Orbital-use fees could more than quadruple the value of the space industry

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The space industry's rapid recent growth represents the latest tragedy of the commons. Satellites launched into orbit contribute to—and risk damage from—a growing buildup of space debris and other satellites. Collision risk from this orbital congestion is costly to satellite operators. Technological and managerial solutions—such as active debris removal or end-of-life satellite deorbit guidelines—are currently being explored by regulatory authorities. However, none of these approaches address the underlying incentive problem: satellite operators do not account for costs they impose on each other via collision risk. Here, we show that an internationally harmonized orbital-use fee can correct these incentives and substantially increase the value of the space industry. We construct and analyze a coupled physical–economic model of commercial launches and debris accumulation in low-Earth orbit. Similar to carbon taxes, our model projects an optimal fee that rises at a rate of 14% per year, equal to roughly $235,000 per satellite-year in 2040. The long-run value of the satellite industry would more than quadruple by 2040—increasing from around $600 billion under business as usual to around $3 trillion. In contrast, we project that purely technological solutions are unlikely to fully address the problem of orbital congestion. Indeed, we find debris removal sometimes worsens economic damages from congestion by increasing launch incentives. In other sectors, addressing the tragedy of the commons has often been a game of catch-up with substantial social costs. The infant space industry can avert these costs before they escalate.

common-pool resources | externalities | satellite tax

In 2017, 466 new satellites were launched—more than double the previous year's launches and more than 20% of all active satellites in orbit in 2017 (1, 2). Rapid space industry growth is projected to continue, driven largely by commercial satellites (Fig. 1). This growth is driving buildup of debris in low-Earth orbit, currently including over 15,000 objects (3). Collision risk from debris is costly; collisions damage or destroy expensive capital assets that are difficult or impossible to repair. Debris buildup could eventually make some low-Earth orbits economically unviable and other orbits difficult or impossible to access (4). In the worst case—although uncertain and occurring over long time horizons—debris growth could become self-sustaining due to collisions between debris objects, a tipping point called Kessler Syndrome (4, 5).

Proposed solutions have so far largely been technological and managerial, aimed at mapping, avoiding, and removing debris (6, 7). These include end-of-life deorbit guidelines and "keep out" zones for active satellites and nets, harpoons, and lasers to deorbit debris (6). However, with open access to orbits, reducing debris and collision risk incentivizes additional satellite launches, which eventually restore the debris and risk. For instance, if firms were willing to tolerate a 0.1% annual risk of satellite loss before a technological improvement in debris removal, they will be willing to launch more satellites until the 0.1% annual risk of satellite loss was restored.

Thus, the core of the space debris problem is incentives, not technology. Since satellite operators are unable to secure exclusive property rights to their orbital paths or recover collision-related costs imposed by others, prospective operators face a choice between launching profitable satellites, thereby imposing current and future collision risk on others, or not launching and leaving those profits to competitors. This is a classic tragedy of the commons problem (1, 3, 8, 9). It can be economically efficiently addressed via incentive-based solutions, such as fees or tradable permits per year in orbit, analogous to carbon taxes or cap and trade (8, 10–12). Incentives should target objects in orbit—rather than launches—because orbiting objects are what directly imposes collision risk on other satellites (13). We quantify the economic benefits of implementing such incentives to correct the underlying open-access problem.

We use a coupled physical–economic model combining rich physical dynamics with satellite economics to quantify the benefits of an internationally harmonized "orbital-use fee" (OUF) relative to a business as usual (BAU) open-access scenario and relative to a scenario with active debris removal. An OUF is a type of Pigouvian tax—a well-known economic instrument for addressing externality problems (14). Our model accounts for the effects of each scenario on satellite launch decisions (*Materials and Methods* and *SI Appendix*). While we focus on an OUF for analytical convenience, it is conceptually equivalent to other mechanisms for pricing orbits, such as tradable permits.

Significance

The commercial satellite industry is rapidly expanding. A side effect of this expansion is a growing buildup of space debris that imposes costly collision risk on satellite operators. Proposed solutions to this debris have been primarily technological, but the core of the problem is incentives—satellites are being launched without consideration of the collision risks they impose on other operators. We show that this incentive problem can be solved with an internationally harmonized "orbital-use fee" (OUF)—a tax on orbiting satellites. Using a coupled physical–economic model, we project that an optimally designed OUF could more than quadruple the long-run value of the satellite industry by 2040.

