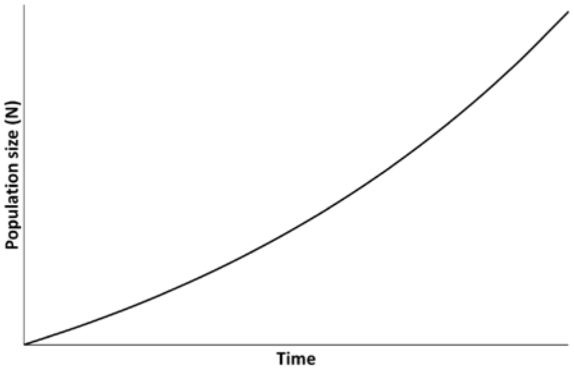

Figure 2. Example of exponential population growth.

Observations of natural populations have shown that density dependence modifies the exponential equation. As the population size increases, the intrinsic growth rate, r, tends to decrease, perhaps due to limited resources [12] (see Fig. 3).

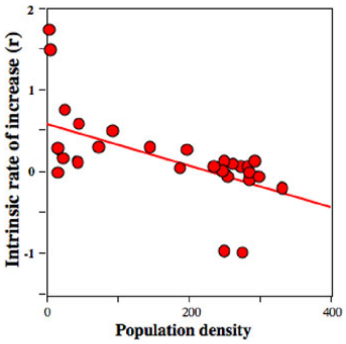

Figure 3. The intrinsic rate of increase as a function of population density for a laboratory population of Paramecium [12].

Hence, we can replace the intrinsic growth rate, r, with

$$\frac{dN}{dt} = [f(N)]N \tag{5}$$

Assuming $f(N)$ is linear we have $f(N) = a - cN$ and the differential equation in Eq. 5 takes on quadratic form:

$$\frac{dN}{dt} = [a - cN]N = aN - cN^2 \tag{6}$$

This is the logistic growth equation, which is another standard model describing the growth of a single population where there is competition for limited resources. If we let $a = r$ and $c = r/K$ then via simple algebra we can write:

$$\frac{dN}{dt} = rN\left(\frac{K - N}{K}\right) \tag{7}$$

where K is the carrying capacity. Initially, when there are relatively few individuals in the population and the competition for resources is limited, the population grows exponentially (Fig. 4). However, as the population size, N, continues to increase, the rate of change of the population size decreases, ultimately reaching an equilibrium $N = K$.

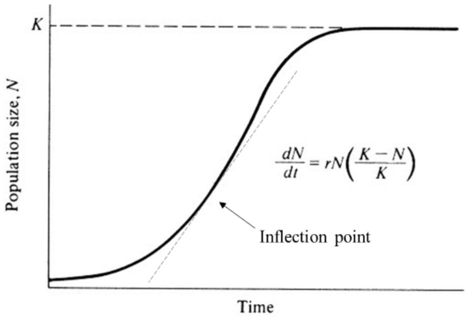

Figure 4. Example of logistic population growth. K is the carrying capacity – the maximum population size that can be supported by the resources available.

2.2 Growth model for the space debris population

As a purely artificial system, the growth of the space debris population cannot be described in terms of the "births" and "deaths" of its individual members. However, systems thinking [13] enables us to introduce alternative concepts: *inflows* and *outflows*, which are sources and sinks for space debris. In the absence of new space launches, the inflow corresponds to new fragments created from the breakup of existing individuals in the population. If we further set-aside fragmentations arising from on-board energy sources (e.g. propulsion-related explosions) the inflow is due solely to collisions between individuals in the population. The outflow corresponds to the decay of individuals out of the environment due to atmospheric drag (see Fig. 5).

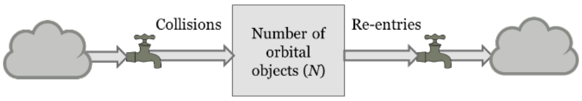

Figure 5. Simple systems model for the space debris population showing inflow due to collisions and outflow due to decay and re-entry. The symbols used for this representation follow the suggestions made by Meadows in [13].

