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Summary and Introduction

We are an international group of academic economists active in the emerging literature on orbital-use management. Our areas of expertise include environmental and natural resource economics, industrial organization, media economics, econometrics, dynamical systems, and computational economics. Our Comment responds to questions (1), (3), and (4) of Federal Notice 86 FR 61335 ("the Notice") and addresses topics in all three focus areas of the Orbital Debris R&D Plan ("ODRP"). We thank the National Science and Technology Council ("NSTC"), the Office of Science and Technology Policy ("OSTP"), and the Orbital Debris Research and Development Interagency Working Group ("IWG") for their attention towards the issue of research and development efforts into promoting the sustainability of the space environment and orbital debris risk management. We are pleased to be able to offer economic insights to support these activities.

The questions raised in the Notice and the topics raised in the ODRP bear on several issues of long-standing and ongoing interest in the economic literature on environmental quality and innovation as well as issues in the economic literature on orbit use. Understanding the role of economic forces and the efficiency of various economic incentive mechanisms is crucial for developing an effective orbital debris risk management plan. However, research on economic policy design and modeling for the orbital environment is still relatively scarce. We believe it would be a missed opportunity if OSTP and NSTC were to ignore R&D efforts in this direction. Such R&D efforts include but are not limited to theoretical and computational economic modeling of orbit use and building new and supporting existing infrastructure to collect economic data on the space industry and conduct policy evaluation.

In this Comment we emphasize the importance of three economic policy design and modeling areas. These three areas emerge from analysis of the existing economic literature on environmental quality and innovation and orbit use. R&D effort into the areas we identify will improve both the direction and pace of innovation in all three focus areas of the ODRP and support orbital sustainability. Whether and how the United States addresses these economic R&D areas will play a pivotal role in ensuring that ODRP goals are met quickly and efficiently, and in ensuring that the United States continues to lead the world in technological development and space industrial capacity through the next century and beyond.

The three economic policy and modeling we recommend the IWG address are:

1. Research into efficient economic mechanisms that rely on natural capital pricing for orbit use and effective ways to implement them. This includes theoretical, empirical, and experimental research into appropriate policy instruments for the orbital environment.

2. Research into technology R&D support mechanisms for ODRP focus areas. This includes theoretical, empirical, and experimental research into support mechanisms to direct innovation efforts towards less-debris generating technologies, and research into how technology R&D support policies ought to be paired with orbital-use pricing or other policies based on economic incentives.

3. Research into and development of tractable and validated integrated assessment models (IAMs) to compute efficient natural capital prices, measure behavioral responses to deployment of debris responses and mitigation technologies, and identify relevant physico-economic scenarios. This includes collection of relevant economic data and support for developing and validating equations and models to describe and predict physico-economic feedback loops from technology deployment and policy implementation. Such models would also enable forecasts of future economic activity in orbital space.

The rest of this Comment is split into two sections. First, we describe some high-level insights from the economic literature on environmental quality and innovation. These insights provide suggestive evidence regarding fruitful directions of economic policy and modeling R&D effort to support the ODRP. Second, we identify key knowledge gaps relating to the orbital environment and debris risk and recommend some ways that economic policy and modeling R&D can be supported by relevant agencies. Addressing these gaps will significantly enhance relevant agencies' ability to meet the ODRP goals rapidly and efficiently.

Background

One of the main challenges the Notice and ODRP seek to address is rapid stimulation and deployment of “clean” technologies, and rapid reductions in the use of “dirty” technologies, for using orbital space. “Clean” technologies broadly encompass those which support remediation and mitigation, including technologies to improve resilience of spacecraft surfaces, designs that will reduce or limit fragmentation processes, improvements to maneuverability capability, end-of-mission approaches to minimize debris generation, and remediation and repurposing technologies and techniques for large and small debris objects. “Dirty” technologies are those which create greater debris and collision risk than is technically or economically necessary to generate useful services from satellites. Under this typology, the ODRP notes a high prevalence of dirty orbital-use technologies among orbiting objects (element I, page 5, (IWG, 2021)).