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Data deposition: All data and code used in the analysis can be found on GitHub, https://github.com/akhilrao/tragedy-space-commons/, and at the Middlebury College data repository, https://repository.middlebury.edu/islandora/object/datm%3A59.

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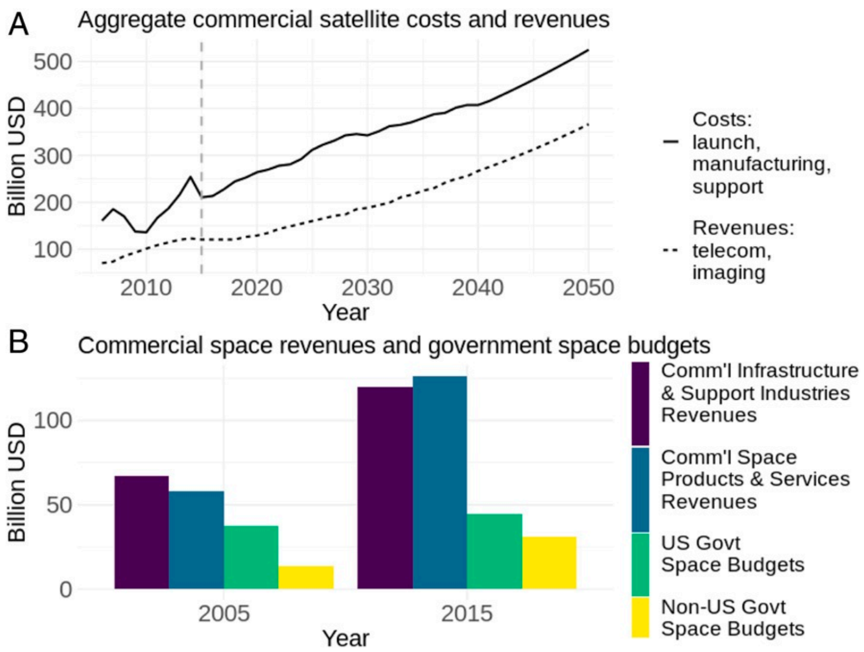


Fig. 1. State of the industry (data from refs. 6, 7, and 16). (*A*) Projected growth of satellite industry costs and revenues. Revenues and costs are yearly flows. Costs are not annuitized over the satellite lifetime. (*B*) Observed growth in commercial space sector revenues and government space budgets. Values are shown in billions of US dollars (USD).

Our physical model of satellite and debris evolution in orbit obeys relevant accounting identities and utilizes reduced form approximations of physical processes validated in other works (15, 16). We fit and calibrate the model using data on collision risk and orbital debris from the European Space Agency (ESA) (17) and data on active satellites from the Union of Concerned Scientists (UCS) (2) (*Materials and Methods* and *SI Appendix*). The ESA dataset covers 1958 to 2017, and the UCS dataset covers 1957 to 2017. Our physical model assumes runaway debris growth (Kessler Syndrome) cannot occur, which likely leads our model to understate the benefits of OUFs (*Materials and Methods*). Our economic model assumes that satellites are launched and operated to maximize per satellite private profits, net of any fees, subject to collision risk. We calibrate the model by fitting the BAU scenario (no fees or debris removal) to historical industry data and launch trends (1, 2) (*Materials and Methods* and *SI Appendix*).

We project future launch rates to 2040 under the BAU scenario using our fitted model and published projections of future growth of the space economy (18). The projections in ref. 18 were developed by projecting how the industries constituting the space sector—telecommunications, imaging, etc.—would grow from 2017 to 2040 under different assumptions on their individual profitability over time, then aggregating up to obtain projections for the space sector. We then calculate launch rates that would maximize the long-run value of the industry, and we calculate the time series of OUFs that would incentivize these optimal launch rates. The industry value is measured as net present value (NPV)—the long-run value of the entire fleet of satellites in orbit, accounting for both the financial costs of replacing satellites due to natural retirement and collisions as well as the opportunity cost of investing funds in satellites rather than capital markets. For instance, an NPV of $1 trillion in 2020 means the sum total of the stream of net benefits, looking from 2020 into the future and accounting for the timing of the net benefits, is $1 trillion.