A fundamental assumption in the exponential model of natural population growth in Eq. 4 is that the birth rate and death rate are constant, such that we can describe the population growth exclusively in terms of a single parameter, the intrinsic rate of natural increase, r. However, as we have seen for natural populations, the value of r changes in response to the population density. For natural populations, higher densities tend to reduce the population growth rate (Fig. 3). In contrast, higher space debris densities tend to result in higher collision rates and corresponding increases in the population growth rate.

This density dependence is explicit in the formulation of most collision prediction methods used in computational models of the space debris population, where kinetic gas theory is employed [14]. In this approach, the mean number of collisions, C, encountered by an individual object of collision cross-section A_C, moving through a uniform object density, D, at a constant velocity, v, during a time interval Δt is

$$C = v\,D\,A_C\,\Delta t \tag{8}$$

where, the particle density is defined as

$$D = N/U \tag{9}$$

for volume U containing the population of N objects. The combination of Eq. 8 and Eq. 9 shows that the collision rate associated with an individual, and therefore the contribution of an individual to the rate of change of population size, r, is directly proportional to the number of individuals in the population, N. In other words, we can replace the intrinsic growth rate, r, in Eq. 4 with

$$\frac{dN}{dt} = [f(N)]N \tag{10}$$

where $f(N) = a + cN$ and $c > 0$ for the space debris population. The differential equation now takes the form

$$\frac{dN}{dt} = [a + cN]N = aN + cN^2 \tag{11}$$

Again, we let $a = r$ where r is the difference between the rate at which new fragments are produced by collisional breakups, b, and the decay rate, d. The right-hand side of the differential equation in Eq. 11 is a quadratic and is similar to the form obtained via systems thinking [15] or a physics-based approach (e.g. [16]).

Although seemingly just a minor change compared with the corresponding logistic growth equation for a natural population (Eq. 6), the effects of this change are substantial. Instead of the characteristic S-shaped growth curve (Fig. 4), we have unconstrained and accelerating growth for all $r > 0$ (equivalently, $R > 1$; Fig. 6) and even for some cases where r is negative. The population will undergo exponential decay for some values of $r < 0$ (equivalently, $R < 1$; Fig. 7).

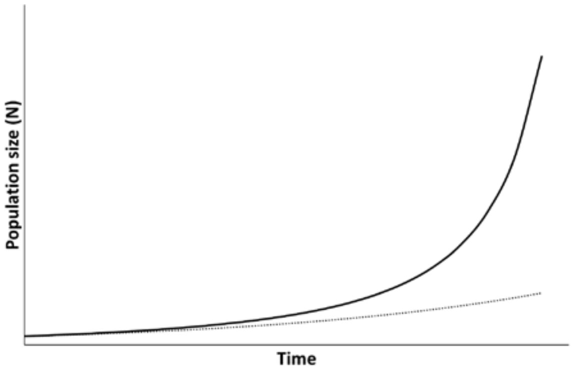

Figure 6. Example of fast exponential growth resulting from Eq. 11 for $r > 0$. The dashed line shows the equivalent exponential population growth obtained using the differential equation in Eq. 4.

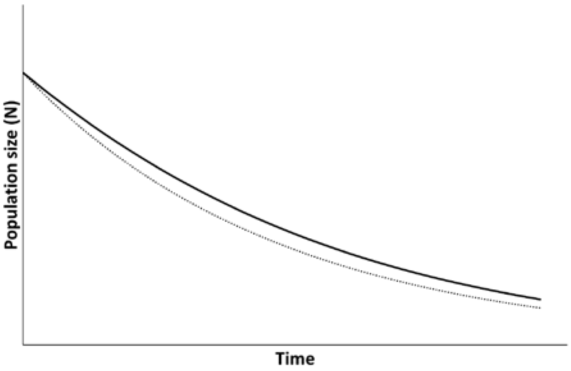

Figure 7. Example of the exponential decay resulting from Eq. 11 for a particular value of $r < 0$. The dashed line shows the equivalent exponential population decay obtained using the differential equation in Eq. 4.