In general, ensuring innovation proceeds in clean rather than dirty directions may be more important for environmental quality than the pace of innovation (Acemoglu et al., 2012, 2016; Aghion et al., 2016). Private innovation efforts occur when innovators expect them to be profitable, which in turn requires expectations of adoption. Clean orbital-use technology adoption hinges on finding ways, through innovation and public policy, to bring the costs of clean technologies below those of dirty technologies. Government policies have a key role to play in shaping the direction, quality, and pace of such innovations (Dechezleprêtre et al., 2016), and research is needed to identify efficient policies to do so in the orbital context.

The Notice also seeks input on actions which the Federal government can take to address orbital debris challenges in the near-term and long-term. These questions speak to issues of “marginal” vs “early-stage” technologies as well as issues of orbit users’ behaviors. Marginal technologies are those which are already relatively close to market and can provide near-term environmental benefits, while early-stage technologies can provide long-term benefits with sufficient R&D effort. Technology R&D support policies can be designed to induce development in both directions.

However, technology development and even adoption are necessary but not sufficient conditions to address orbital debris challenges. Orbit users must also refrain from engaging in risk-compensating behaviors which erode gains from technological improvements (Gillingham et al., 2016). R&D effort into economic policy design, specifically natural capital pricing, is necessary to identify how relevant agencies can coordinate orbit users away from such behaviors.

More broadly, many of the issues involved in orbital-use management mirror those encountered in climate policy. A recent working paper identifies some of the parallels between the two areas (Adilov et al., 2021). One such area is the development and use of Integrated Assessment Models (IAMs). IAMs are approaches that integrate knowledge from two or more domains into a single framework (Nordhaus, 2013). In the orbital context, such models would allow researchers to both quantify the pathways through which debris accumulates and collision risk is created and to assess their environmental and economic impacts. There is ample precedent for IAM use by US Federal government agencies, e.g. the Interagency Working Group on Social Cost of Carbon (SCC) used three well-known IAMs to generate the SCC estimates and ranges used in US regulatory analyses (Metcalf & Stock, 2017). The development of such models for the orbital context could greatly aid in achieving ODRP goals.

Below we describe specific insights from the economic literature from the three areas of economic policy design and modeling we identify as necessary to support ODRP goals (natural capital pricing policies, R&D support policies, and IAM development). These high-level insights motivate the need for economic R&D to support the IWG's activity for building out an implementation plan and the types of questions such efforts might be tasked with answering.

Orbital sustainability is and will be limited by environmental externalities: the need for natural capital pricing policies

As noted in the ODRP, there is insufficient adherence to existing orbital sustainability guidelines, insufficient use of existing clean orbital-use, insufficient private R&D into clean orbital-use technologies, and insufficient private incentive to engage in orbital debris remediation and mitigation activities.[1] These observations paint a bleak picture: existing clean technologies and best practices are far from widespread and the profitability of more-advanced clean technologies appears uncertain, suggesting private incentives for clean orbital-use technology R&D are and will remain low. These observations are also in line with results in the economic literature on the effort private orbit users will exert to remediate or mitigate debris risk in the absence of environmental policy – specifically, natural capital pricing policy.

"Natural capital" refers to natural resources through which humans derive services. Orbital space is a type of natural capital. The economics literature consistently finds that pricing natural capital – i.e. policies which force resource users to account for the costs they impose on other current and future users through dirty activities – is the most important policy for stimulating clean innovation and sustainable behaviors (Hepburn et al., 2018; Adilov et al., 2021). Though it is not typically thought of as innovation policy, the economics literature has consistently found that pricing natural capital is the most efficient way to stimulate clean technology innovation and adoption (Dechezleprêtre & Popp, 2017). By providing a continuous financial incentive toward cleaner activities and disincentive against dirtier activities, natural capital pricing encourages markets in clean technologies to form, spurring innovation in clean R&D and rapid adoption of clean technologies (Baranzini et al., 2017). Pricing natural capital has also been found to significantly shift private sector innovation efforts away from dirty activities and toward clean activities (Gerlagh, 2008; Aghion et al., 2016).