Although our models are deliberately simplified for tractability, they are based on previously validated approaches to orbital object modeling (15, 16), and our calibrations allow us to reproduce observed trends and magnitudes in the growth of orbital debris and satellite stocks as well as the calculated collision risk (Fig. 3). Nonetheless, our projections should be interpreted as order of magnitude approximations that can be refined as needed by more detailed models. In these respects, our approach mirrors integrated assessment modeling approaches that have been useful in developing solutions to other natural resource management problems (e.g., ref. 19).

Results

We project that shifting from open access to the optimal series of OUFs in 2020 would increase the NPV of the satellite industry from around $600 billion under BAU to around $3 trillion—a more than 4-fold increase (4.18- to 6.49-fold increases in 95% of parameter sets randomly drawn from their calibrated distributions) (Fig. 2*D*). Assuming a 5% market rate of return, an increase of $2.5 trillion in NPV would be equivalent to annual benefits of approximately $120 billion in perpetuity. The large immediate increase in NPV that we project in each OUF scenario, relative to BAU (Fig. 2*A*), comes primarily from the immediate effect of reducing launch activity while the satellite and debris stocks are suboptimally high (*SI Appendix*).

Based on our calculations (*Materials and Methods*), the optimal OUF starts at roughly $14,900 per satellite-year in 2020 and escalates at roughly 14% per year (aside from some initial transition dynamics) to around $235,000 per satellite-year in 2040. Rising optimal price paths are common in environmental pricing such as carbon taxes (20), although declining optimal price paths are also possible (21). The rising price path in this case partly reflects the rising value of safer orbits (resulting in rising industry NPV) (Fig. 2*A*) from the OUF. For comparison, the average annual profits of operating a satellite in 2015 were roughly $2.1 million. The 2020 and 2040 OUF values we describe amount to roughly 0.7 and 11% of average annual profits generated by a satellite in 2015.

Forgone NPV from the satellite industry in 2040—which is the cost of inaction under BAU—escalates from around $300 billion if optimal management begins in 2025 to around $700 billion

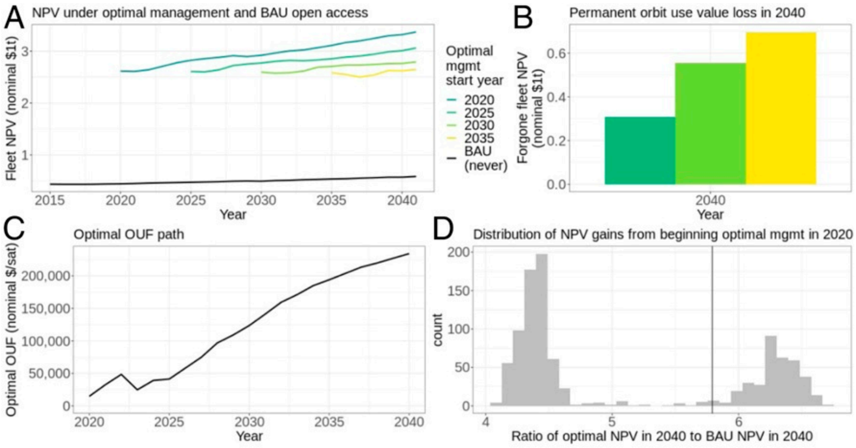


Fig. 2. Projected gains from optimal management via OUFs. (*A*) NPV of orbit recovery, with optimal management beginning in different years. BAU is shown in black. The NPV gain is the difference between optimal management and BAU. (*B*) Loss in permanent orbit-use value from delaying optimal management, relative to 2020 optimal management start. (*C*) Time path of the optimal OUF. (*D*) Distribution of the ratio of optimal NPV in 2040 (assuming optimal management begins in 2020) to BAU NPV in 2040 using 250 draws of alternate parameter sets. The distribution is calculated via a residual bootstrap resampling procedure, which illustrates the effect of calibration uncertainty. We describe the bootstrap in more detail in *SI Appendix*, section 1.4.

if optimal management begins in 2035. Without OUFs, losses remain substantial even when active debris removal (implemented in the model as removal of 50% of debris objects in orbit each year) is available. In a best-case analysis where we assume debris removal is costless (i.e., it requires no payments nor additional satellites to implement), debris removal can only recover up to 9.5% of the value lost under open access. (The satellite industry's willingness to pay for debris removal is not easily calculable in our model [*SI Appendix*, section 1.9.2].) At worst, debris removal can exacerbate orbital congestion via a rebound-type effect, causing additional losses on the order of 3% of the value already lost from open access (Fig. 4 and *SI Appendix*). The inability of debris removal to induce efficient orbit use is driven by open-access launching behavior and underscores the importance of policies to correct economic incentives to launch satellites.