2.3 Piecewise growth model

The model of space debris population growth represented by Eq. 11 provides valuable insight into the nature of the population growth but potentially hinders our ability to extract useful indicators of space sustainability because of the additional complexity. An alternative to the model represented by Eq. 11 is to apply the differential equation in Eq. 4 over discrete (and possibly short) intervals of time, effectively neglecting the N^2 term and adjusting the value of r within each interval. Although imperfect, this approximation enables straightforward interpretation. The choice of interval should, ideally, be one where the growth can be characterised reliably by the simple exponential model.

2.4 Contribution from space launches and non-collisional fragmentations

Other considerations for the model of space debris population growth are the contributions from new space launches and non-collisional fragmentation events. In the former case, the population increases but not in proportion to the number of objects already in the population. New additions from launches are independent of the existing population size (in general). In contrast, it can be argued that the rate of occurrence of fragmentations such as explosions involving the power subsystem or propulsion subsystem of payloads or orbital stages are related intrinsically to the number of such systems in orbit.

Although population dependence in the history of fragmentation events is uncertain due to relatively low numbers ([10] estimates an average of 8.4 accidental fragmentations per year; Fig. 8) we will again neglect the population dependence in the model and use the piecewise approximation instead. Consequently, we can address the contributions from new space launches and non-collisional fragmentations through the addition of two additional parameters, s and e, such that the differential equation in Eq. 4 becomes:

$$\frac{dN}{dt} = s + (e + r)N \tag{12}$$

where $r = b - d$ as before.

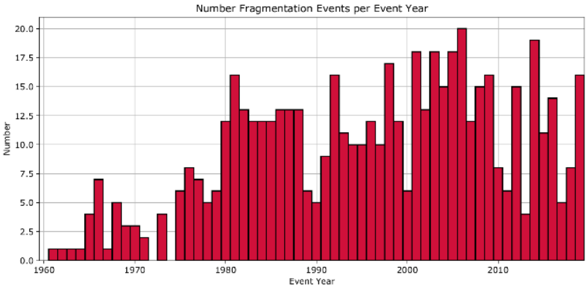

Figure 8. Number of fragmentation events per year [10].

2.5 Final growth model

With simple algebra we have the final, piecewise space debris population growth model:

$$\frac{dN}{dt} = \left(e_i + b_i + \frac{s_i}{N} - d_i\right)N \tag{13}$$

where s_i/N is the proportion of the population in interval i that are from new space launches. Eq. 13 has the same form as Eq. 4, which represents the growth of a single, natural population. Hence, the average intrinsic rate of population increase over the interval, r_i, is the sum of the debris sources (the rate at which new objects are added via explosive and collisional breakups, and new space launches) and the only sink (the rate at which objects decay out of the environment). The approximation in Eq. 13 provides a straightforward model for understanding how the space debris population grows.

2.6 Estimating ‘r’ and ‘R’

An ‘instantaneous’ estimate of the intrinsic rate of population increase can be estimated using:

$$r(t) = \frac{N(t) - N(t-1)}{N(t)} \tag{14}$$

where we have re-introduced the time dependence and $N(t) - N(t-1)$ is the change in the number of objects in the population over a time-step. If the time-step is too short, then estimates of $r(t)$ will be highly variable. In addition, the presence of a periodic signal such as the 11-year cycle of solar activity may hide the characteristic population behaviour of interest. In these cases, it may be sensible to apply an averaging window to reduce their influence.

The corresponding estimate for the finite rate of population increase, R(t), can be made using:

$$R(t) = e^{r(t)} \tag{15}$$

3 APPLICATION TO PAST AND PRESENT SPACE DEBRIS POPULATIONS

The evolution of the catalogued populations of objects in Earth orbits (typically 10 cm in size or larger) is shown in Fig. 9. As can be seen, there has been a considerable increase in the number of objects in the population since the mid-2000s, primarily as a result of the fragmentation of three spacecraft (Fengyun 1C in 2007; Iridium 33 and Cosmos 2251 in 2009) and a substantial rise in the release of small satellites in the Low Earth Orbit (LEO) region.