There are many ways to price natural capital, and a developed literature in environmental economics explores the tradeoffs associated with different policy tools (Goulder & Parry, 2008). Two of the most well-known tools, known as "market-based instruments", are "Pigouvian taxes" and tradable pollution permits. These tools directly place a price on polluting activities. In addition, this literature has also analyzed "indirect pricing" through regulations, i.e. command-

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[1] In ODRP focus area 1, "many satellite owners/operators do not design for or meet guidelines for deorbiting at end of life … [m]any satellite owners/operators do not … employ capabilities for post-mission collision avoidance. Components of launch vehicle upper stages and payload deployment devices continue to contribute to orbital debris growth." In ODRP focus area 3, "the market for debris removal is small, largely due to the lack of defined responsibility for orbital debris removal or economic incentives to do so… [the economic losses of debris] are an externality that the market has little incentive to address."

and-control instruments which set technical standards or outright bans/limits on specific activities.

The economic literature on orbit use has explored several types of natural capital pricing policies, consistently finding that pricing mechanisms (e.g. satellite or launch taxes, deposit-refund schemes) would correct environmental market failures which limit deployment of remediation and mitigation tools and significantly increase the social value generated from orbit use (Macauley, 2015; Adilov et al., 2015; Grzelka & Wagner, 2019; Rouillon, 2020; Rao et al., 2020; Béal, et al., 2020; Guyot & Rouillon, 2021). Further, the literature shows that technical capabilities and cost reductions are insufficient to induce clean technology adoption. Adilov, et al. (2015) show that in the absence of binding regulatory or natural capital pricing policies, private satellite owners/operators will exert insufficient effort to mitigate debris production and collision risk when designing and operating their satellites. Guyot & Rouillon (2021) show similar results for satellite and launch vehicle design choices. On the remediation side, Klima et al. (2016), Klima et al. (2018), Muller et al. (2017), and Rao (2018) show that private satellite owners/operators will only exert remediation effort to the extent that they are able to privately capture the benefits.

Empirical evidence indicates that private actors respond significantly and rapidly to natural capital pricing. Responses to market-based instruments typically occur within 5 years (Hepburn et al., 2018). Responses to direct regulation can be even faster, e.g. Popp (2006) found near-immediate innovation responses to clean air regulations in the US, Japan, and Germany. Both pricing and direct regulation tend induce cleaner behavior from private actors by inducing them to bring marginal technologies online. While direct regulation may induce faster responses than natural capital pricing, it may fail to induce investment in early-stage technologies if marginal technologies are sufficient to cross the regulatory threshold. Further, by allowing firms the flexibility to choose technical solutions to minimize compliance costs, instruments such as taxes or tradable permits can foster organizational change while providing stronger incentives than direct regulation (Jaffe & Stavins, 1995; Burtraw, 2000).

These results point to the importance of natural capital pricing policy for inducing private R&D innovation into clean orbital-use technologies. Absent such policies, private actors will rationally forecast a small market for clean technologies and will not invest sufficiently in their development.

Clean orbital-use technology research and development by the private sector is and will be limited by knowledge spillover externalities: the need for R&D support policies

As noted in the ODRP, there is insufficient private R&D effort into clean orbital-use technologies.[2] These observations are consistent with the economic literature on innovation and environmental quality. Innovation generates "knowledge spillovers", a type of positive externality wherein firms are unable to fully capture the benefits generated by their R&D activity. As a result, the overall level of private investment in R&D is too low and innovations are not sufficiently diffused. Economic research consistently finds that these spillovers generate a wedge between private and social rates of return on R&D investment, pushing private R&D investment below socially-optimal levels (Pakes, 1985; Jaffe, 1986; Jones & Williams, 1998; Bazelon & Smetters, 1999).

The allocation of government spending to support clean orbital-use technology R&D is an important policy lever to ensure short- and long-term sustainability. In this respect government spending on clean technology R&D is highly complementary with natural capital pricing (Acemoglu et al., 2012, 2016). Natural capital pricing tends to favor marginal technologies (Johnstone et al., 2010; Popp, 2010). This suggests R&D support should be targeted at early-stage technologies, which can then be pulled into the market through incentives provided by natural capital pricing.

There are two other important dimensions of R&D support policy design: direct (e.g. grants) vs indirect (e.g. tax credits) instruments, and targeted (i.e. technology-specific) vs broad-based (i.e. technology-neutral) support. Indirect incentives are more likely to be technology-

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[2] In ODRP focus area 1, "many satellite owners/operators do not develop ... capabilities for post-mission collision avoidance ... [m]any launch vehicle operators do not develop approaches for orbital debris prevention."

neutral and can be more reliable and predictable for financial planning than funding awarded through competitions (Hepburn et al., 2018). Their neutrality often means indirect incentives must be targeted to ensure they favor cleaner rather than dirtier innovations, and they tend to encourage firms to invest in marginal rather than early-stage innovations (Hall & van Reenen, 2000). Direct incentives tend to have positive effects on early-stage technologies and small firms, increasing the likelihood of new good or service introduction and improving measures of innovative, financial, and commercial success in small firms (Jaffe & Le, 2017; Howell, 2017). They can also be targeted to specific technologies.