Discussion

The costly buildup of debris and satellites in low-Earth orbit is fundamentally a problem of incentives—satellite operators currently lack the incentives to factor into their launch decisions the collision risks their satellites impose on other operators. Our analysis suggests that correcting these incentives, via an OUF, could have substantial economic benefits to the satellite industry, and failing to do so could have substantial and escalating economic costs.

Escalating costs of inaction are a common feature of the tragedy of the commons, evident in several other sectors in which it went unaddressed for lengthy periods (22). For example, tens of billions of dollars in net benefits are lost annually from open-access or poorly managed fisheries globally (23). Similarly, open access to oil fields in the United States at the turn of the century drove recovery rates down to 20 to 25% at competitively drilled sites, compared with 85 to 90% potential recovery under optimal management (24). Open access to roadways—somewhat analogous to orbits—is estimated to create traffic congestion costs in excess of $120 billion/y in the United States alone (25). In contrast, there is still time to get out ahead of the tragedy of the commons in the young space industry.

The international and geopolitically complex nature of the space sector poses challenges to implementing orbital-use pricing systems, but these challenges need not be insurmountable. Theory suggests countries could each collect and spend OUF revenues domestically, without losing economic efficiency, as long as the fee's magnitude was internationally harmonized (20). Engaging in such negotiations would be in the economic interests of all parties involved (26). An example of such a system is the Vessel Day Scheme (VDS) used by the Parties to the Nauru Agreement (PNA) to manage tuna fisheries. Under the VDS, PNA countries each lease fishing rights within their waters, using a common price floor (27). The European Union's Emissions Trading System provides an example of an internationally coordinated tradable permit system (28). Notably, each of these pricing programs is built on a preexisting international governance institution (the Nauru Agreement and the European Union).

An OUF could also be built within existing space governance institutions, such as the Outer Space Treaty (29). For example, Article VI states that countries supervise their space industries, which provides a framework for OUFs to be administered nationally. Article II prohibits national appropriation of outer space but does not prohibit private property rights, potentially allowing for tradable orbital permitting.

The 1972 Convention on International Liability for Damage Caused by Space Objects ("Liability Convention") could provide another mechanism for internalizing collision risk externalities. The Liability Convention states that the entity that launches a satellite is liable for any damages caused by that satellite to another satellite. To the extent damages can be attributed and the convention is enforced, launching entities may internalize some of the collision risk they impose on others. However, attributing damage caused by small fragments of debris is challenging, and the Liability Convention has yet to be seriously tested at scale. We simulate the effects of improved collision avoidance in *SI Appendix*, section 1.9.4, finding that the gains from optimal management are quantitatively similar to our base model. Indeed, costs of additional evasive actions made necessary by open-access congestion are externalities—similar to collision-related costs—that an OUF should account for. This is analogous to the importance of accounting for adaptation costs in climate policy.

Military and other noncommercial satellites are also important to consider in designing any incentive-based orbital management policy. In December 2018, 430 of 1,957 satellites had acknowledged military users (2). Some ostensibly commercial satellites may also fill national security needs. Furthermore, governments provide satellite-based public goods to their citizens, such as remote sensing and Geographic Information Systems (GIS). In addition to collision risk, satellite and debris buildup may impose costly interference on ground-based space observation systems. OUFs targeting the commercial sector should account for these interests and monitor, as best possible, any "leakage" (30) from the commercial sector to the government sector. Antarctica and the Arctic Circle offer two models of internationally managed regions in which commercial interests, environmental interests, and geopolitical interests interact (e.g., ref. 31).

We focus our discussion on an OUF rather than a launch fee levied on satellites at the time of launch, despite these being equivalent in our simplified model. OUFs should be more robust to additional realism because they directly target the source of the externality—the object in orbit. For instance, if unexpected fragmentations create an urgent need for satellites to be deorbited, an optimal OUF structured as we describe here could automatically increase to provide the necessary incentive for operators to deorbit, whereas a launch fee cannot by itself induce current satellite owners to deorbit their satellites. A launch fee would require an additional instrument, such as a deorbit rebate (described in refs. 11 and 12). By deterring new entrants, launch fees would also have the drawback of encouraging incumbents to remain in orbit. Furthermore, launch fees combined with deorbit rebates are not necessarily revenue positive, which could limit their attractiveness to governments.