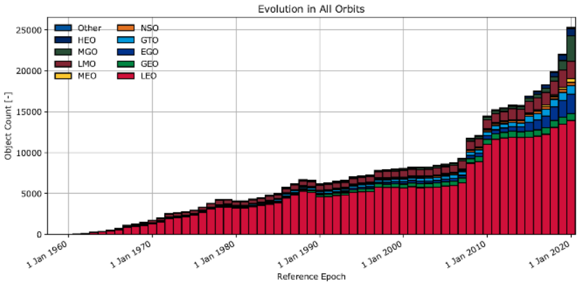

Figure 9. Evolution of the catalogued population of objects in Earth orbits 1957-2020 [10].

Using the method outlined in Section 2.6 estimates of the yearly intrinsic growth rates were found. Fig. 10 shows these estimates for two key periods, 1981-2006 and 2006-2021, together with the 11-year moving average for 1987-2016.

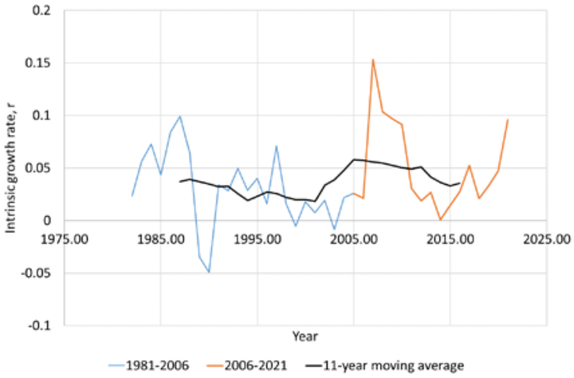

Figure 10. Evolution of the intrinsic rate of population increase April 1981-April 2021.

The average value of r for the 1981-2006 period was 0.0297. For the 2006-2021 period, the corresponding average growth rate was $r = 0.0521$. The change in r represents a 75% increase in the intrinsic growth rate between the two periods, likely driven by the significant effects of the Fengyun 1C, Iridium 33 and Cosmos 2251 fragmentations on the population (and corresponding to an increase in the value of e in Eq. 13). The average value of R for the latter period indicated that each individual in the population contributed an average of 1.0535 to the total population size. Together with the moving average result, which showed $r > 0$ (and subsequently $R > 1$), we can say that the historical growth trend is one of *exponential increase*. Although some caution should be applied because of the short time interval, Fig. 10 also shows possible consequences of increasing numbers of small satellites in LEO (i.e. increasing dominance of the s/N term in Eq. 13) perhaps equivalent in terms of their effect on r to the three important fragmentation events mentioned above. Indeed, in the last year, SpaceX alone have released approximately 1000 satellites into the LEO region – about 4% of all objects in the current catalogued population.

4 ANALYSIS USING A COMPUTATIONAL MODEL

Although we might not want to use them for making predictions of the future state of the space debris population, computational models can be used to provide a deeper understanding of the potential impacts of different behaviours on the population dynamics. In this case, we can employ a computational model to explore selected 'what if' scenarios, e.g. highlighting the effects of different levels of compliance with a space debris mitigation guideline.

Here, the Debris Analysis and Monitoring Architecture to the Geosynchronous Environment (DAMAGE) was used to generate two different space debris population trajectories to which the exponential growth model derived in Section 2.5 could be applied. The use of DAMAGE here was not to make predictions of the future but instead to provide insight into the effects of debris mitigation behaviour in the present on the fundamental growth dynamics of the space debris population.

4.1 Simulations using DAMAGE

The DAMAGE model is a high-fidelity three-dimensional computational model capable of simulating the evolution of future debris populations. DAMAGE projections make use of a Monte Carlo approach to simulate future collisions. The Monte Carlo process requires multiple projection runs to be performed and analysed before reliable and meaningful conclusions can be drawn from the outcome.

The basic scenario used for this study corresponds to the one currently used by the IADC.

- A 1 February 2018 epoch with an initial population corresponding to all objects ≥ 10 cm residing within or crossing the LEO protected region.
- Launch traffic was assumed to be represented by the repetition of recent launches (taken from 1 January 2010 to 31 December 2017) with small random adjustments made to the exact launch date and orbital parameters to avoid artificially enhancing the likelihood of collisions on launch. Large constellations were not included.
- In the first scenario, new spacecraft and rocket upper stages were assumed to achieve a 90% success rate with respect to post-mission disposal (PMD), targeting an uncontrolled re-entry within 25 years by reducing the perigee altitude. A graveyard option above the LEO Protected Region was not permitted. In the second scenario, no post-mission disposals were performed.
- No collision avoidance manoeuvres were implemented. Vehicle passivation was assumed to be 100% successful such that no explosions were permitted within the projection period.