Research into clean energy technology innovations indicates governments should supplement broad-based policies with limited targeted subsidies for technologies furthest from the market (Fischer & Newell, 2008; Fischer et al., 2017). Such support can offset other market failures such as learning-by-doing (which justifies additional deployment policies to hasten technology development), path dependency (where switching costs lead to lock-in of established technologies), and capital market failures such as risk aversion (which limit the amount of private capital available for new clean technologies) (Lehmann & Söderholm, 2018). Similarly, when clean technology development is far behind dirty technologies, initial R&D subsidies are necessary to make private R&D on clean technology profitable (Acemoglu, et al., 2016). However, uncertainties in the innovation process means successful technologies are difficult to predict, and policymakers often lack the information necessary to determine which technologies are most viable and therefore merit the most targeted support (Rosenberg, 1982; Owen, 2012; Nathan & Overman, 2013). This insight favors a portfolio approach to reduce the risk of support funds being wasted by project failure. This conclusion is tempered by the evidence that technology success is the culmination of several advances building upon one another rather than a single breakthrough and that knowledge spillovers may be technology-specific (Noailly & Shestalova, 2017). A recent working paper finds that the cumulative nature of innovation and the potential for product redundancy can lead the benefits of concentrating R&D activity in a few areas (e.g. through a cap on the total number of technologies funded) to outweigh the benefits of diversification, particularly when technologies are substitutes rather than complements (Ericson, 2020).

Finally, there is the question of how technology R&D support will affect the composition of firms' R&D investments and the diffusion of new technologies. Economic research shows that the degree to which "crowding out" occurs, i.e. the degree to which clean technology R&D effort displaces less-clean R&D effort, can have substantial effects on the social value derived from innovation and natural capital pricing policies (Gerlagh, 2008). Greater crowding out of dirty innovation by clean innovation is desirable from an environmental sustainability perspective (Popp, 2004). But even with natural capital pricing and targeted R&D support which successfully crowds out dirty innovation and gives firms the flexibility to invest in projects they deem most likely to be successful, there may be other market failures (e.g. first-of-a-kind costs incurred by the first mover) or competitive incentives (e.g. raising rivals' costs by keeping innovations secret) which limit technology diffusion. Government policies – including regulatory policies such as landfilling and reforms such as patent replacement – can therefore aid in ensuring socially-valuable new technologies diffuse more rapidly and widely than they otherwise might (Jaffe et al., 2005; Grinols & Lin, 2011; Schreck & Wagner, 2017).

Current models to assess the effectiveness of orbital sustainability efforts and identify efficient policies are lacking: the need for R&D into Integrated Assessment Models of orbit use

Debris remediation and mitigation changes the complex landscape in which orbit users operate, altering both the physical environment as well as the economic incentives to use it. The ODRP recognizes this and tasks relevant agencies with developing models to study how these changes will affect the orbital environment.[3] We believe the ODRP goals will be well-supported in the near- and long-term by R&D effort into producing tractable and validated Integrated Assessment Models (IAMs) of the orbital environment. IAMs are approaches that integrate knowledge from two or more domains into a single framework (Nordhaus, 2013). IAMs of the orbital

[3] In ODRP focus area 3, "Some remediation methods may reduce the near-term risk of orbital debris without addressing the long-term sustainability of space." Topical focus area 3.3 tasks agencies with "support[ing] the development of improved models and analyses of the risks and economic impacts associated with orbital debris and remediation methods to help identify tradeoffs … Such tools could be used in support of a comparative cost-benefit analysis of mitigation and remediation technologies."

environment would therefore integrate engineering knowledge of how orbiting objects interact with economic knowledge of how orbit users choose to place and manage objects in orbit.