Accounting for operators' ability to deorbit satellites would not affect the qualitative conclusions of our model. Open access would still cause collision risk to be maintained at a level dictated by the profitability of satellite ownership. Should one firm deorbit a satellite, they or another firm would have incentive to take advantage of the reduction in collision risk by launching another (*SI Appendix*, section 1.7).

Weitzman (32) considers whether managers should choose price-based policies (e.g., fees, as proposed here) or quantity-based policies (e.g., tradable permits) when uncertain about the marginal costs firms face in abating pollution. When the marginal costs of abatement are steeper than the marginal benefits of abatement, price-based policies are favored over quantity-based policies. These results generally lead economists to favor price-based policies for mitigating climate change. Although our model does not consider such uncertainty, Weitzman's (32) results should apply. Further research could explore the relative benefits of using fee- or quantity-based pricing instruments for orbital use.

We project a single fee for all satellites in our simplified model, but in practice, economically optimal OUFs could vary according to factors that cause satellites to differ in the collision risks they pose. Such factors may include satellite composition, orbital path and altitude, and degrees of risk internalized by satellite ownership structures, among others. Ownership structure may affect the collision risk externality because some firms—for example, megaconstellation operators—may tolerate less risk while potentially strategically imposing more risk on competitors. The next generation of orbit-use models could account for these features by computing an optimal OUF for a "standard unit" of risk, similarly to how existing models of carbon pricing calculate Pigouvian taxes for emitting 1 ton of carbon dioxide. While our estimates do not use data from megaconstellations and the dollar value of the OUF is likely too high for "smallsats," the percentage gains from optimal management calculations are more robust to such scale effects.

Despite the simplifying assumptions of our model, its key qualitative results may be robust to geopolitical and other complexities. Experience in other resource contexts supports our projection that technological or managerial solutions to the space debris problem are unlikely to be as effective as incentive-based solutions. For instance, in fisheries, attempts to restrict entry have led to "capital stuffing," where existing vessels heavily invest in harvest capacity (33). Similarly, catch limits led to the "race to fish" phenomena (34), whereby fishermen exert extreme effort to harvest as much as possible before the catch limit is reached. Attempts to build new highway capacity to reduce traffic congestion have been frustrated because new capacity induces new demand for travel (35). By contrast, policies such as individual tradable quotas (36) and congestion charges (37) directly target the underlying incentive issue and have proven more successful, although they are not without some controversy due to distributional effects (38).

The tragedy of the space commons is an international incentives problem and therefore needs an internationally coordinated incentive-based solution. Our analysis suggests such solutions could add trillions in value to the industry. Programs such as the European Union Emissions Trading System and the PNA's VDA offer potential models for success.

Data Archival

All data and code used in the analysis can be found on GitHub, https://github.com/akhilrao/tragedy-space-commons/, and at the Middlebury College data repository, https://repository.middlebury.edu/islandora/object/datm%3A59.

Materials and Methods

Here, we describe the data sources, calibration procedures, and dynamic optimization model used to quantify the economic benefits of orbits under BAU and under optimal management via an OUF.

Data. We use data on collision risk, orbital debris counts, and satellite counts provided by the ESA (17) and the UCS (2) to calibrate our physical models of aggregate active satellite and debris evolution. We use data on destructive antisatellite missile tests compiled by Brian Weeden of the Secure World Foundation (39). We calibrate our economic model of open access using historical aggregate revenues and costs for the space industry obtained from ref. 1 and launch data calculated from ref. 2. Our physical data cover 1957 to 2017, while our historical economic data cover 2005 to 2015.

For each year, the ESA data provide counts of the number of debris objects in orbit within a specified 50-km altitude band (average orbital altitude) from 100 to 2,000 km above mean sea level as well as the estimated probability that a collision occurs in the same bands. Each observation in the ESA data corresponds to a year, and each column corresponds to an altitude band. The UCS data describe all known active satellites currently in orbit, including variables for stated purpose, date of launch, and date of deorbit (if applicable). Each observation in this dataset corresponds to an active satellite, with corresponding variables describing that satellite. This dataset is spread over a series of files, released at roughly quarterly to semiannual frequencies between 2005 and 2018, from which we reconstruct yearly counts of the number of active satellites in the 100- to 2,000-km range from 1957 to 2015.