4.2 DAMAGE results

The evolution of the average number of objects ≥ 10 cm in the LEO orbital object population is shown in Fig. 11 for the two simulation cases.

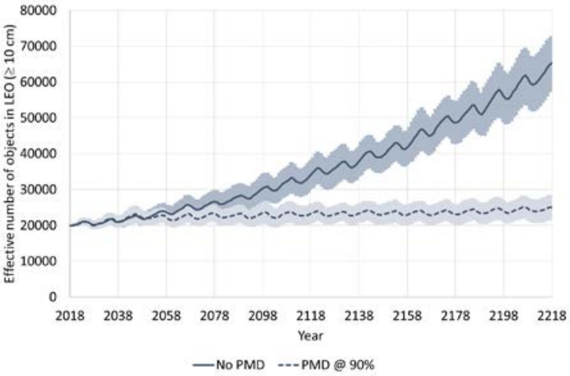

Figure 11. Effective number of objects predicted by DAMAGE for the two simulation cases. The shaded areas represent the 1-sigma variation.

An 11-year moving average window was applied to the number of objects to remove the periodic effect of the solar cycle. The intrinsic rate of population increase, and the finite rate of population increase were then calculated using Eqs. 14 and 15. The R value distributions for both of the simulation cases are shown in Fig. 12.

To demonstrate the robustness of the exponential model, the average values of r over the 200-year interval, for the two simulation cases, were computed and Eq. 2 was used to calculate the number of objects in the space debris population over the interval (Figure 13). Although the average values of R indicated that individuals in both populations contributed fewer than ~1.0058 to the total population size, the results showed R to be consistently greater than 1 (and correspondingly $r > 0$). Hence, we can say that even with good compliance with respect to the IADC space debris mitigation guidelines, the fundamental population growth tendency of the present debris population is again one of *exponential increase*.

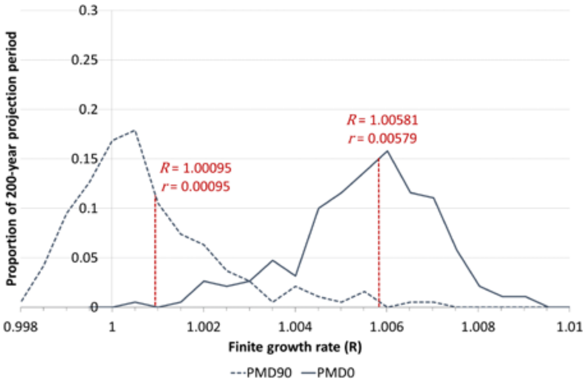

Figure 12. Distributions of the finite growth rate, R, for the two simulation cases. The dashed red lines indicate the average values of R for the 200-year projection period.

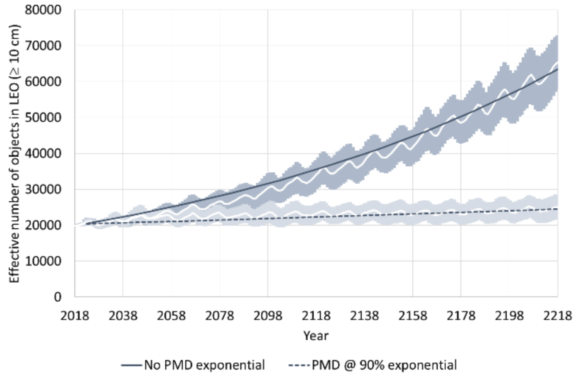

Figure 13. Effective number of objects predicted by the exponential model (Eq. 2) for average values of r computed from the DAMAGE simulation cases. The shaded areas represent the 1-sigma variation.

4.3 The need for deep time thinking

One of the key questions to ask about natural population growth is how long it will take the population to double in size. At that time the population will be twice the starting size, or $2N(0)$. The doubling (or what we call *generation*) time, t_G, is:

$$t_G = \frac{ln(2)}{r} \tag{16}$$

Applying Eq. 16 to the average values of r obtained from the analysis of the past and present space debris populations (including the values of r obtained for the DAMAGE simulation cases) produced the generation times shown in Tab. 1.