A central challenge in implementing efficient natural capital pricing and R&D support policies is identifying the appropriate price to levy on dirty activities and the appropriate instrument(s) through which to levy it. The economics literature is clear that efficient natural capital pricing ought to be based on the marginal external cost (MEC) of resource use. The MEC of an orbiting object will incorporate information on its orbital and design parameters (e.g. altitude, inclination, mass, cross section, fragmentation properties, probability of collision, properties of nearby objects) and its economic parameters (e.g. value of services provided, cost of replacement) (Adilov, et al., 2015; Rao, et al. 2020; Rouillon, 2020; Rao & Rondina, 2021). Calculating MECs in many natural resource settings is a non-trivial endeavor requiring bespoke coupled-systems models.

Another issue is the extent to which deployment of clean orbital-use technologies will induce risk-compensating behaviors (e.g. “rebound” effects) or sorting across orbits. Such effects have been observed in other settings with environmental externalities, e.g. road use (Duranton & Turner, 2011), energy efficiency (Gillingham et al., 2016), and neighborhood development (Heblich et al., 2021). Ensuring orbital sustainability also requires understanding how remediation and mitigation technologies can be effectively deployed to minimize behavioral rebounds and undesirable sorting effects.

IAMs can help address these challenges by providing key inputs to efficient natural capital pricing and technology policy. These inputs include the monetized damages from continued debris accumulation, the costs of mitigation or remediation options net of behavioral responses, explicit tradeoffs of damages against costs, the sensitivity of projections to model assumptions about policy implementation and degrees of international cooperation, and internally-consistent multi-sector feedback loops created by policy implementation and technology deployment (Metcalf & Stock, 2017; Weyant, 2017). IAMs can also help with targeting R&D support, as they can indicate which technology areas might be most beneficial to prioritize.

Some IAMs focus on disaggregated models of specific physico-economic processes and identify the impacts of specific policies or technologies ("detailed process" models, or DP IAMs), while others aggregate these processes to calculate global costs and benefits from high-level policy implementation and technology deployment ("benefit-cost", or BC IAMs). Climate change analyses utilize both types of IAMs (Weyant, 2017).

DP IAMs have been used to study climate change impacts on specific sectors like agriculture (Boehlert & Strzepek, 2013), impact areas like water use (Blanc et al., 2014), as well as across multiple sectors competing for common scarce resources (Reilly & Paltsev, 2009). BC IAMs have been used to estimate the MEC of pollutant accumulation (Weyant, 2017), compare alternative policies (Nordhaus, 2007), and identify "optimal" policies which balance the MEC of pollutant accumulation against the incremental cost of pollutant reduction (Hope, 2011), (Nordhaus, 2014). Though there are limitations to the use of IAMs in climate analysis and critiques of their utility (Pindyck, 2017), IAMs for orbit use are still in their infancy and will need considerable R&D effort before they are as useful as climate IAMs (Adilov et al., 2021).

Knowledge gaps and how to close them

The ODRP notes that "relevant agencies should support R&D to reduce the cost of [clean orbital-use technology] implementation, increase their effectiveness, and determine barriers to wider use" (element 1, topical area 1.1). We agree with this emphasis and recommend going one step further. Relevant agencies should support R&D into economic policy mechanisms which can most effectively induce private actors to bring marginal technologies to market and induce private R&D effort into early-stage technologies. Relevant agencies should also support R&D into modeling efforts which can jointly study the effects of physico-economic feedback loops induced by technology deployment or policy implementation on the orbital environment. Such research is also consistent with the goals of Space Policy Directive-3.

In the preceding section we provided evidence from the economics literature in support of our argument that economic policy and modeling are necessary to

1. identify the technologies and best practices most likely to rapidly remediate and mitigate orbital debris risk;

2. achieve necessary levels of R&D investment into clean orbital-use technologies in the near- and long-term; and

3. ensure clean orbital-use technologies and best practices are adopted while minimizing undesirable behavioral feedbacks, e.g. rebound effects.

While the literature finds strong evidence in favor of natural capital pricing and R&D incentives as tools to induce rapid clean technology innovation and adoption, the impact and efficacy of these policies can vary by instrument choice. Impacts can also depend on interactions between market structures, other government regulations, scope for regulatory updates, access to capital markets, bankruptcy risk, international agreements and regulations, and characteristics of natural resource users. There is very little work assessing these features of the space sector and how they might affect natural capital pricing and R&D support policies, or how they ought to be modeled to accurately capture physico-economic feedback loops. Below we describe a few of the key knowledge gaps which must be closed to meet ODRP goals; more gaps exist, and still more may be identified through further research.