The economic dataset we use comes from refs. 1 and 18, with data from ref. 1 representing historical data. An observation in the dataset represents a year, with variables for dollars spent on different space sector activities (e.g., satellite construction and launch services, ground observation services, government spending by different national governments). We classify these entries into yearly revenues flowing to satellite owners and yearly costs of building, launching, and operating satellites (which we refer to as "launch costs" for brevity).

An observation in the final merged dataset we use for physical model calibration represents a year in 1957 to 2015, which includes variables for active satellite count, debris count, estimated collision probability, and estimated revenues and costs of launching a satellite in the 100- to 2,000-km range. An observation in the final merged dataset we use for economic model calibration represents a year in 2005 to 2015, with variables for aggregate satellite sector revenues and costs, the yearly gross rate of return on a satellite, the year over year change in launch costs, and the estimated collision probability. We describe our data and variable construction procedures in greater detail in *SI Appendix*.

Calibrating the Physical Model. We construct the laws of motion for aggregate active satellite and debris stocks from accounting relationships. We assume 1) a constant fraction (estimated per below discussion) of undestroyed active satellites naturally deorbits each period (without creating additional debris), 2) a constant fraction (50%) of debris deorbits each period, and 3) new fragment creation occurs due to launch debris, antisatellite missile tests, and collisions between orbital objects. We parameterize the probability an active satellite is destroyed in a collision using an approximate form validated in other works (15, 16) and from that functional form, derive an expression for the number of new fragments created in collisions. The parameters in these functions are calibrated separately. Specific formulas are presented in *SI Appendix*.

We first calibrate the collision probability function by fitting it to data on the estimated probability of a collision between 100 and 2,000 km, using constrained nonlinear least squares. We constrain the parameter estimates to be positive, which is consistent with the physical interpretation of the collision probability parameters as products of positive values: the magnitude of velocity differences between colliding objects, the total cross-sectional area of the collision, and scaling constants that relate object counts to object densities.

We then calibrate the debris law of motion, using the estimated collision probability parameters, by constrained ridge regression. We use ridge regression to improve the debris model out-of-sample fit, given we have relatively few observations for the number of parameters. We constrain the parameters to comply with their physical interpretations: parameters representing numbers of fragments created in collisions must be positive, while the debris decay rate must be between zero and one. Given the uncertainties involved in modeling and calibrating the potential for Kessler Syndrome, we disallow the possibility of debris objects colliding with each other. This likely makes our conclusions conservative, as it likely understates the growth in collision risk over time due to debris–debris collisions. Consequently, the estimated optimal OUF is likely less than what a model with debris–debris collisions would predict, as are the estimated benefits of implementing the OUF.

Finally, we calibrate the fraction of active satellites that naturally deorbit by fitting the active satellite law of motion using ordinary least squares. This yields an estimated average lifespan of approximately 30 y (a 3.3% deorbit rate), which is consistent with an average mission length of 5 y followed by compliance with the Inter-Agency Space Debris Coordination Committee's (IADC) 25-y deorbit guideline (40). We assume full compliance with the guideline to be conservative in our estimates of debris production. We describe our physical calibration procedures in greater detail in *SI Appendix*. We show sensitivity analyses of our calibrations in *SI Appendix*, Fig. S3 and of our model projections in *SI Appendix*, Fig. S4–S6 and describe the sensitivity analysis procedure in *SI Appendix*, section 1.4.

Calibrating the Economic Model. Economic theory predicts the collision probability will be determined by the excess rate of return on an active satellite (13). However, the excess rate of return includes the unobserved internal rate of return on a satellite asset as well as factors relating to the economic structure of the various satellite-using industries involved, which we do not model. To account for these issues, we model the excess rate of return using observed aggregate revenues and costs for the satellite industry and then include the various unknown and unmodeled factors as parameters to estimate. We fit this model to the estimated collision probability data using ordinary least squares. Since the signs of the parameters representing the unknown and unmodeled factors are ambiguous, we do not constrain the estimates. The estimated parameters are incorporated into the economic model and used to calibrate the data for unmodeled economic factors. The calibration produces estimated "implied aggregate costs," shown in *SI Appendix*, Table S5. We describe this calibration procedure and discuss the relevant unmodeled factors in *SI Appendix*. We assume a market discount rate of 5% (41). The economic gains from an OUF would be even larger in magnitude at lower discount rates (*SI Appendix*, Fig. S8).