Table 1. Time taken for the space debris population to double (the generation time) calculated for space debris populations of the past and present.

Estimation period/scenario	**r (#/year)**	**t_G (years)**
1981-2006	0.0297	23.3
2006-2021	0.0521	13.3
2018-2218/PMD @ 90%	0.00095	731.4
2018-2218/No PMD	0.00579	119.7

The results in Tab. 1 highlight a discrepancy between the values of r and t_G calculated using the catalogue population and the DAMAGE populations. The reason for this discrepancy is currently under examination, but preliminary investigations point to the combination of a lack of explosions and a relatively low launch traffic rate in the DAMAGE simulations compared to current and historic levels. If this is indeed the case, then the discrepancy actually points to the importance of these two factors and the value of the exponential model in identifying them. The implementation of passivation in future space systems, something called for in the IADC space debris mitigation guidelines, would tend to reduce the number of explosions and thereby reduce the population growth rates substantially. Taking this into account, the expectation is that the best-case intrinsic and finite growth rates would be close to the values calculated for the first DAMAGE simulation case, where the doubling time is approximately 730 years.

So, exponential growth does not necessarily imply large quantities, and it is not necessarily fast (at least at the beginning). The growth of space debris might appear to be unspectacular in our present, even in the worst case, but it *is* exponential. Hence, we need to consider carefully the real meaning of the words "*indefinitely into the future*" in the UN definition of space sustainability [1]. Taking responsibility for the future in our present means that any changes we can make to our behaviour in at this relatively early stage (e.g. by reducing the number of explosions in orbit, as seen above) can make a substantial difference to the demands on future generations to change their behaviour. This is essence of the deep time thinking required [8].

4.4 Limitations

The space debris population growth model described in Section 2 is based on some important assumptions:

1. All individuals in the population are identical and contribute equally to the growth.
2. The growth rate parameters (r, R) remain constant over selected intervals of time.
3. The effect of the N^2 term in Eq. 11 is negligible over any interval of time for which the growth

rate parameters are assumed to remain constant.
4. The population can grow unconstrained.

The results shown in Fig. 13 suggest that the simple exponential model, with one interval, was able to represent the underlying growth dynamics of the space debris population (as modelled by DAMAGE), and that assumptions 1-3 were not overly limiting.

Using DAMAGE for a projection of scenario 1 over a 1000-year period, Lewis [15] found that the population did not grow uniformly, with the first 200-year period showing substantially different population dynamics to the remaining period (see Fig. 14). The cause of the change in dynamics was found to be a result of essentially two populations with quite different characteristics growing within the LEO region.

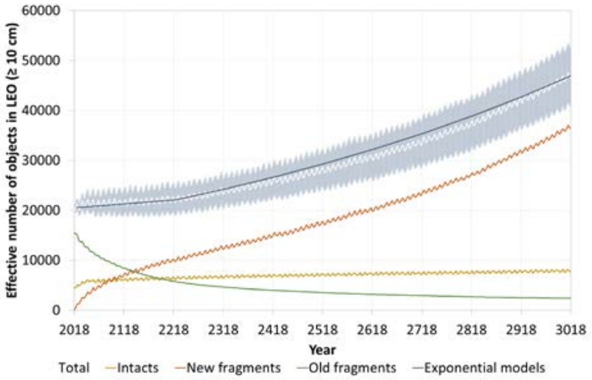

Figure 14. Effective number of objects predicted by two exponential models (Eq. 2) based on average values of r computed from a 1000-year DAMAGE simulation [15]. The shaded areas represent the 1-sigma variation.

The first population consisted of objects at altitudes below 1000 km. This population was the most numerous and, as such, dominated the growth characteristics for the first 200 years of the simulated projection period. Although the collision rate in this altitude region was relatively high, the population reached an equilibrium quite quickly. The second population – much smaller in number than the first – consisted of objects at altitudes above 1000 km. Here, the effect of atmospheric drag was negligible, and this meant the very low collision rate still created a persistent growth of the population. This growth was exponential and after 200 years began to dominate the overall population dynamics. Hence, these 'patchwork' populations created two quite distinct intervals where two different exponential models were needed to capture the dynamics (Figure 14).