Which natural capital pricing instruments are best suited to managing the orbital environment?

A long-standing literature in environmental economics notes numerous conditions under which different implementations of natural capital pricing may be preferred, e.g. direct taxes vs tradable permits or insurance requirements vs liability (Weitzman, 1974; Pizer & Prest, 2020; Deffains & Rouillon, 2018; Boomhower, 2019). While Rao (2018) finds that fundamental uncertainty over collision risks due to unmeasured debris stocks do not favor direct taxes or tradable permits, there is very little economic evidence on how a wider slate of issues (e.g. asymmetric information between firms and regulators, bankruptcy risk, liability protection) might pertain to the space sector. Similarly, while Rao (2018) finds that natural capital pricing targeted at satellite owners/operators is preferable to natural capital pricing targeted at satellite launchers, Guyot & Rouillon (2021) find that a mix of both instruments is preferable when satellite and launch vehicle design considerations are included. Lemoine (2020) offers promising evidence in favor of a new instrument, “carbon shares”, for mitigating atmospheric pollution and incentivizing negative emissions while limiting the problem of bankrupt or no-longer-existing polluters being beyond regulatory judgment. Whether and how such an instrument can be extended to the orbital context is an open question. More generally, economic research into appropriate natural capital pricing mechanisms for incentivizing sustainable orbit use and clean innovation is needed.

How will existing government regulations, market structures, and firm behavior in the space sector affect policy and innovation outcomes?

The economics literature has also noted that policy outcomes may be highly dependent on sectoral market structures. For example, in contrast to the auto industry and renewable energy sector, studies of residential energy efficiency find that stringent building codes are more effective at inducing innovation than higher energy prices (Noailly, 2012; Costantini et al., 2017). Noailly (2012) also finds that prices tend to induce more innovation in visible and portable technologies such as boilers and lighting rather than less-visible technologies such as insulation installed by builders. These findings are consistent with the idea that market failures such as principal-agent problems will reduce the innovation effects of policies based on direct prices. The extent to which such market failures are pervasive in the space sector is unclear. It is also unclear how existing government involvement in the space sector, e.g. through defense contracting and arms control measures, would interact with innovation policies such as natural capital pricing and technology R&D support incentives. Economic research on the space sector is needed to identify the kinds of R&D investments and technology adoption different policies will induce.

Similarly, market structures and consumer preferences will alter the cost-benefit calculations of different technology and policy options in ways that require careful theoretical and empirical economic analysis. Bento et al. (2018) offer an instructive case study of technical standards in this regard. They analyze a cost-benefit calculation of Corporate Average Fuel Economy (CAFE) and greenhouse gas (GHG) standards conducted by multiple Federal agencies in a 2018 Notice of Proposed Rulemaking (NPRM). The 2018 NPRM found that previous CAFE and GHG standards had costs exceeding their benefits. But the analysis in the 2018 NPRM neglected changes in the distribution of vehicle characteristics, environmental externalities, consumers' risk preferences and preferences for vehicle attributes, and interactions between the used and new vehicle markets. These oversights led to the 2018 NPRM analysis discarding at least $112 billion in benefits. This outcome underscores the need for further theoretical and empirical economic research into the space industry. Without it, accurate cost-benefit analysis of different technology and policy options is likely not possible and ODRP goals will be difficult to meet.

Which types of firms will engage in clean orbital-use technology R&D?

We have already discussed results regarding how economic policy measures may differentially affect marginal and early-stage technology deployment and research. A related question is which types of firms are more likely to supply clean orbital-use technology R&D in response to different policy measures. One such margin along which firms may differ in their responses is "upstream" (technology suppliers) and "downstream" (technology buyers). We briefly describe two studies to illustrate the ways in which existing government regulations and market structures can complicate this question.

Sanyal & Ghosh (2013) found evidence that US electricity market deregulation in the 1990s reduced innovation at upstream firms, while new Clean Air Act regulations increased innovation from upstream firms producing pollution abatement equipment. (Franco & Marin, 2017) focused on manufacturing sectors in European countries and found evidence of greater net innovation in response to environmental regulations. However, Franco and Marin found that downstream firms responded most strongly to policy measures, while regulations on upstream sectors constrained innovation. Research on upstream and downstream segments of the space sector is needed to understand which types of firms will respond to different policy measures and how.