Projecting Open-Access and Optimal Launch Rates. To project launch rates under BAU and optimal management via an OUF, we solve the dynamic optimization problems associated with launching new satellites. Under open-access BAU, each firm maximizes its own lifetime satellite profits, and the optimization problem determines each firm's decision of whether to launch or not and thus, the total launch rate across all firms. This involves calculating whether the expected lifetime revenues from another satellite exceed the cost of launching it and aggregating up from the individual decisions to the total launch rate. Under optimal management, the optimization problem directly determines the total launch rate that maximizes the NPV of the satellite fleet. This involves calculating whether the expected lifetime revenues from another satellite exceed the marginal industry-wide costs of launching it, including the expected costs of replacing other satellites lost due to collision risk created by the new satellite and its associated debris.

Solving these dynamic optimization problems yields "launch policy functions," which map the possible orbital states—satellite and debris counts, given current revenues and costs—into an annual launch rate. As the launch policy functions encode physical conditions and behavioral and institutional assumptions, the launch rates they generate are more realistic approximations of orbital outcomes than simple sensitivity analyses over all possible launch rates. That is, the launch decisions are consistent with, and respond to changes in, economic and orbital conditions. By using the launch policy functions along with the laws of motion for the satellite and debris stocks and an initial condition, we can project the number of satellites and debris in orbit each year under a specified type of management institution. We

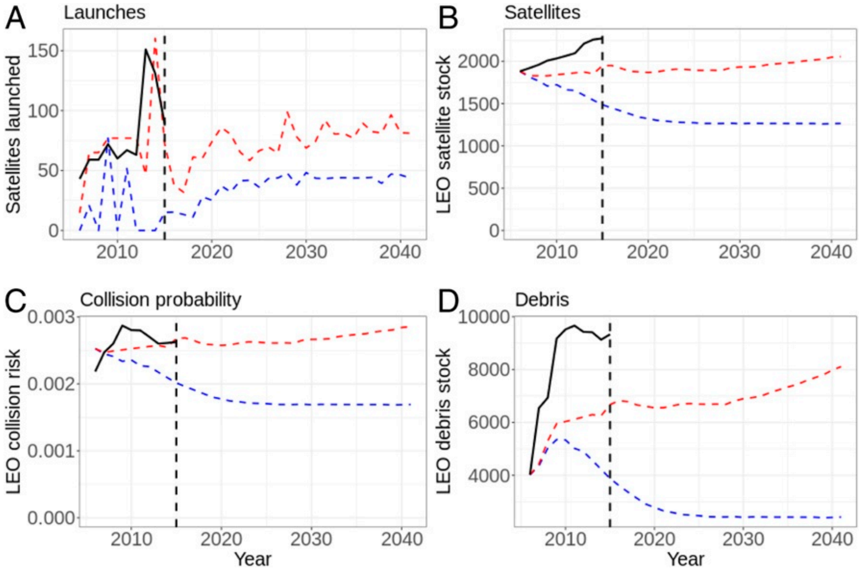
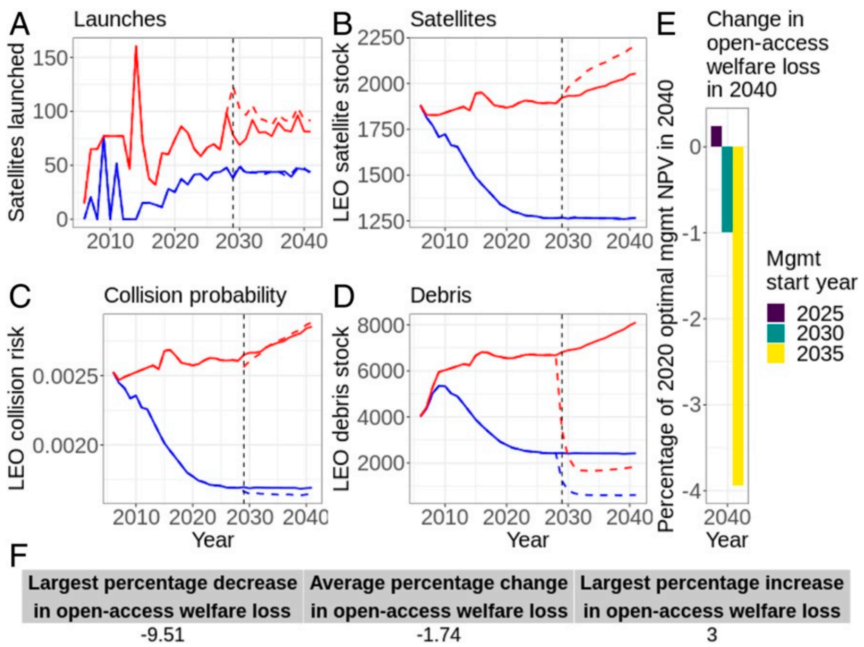