Despite the use of two intervals to capture these patchwork populations, the effects of assumption 3 can be seen in Figure 14 for the years 2218 to 3018. The mismatch between the exponential model and the DAMAGE population was apparent for this relatively long interval. A better solution could have been obtained by separating this period into two or more intervals and applying the exponential model to each. However, the results from [15] were used here solely for illustrative purposes, so this action was not undertaken.

5 INDICATORS OF SUSTAINABILITY

The use of an exponential model has enabled particular measures, which characterise the growth of the space debris population effectively, to be extracted easily from the satellite catalogue or from simulations performed using computational models. The measures introduced so far in this paper have been the intrinsic rate of population increase (r), the finite rate of population increase (R) and the doubling, or generation time (t_G).

Additional measures, based on other descriptors of population growth and disease spread, which could be relatively easily obtained include:

1. *Serial interval*. In epidemiology this refers to the time between successive cases in a chain of transmission. Here, it can be used to describe the interval between catastrophic collisions (which is the key mechanism by which space debris is proliferated). In the exponential model, it would be derived from the parameter b.
2. *Attack rate*. Again, from epidemiology this refers to the percentage of an at-risk population that contracts the disease during a specified time interval. For space debris, it can be used to describe the proportion of objects involved in collisions over a time interval. In the exponential model, it would be derived from the parameters b and N.

The framework briefly outlined in Section 1.1, also specified the need to understand (and quantify) potential impacts on the use of space. This aspect has not been the focus of this paper, but measures under consideration include:

1. *Occupancy*. This refers to the volume swept out by objects in the population over a (long) interval of time, and is based on the measure introduced in [18]. Some optimisation would be required to reduce the computational load involved in the calculation, but this measure offers additional benefits. It can be compared with the volume that is protected (e.g. the LEO Protected Region) or the volume that has been *restored* (i.e. returned to its 'natural' state).
2. *Adaptation*. Again, some optimisation and support for the parameterisation would be needed, but this refers to the proportion of spacecraft and orbital stages that have had their designs or operations modified to reduce the risk. It is related to the proportion of these objects that are compliant with space debris mitigation guidelines (and hence similar

measures used in the SSR) but the objective is different. These modifications represent impacts induced by the debris hazard.

6 CONCLUSIONS

The adoption of the UN LTS Guidelines and definition of space sustainability has generated new interest in initiatives for quantifying the environmental impact of space missions, the sustainability of space activities and the so-called “carrying capacity” of Earth orbital regions. The principles conveyed by the UN definition of space sustainability are related to those articulated by the Long Time Project and deep time thinking, yet most initiatives aiming to quantify space sustainability lack an awareness of these issues, which arise from the enduring nature of the space debris problem and the need to empathise with future generations of humanity. We need to understand what our present use of space will mean for future generations.

Consequently, we have used this paper to explore such thinking and to outline the beginnings of a framework that brings the necessary elements together:

1. An awareness of the current environmental status
2. An understanding of how the space debris population will grow
3. An understanding of the potential impacts on the use of space

The main focus of this paper was to understand how the space debris population will grow. By first considering the growth of natural populations, a simple model of exponential growth was derived for the space debris population. The model was used to illustrate how useful measures, which characterise the fundamental population dynamics, can be generated for the current orbital object population. In particular, the paper focused on the intrinsic rate of population increase (r) and the finite rate of population growth (R). These are simple measures that are easy to interpret: e.g. if $R > 1$ the population is growing, if $R < 1$ the population is declining. The application of the model showed that the current population is growing exponentially and will continue to do so even with widespread adoption of space debris mitigation measures.

The growth rate is currently high, potentially due to substantial launch and explosion rates. High levels of compliance with the IADC space debris mitigation measures will reduce the growth rate substantially. However, this introduces a new challenge because the population growth would still be exponential, though slow. The estimate of the doubling, or generation, time for the space debris population in the best-case scenario was approximately 730 years. This quantity highlights the need for deep time thinking associated with the space debris problem.

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