How should clean orbital-use technology R&D policies be paired with natural capital pricing policies?

The environmental economics literature finds complementarities between natural capital pricing and R&D support policies, e.g. Acemoglu et al. (2016). There is some research on orbital-use pricing policies such as Pigouvian taxes on satellites or launch vehicles (Adilov et al., 2015; Rao, 2018; Rouillon, 2020; Rao et al., 2020; Béal et al., 2020; Adilov et al., 2020; Buchs, 2020; Guyot & Rouillon, 2021). Similarly, there is some research on policies to ensure demand for and stimulate R&D into debris remediation and mitigation technologies such as Advance Market Commitments (Lifson & Linares, 2021). But there is very little research studying effective pricing-and-support policy pairings for orbital sustainability.

Innovation policies can also have very heterogeneous effects on the composition of firms' R&D efforts. In some cases, natural capital pricing and environmental regulations can crowd out dirty innovation (Popp, 2004; Gerlagh, 2008; Aghion et al., 2016). In other cases, it can crowd out other types of productivity-improving ("neutral") innovation (Gray & Shadbegian, 1998).

These effects can be particularly pronounced for small credit-constrained firms (Hottenrott & Rexhauser, 2015). Research into the market structures of the space sector is needed to identify attractive natural capital pricing-R&D support policy pairings.

What are the likely magnitudes and patterns of rebound and sorting effects from clean technology deployment?

There is very limited analysis of rebound or sorting effects in orbit use. Rao (2018) mathematically shows that, under profit-maximizing behavior by satellite operators, the net reduction in collision risk due to debris removal is increasing in the costs paid by operators rather than the amount of debris removed. Rao et al. (2020) simulate zero-cost active debris removal in a calibrated model of orbit use and find that it can increase launch activity till most of the mechanical collision risk reductions are eroded. Rao & Letizia (2021) study sorting effects and find that increased compliance with 25-year disposal guidelines can induce greater launch activity to orbital shells just above the naturally-compliant region – increasing collision risk and causing more fragments to accumulate there over time. Natural capital pricing avoids these effects by mitigating the relative price changes due to environmental quality improvements which incentivize these behaviors. For example, Duranton & Turner (2011) and Rao et al. (2020) find that time-of-use pricing and orbital-use fees can prevent rebound effects in traffic congestion and orbital collision risk. Development of tractable and validated IAMs for orbit use will help with predicting and measuring such effects and designing policies to prevent them.

How will intellectual property law and competitive considerations affect innovation and debris risk mitigation?

Technology diffusion is supported when firms disclose clean technology innovations, e.g. through patents, but competitive incentives between firms can limit such disclosure, e.g. maintaining trade secrets so as to raise their rivals' costs. Such duplicative R&D effort is socially wasteful and limits the degree to which clean technology innovations are dispersed and adopted. In sustainable waste management contexts including orbit-use, the economics literature has found that stronger intellectual property rights can incentivize greater clean technology innovation in product design (Krystofik et al., 2015; Schreck & Wagner, 2017; Grzelka & Wagner, 2019). In the pharmaceutical context (where, like space, high fixed costs are ubiquitous), research has found that replacing patents with intertemporal sales bounties could substantially boost value generated by the sector (Grinols & Lin, 2011). Further economic research into how such tools can be leveraged to boost clean orbital-use technology R&D effort and adoption is warranted.

When and how should government support for clean orbital-use technology R&D be targeted?

Competing forces push for targeted and broad-based technology support policies. On the one hand, picking successful technologies is hard and may result in an entire line of research funding going to waste, supporting broad-based funding. On the other hand, concentrating funding in particular technologies increases their likelihood of success and may more directly address knowledge spillovers, supporting targeted funding. While the question of targeted vs broad-based R&D funding is of broad interest for technology policy beyond the space sector, it is particularly important for orbital-use technologies given the pre-existing levels of government involvement in the space sector. For example, national security goals may create a preference in favor of technology-specific policies while simultaneously creating a need for broad-based policies to support industrial base development. Ensuring clean orbital-use technology R&D policies are targeted appropriately to balance competing forces will require careful economic analysis to measure the costs and benefits of different approaches and to maintain a clear and current picture of the industrial base.