Fig. 3. Historical and future model simulations of low-Earth orbit (LEO) use. (*A*–*D*) Time paths of (*A*) satellites launched, (*B*) the satellite stock, (*C*) collision risk, and (*D*) the debris stock over time in both open-access and optimal management simulations. The solid black lines show the observed data from 2006 to 2015. The vertical dashed black lines show the end of the historical sample in 2015. The red dashed lines show the fit of the open-access model simulation, and the blue dashed lines show the fit of the optimal model simulation. Simulation paths begin from the initial condition of observed satellite and debris levels in 2006 to emphasize that the open-access model is consistent with the observed data from 2006 to 2015. Simulation procedures and discussion of the discrepancies between observed and modeled outcomes are found in *SI Appendix*, section 1.3 and Fig. S1.



Largest percentage decrease in open-access welfare loss	Average percentage change in open-access welfare loss	Largest percentage increase in open-access welfare loss
-9.51	-1.74	3

Fig. 4. Model simulations of low-Earth orbit (LEO) use with debris removal. (*A–D*) Time paths of launches, satellites, debris, and collision risk with 50% debris removal beginning in 2029. The red lines show open-access paths, while the blue lines show optimal management paths. The dashed lines show time paths with debris removal. The vertical dashed black lines mark 2029, when removal begins in the simulation. (*E*) Change in fleet NPV in 2040 with debris removal and open access, relative to a baseline of switching to optimal management in 2020 with debris removal beginning in 2029. (*F*) Summary statistics for changes in open-access welfare loss assuming 50% debris removal occurs for free beginning in each year from 2021 to 2024. Positive values in *E* and *F* indicate increased losses due to open access (debris removal makes open access worse), and negative values indicate reduced losses due to open access (debris removal makes open access better). We discuss the intuition for the results in *SI Appendix*, section 1.9. Mgmt, management.

describe the computation of the launch policy functions in more detail in *SI Appendix*, Algorithms S1–S3. Fig. 3 compares optimal and open-access projections from the calibrated model assuming no debris removal against the observed data, while Fig. 4 compares projections with and without debris removal.

Calculating the Optimal OUF and Its Benefits. The optimal OUF for each year *t* is calculated as the marginal external cost of another orbiting satellite, which is the additional industry-wide cost of another satellite in orbit (additional collision risk and debris production both now and in the future) not internalized by individual firms under BAU (*SI Appendix*, Eq. **S18**). By charging firms the marginal external cost of their satellite through an OUF, each firm's incentives and thus, their launch rates are aligned with those under industry-wide, NPV-maximizing optimal management.

To calculate the benefits of imposing the OUF, we use the launch policy functions described above to compute the NPV of the entire satellite fleet under BAU and optimal management. These NPVs reflect the value of the entire satellite fleet, in perpetuity, assuming society stays on the BAU or optimal management path. The difference between the NPVs yields the gains from the optimal OUF and moving from BAU to the optimal management path.

Although we abstract from many of the economic and physical complications in modeling orbit use, we consider how those factors would affect our analysis in *SI Appendix*. In particular, *SI Appendix*, section 1.4 details our sensitivity analyses with respect to physical parameter uncertainty, and *SI Appendix*, section 1.9 considers how these concerns may impact our conclusions. Our conclusions are likely robust to the complications we abstract from, with our calculated optimal OUF and the NPV benefits of implementing it providing the correct order of magnitude with the correct qualitative features. Future research will improve our estimates and provide more detailed guidance to policy makers.

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