How should economic models of orbit use be integrated with engineering models of the orbital environment?

While the engineering models needed to model debris at multiple spatio-temporal scales are relatively well-developed, e.g. Krisko (2014) and Lewis (2020), the necessary quantitative dynamic economic models of orbit use and the space sector are still very early-stage (Adilov et al., 2021). Research into how engineering models of the debris environment ought to be integrated with economic models at multiple spatio-temporal scales without excessive computational cost is also nascent. Relevant agencies should prioritize R&D effort into developing and validating IAMs for orbit use.

What would it take to close the economic policy and modeling R&D gaps?

Closing key knowledge gaps regarding the effects of government policies on the orbital environment requires R&D effort into developing economic theory, producing empirical results, and running experiments. It also requires effort to collect economic and engineering data about the space sector, support existing data collection processes, and make this data broadly available within privacy constraints. Below we list a few ways that relevant agencies can support the necessary R&D into economic policy design and modeling.

- Agencies should support development of equations, tractable and validated computational methods to integrate engineering and economic models, and simulation tools which predict the effects of policies (e.g. Pigouvian taxes, R&D tax credits, guidelines and rules, resource allocation procedures) on R&D efforts, technology adoption, and orbital-use behaviors. Such research would support efficient policy design and enable measurement of policy effectiveness and additionality. Results applicable to the space sector may also be applicable to technology policy broadly.

- Agencies should request and support empirical economic analyses of the specific subsectors of the space industry, e.g. satellite design, launch, and operation, to measure historical responses to market prices, environmental outcomes, and policy changes. Such analyses would enable quantification of key behavioral response patterns and parameters (such as price elasticities and induced demand) and forecasts of future economic activity in orbital space.

- Agencies should support and conduct experimental analyses of responses to policies aimed at specific subsectors of the space industry to measure current behavioral responses and generate data for future empirical analyses. Where feasible, randomized control trials should be conducted. Where randomized control trials are not feasible, policies should be designed to enable later "quasi-experimental analysis" (i.e. econometric methods to conduct causal inference from observational data). This includes use of eligibility thresholds likely to be exogenous to industry features of interest, staggered policy rollouts, and maintenance of detailed firm-level datasets which allow researchers to control for likely confounding factors.

Data collection is a fundamental requirement to enable economic policy and modeling research. Access to relevant economic data also benefits the space industry, researchers, and other stakeholders. Below we list a few ways that relevant agencies can support the necessary data collection to enable economic research.

- Agencies should require sufficient data disclosure by satellite owners/operators and launchers to enable later econometric analyses of behavioral patterns and measurement of key parameters.

- Agencies should, in parallel with efforts to improve data collection on the orbital environment, improve data collection on the actors who use the orbital environment. Such data includes revenues and costs as well as surveys to elicit perceptions regarding the business, policy, and physical environments.

- Agencies should investigate potential to utilize already-collected data regarding satellite owners/operators and launchers, e.g. in the Census of Manufacturers, to support theoretical and empirical research. Agencies should broadly share their findings regarding the potential of utilizing such data.

- Where applicable, auctions and related mechanisms should be considered for their potential to both generate efficient resource allocations and generate important economic data regarding technology costs and willingness-to-pay.

- Where applicable, collected data should be kept securely so as to avoid compromising firms' or individuals' privacy. There is ample precedent for such data collection and management in the US Federal Government, e.g. detailed Census of Manufacturers data is stored securely and shared under restricted access in a manner which balances public interests in research insights with private interests in limiting information disclosure.

Conclusion

Economic research can support the ODRP in two ways. First, by identifying promising policy options to induce and direct technology R&D. These policy options are of two types: those which correct environmental externalities, and those which correct knowledge spillover externalities. Second, by developing Integrated Assessment Models (IAMs) which can trace out physico-economic feedback loops. These models are also of two types: aggregated models measuring costs and benefits at a global scale, and disaggregated models focused on interactions between specific subsectors. Collection and broad dissemination of economic data is a crucial enabler of economic research into policy design and IAM development, so relevant agencies should prioritize activities to collect and distribute economic data about the space sector. Economic research into these areas is missing from the ODRP and will support ODRP goals.

Respectfully,

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