Collective funding for the protection of the global commons under asymmetric benefits

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Abstract

The challenges associated with managing shared resources have frequently been highlighted in economic scholarship. This paper examines a particular form of cooperative mechanism aimed at encouraging the investment of greater effort in the preservation of shared resources in the context of space debris mitigation, namely, a collective fund dedicated to the promotion of mitigation efforts. Adopting a simple two-player game theoretic model that considers the existence of asymmetry in benefits accruing to the potential benefactors, this paper demonstrates not only that such a fund would not attract optimal funding levels but also that the players' only sensible response would be that, irrespective of the degree of asymmetry in benefits, all contributions should come from the player who receives the relatively larger benefit from the shared resources while the other player should contribute no funding at all. This implies that a collective fund dedicated to the promotion of mitigation efforts would struggle to attract contributions from actors who derive relatively fewer benefits from the utilization of outer space.

1. Introduction

Owing to the pursuit of self-interest by individual members of society, shared resources tend to be overexploited, leading to suboptimal consequences for society as a whole, a situation often referred to as the "tragedy of the commons" [4]. The management of the global commons, which are internationally shared resources, face particular challenges due to the absence of a supranational authority that can compel the relevant actors to behave in socially optimal ways.

Earlier studies have applied game theoretic models to analyze the possibility of cooperation in preserving such global commons as clean air and outer space. Some of these studies have considered the presence of asymmetry in benefits and costs among different actors [1,8,10]. This paper likewise employs a game theoretic approach to examine a particular form of cooperation that has not been analyzed in earlier literature—a collective fund dedicated to protecting the global commons.

The idea of establishing regional or global funds has recently been proposed in the context of space debris mitigation [9]. Space debris comprises disused human-made objects in space, including abandoned satellites and launch vehicle parts. Pieces of space debris may collide with and disable functioning spacecraft, thereby posing a significant threat to space activities. Countless pieces of debris are already orbiting Earth (as of February 2020, ESA estimates 34,000 objects larger than 10 cm, 900,000 objects ranging between 1 cm and 10 cm, and 128 million objects ranging between 1 mm and 1 cm [2]), and the number is increasing. Donald J. Kessler and Burton G. Cour-Palais notably predicted that the space debris population will begin to grow exponentially at some point in a phenomenon termed "Kessler syndrome" [6,7]. To mitigate the threat posed by space debris and avoid potentially catastrophic consequences, the proposed funds are intended to subsidize clean launches and debris removal activities [9].

2. Methods

This paper employs a game theoretic model in which the potential benefactors are players who try to maximize their utilities. The players' utilities are represented by a set of utility functions, and the players' behavior is analyzed by finding the Nash equilibrium, a standard solution concept in game theory whereby all actors employ their mutual responses and no actor can gain from individual deviation [3].

The game has two players, both of whom are potential benefactors of a collective fund dedicated to the protection of the global commons, specifically, outer space in this context. Although there are likely to be more than two potential benefactors for an international or regional fund for space debris mitigation, restricting the number of players will help to simplify the analysis without fundamentally affecting the results and implications of the analysis. The two players may either be interpreted as two individual states or two separate groups of states. Each player chooses a non-negative real value ($c_1 \in \mathbb{R}_+,\ c_2 \in \mathbb{R}_+$), which is the amount of respective contribution to the fund. Reflecting the properties of collective funds, contributions of the same amount from different countries are assumed to carry the same weight. Consistent with this assumption, the fund's total size would simply be the sum of c_1 and c_2. The benefit produced by the global commons is represented by a positive real value ($p \in \mathbb{R}_{++}$) which is common to both players, but the benefit gained by one of the players (player 2) is multiplied by a discount factor ($\delta \in (0,1]$). This factor is introduced to capture the real-world situation whereby the exploitation of outer space is subject to significant technological constraints and differences in technological capabilities result in differences in the benefits derived from outer space utilization. Although any state or corporation can potentially take advantage of advanced technologies by acquiring them from states and corporations that have such technologies, in reality, trade in products and technologies relating to outer space activities is rigorously controlled by national governments, primarily owing to national security and diplomatic concerns [5]. Even when they are to be traded, the governments or relevant industries of technologically advanced states can derive profit through exercising their market power. It is assumed that a complete absence of contribution would lead to a catastrophic event whereby the global commons would be entirely depleted. In this case, the benefit produced by the global commons (p) would be zero. This corresponds to a real-world situation where, for example, a specific range of orbit might become practically unusable due to the presence of overwhelming amounts of space debris, perhaps due to Kessler syndrome having been triggered. By increasing the contribution to the collective fund (c_1, c_2), the players can reduce the probability of such outcomes to zero at maximum, but with diminishing marginal returns.

The utility functions of player 1 (u_1) and player 2 (u_2) capture the above settings.

$$u_1(c_1, c_2) = -c_1 + \left(1 - e^{-\lambda(c_1+c_2)}\right)p$$
$$u_2(c_1, c_2) = -c_2 + \left(1 - e^{-\lambda(c_1+c_2)}\right)\delta p$$

The common coefficient of p and δp that appears in both u_1 and u_2 takes the form of the cumulative distribution function of the exponential distribution, which captures a situation in which uncertainty exists regarding the amount of collective investment that would be sufficient to avoid catastrophic consequences. The uncertainty may arise from the difficulty in accurately estimating and predicting the status of space debris as well as the difficulty in eliminating the possibility of making accidental addition to space debris even when an appropriate mitigation measure is in place. While the exponent in the cumulative distribution function is often interpreted as the waiting time until the event occurs, with a longer waiting time leading to a higher probability that the event will occur, it is interpreted in this model as the level of total contribution to the fund in this model, with a greater contribution leading to a higher probability that the catastrophic consequence will be successfully prevented. The higher probability that the catastrophic consequence may be avoided can alternatively be interpreted as the higher level of utility gained from space utilization, associated with the lower probability that functioning spacecraft will collide with space debris and the lower cost of making spacecraft robust against space debris. λ is an exogenous positive real parameter that allows for adjustment with respect to the fund's effectiveness in preventing catastrophic consequences. Although e, the base of natural logarithm, is selected as the base here, any real base larger than 1 other than e can be represented by adjusting λ by multiplying the exponent by the natural logarithm of the real base without affecting the analysis.

3. Results

The partial derivatives of u_1 and u_2 with respect c_1 and c_2, respectively, are

$$\frac{\partial u_1}{\partial c_1} = -1 + \lambda e^{-\lambda(c_1+c_2)}p$$

$$\frac{\partial u_2}{\partial c_2} = -1 + \lambda e^{-\lambda(c_1+c_2)}\delta p$$

Accordingly, the optimal contribution levels for player 1 and player 2 are as follows:

$$c_1^* = \frac{\log \lambda p}{\lambda} - c_2 \quad if\ c_2 \leq \frac{\log \lambda p}{\lambda}$$

$$c_1^* = 0 \quad if\ c_2 > \frac{\log \lambda p}{\lambda}$$

$$c_2^* = \frac{\log \lambda \delta p}{\lambda} - c_1 \quad if\ c_1 \leq \frac{\log \lambda \delta p}{\lambda}$$

$$c_2^* = 0 \quad if\ c_1 > \frac{\log \lambda \delta p}{\lambda}$$

When $\delta = 1$, both player 1 and player 2 optimally should contribute to the fund until the total contribution amount reaches $\log \lambda p/\lambda$. The Nash equilibrium solution does not reveal how much players 1 and 2 would each contribute. However, when $0 < \delta < 1$, irrespective of the magnitude of δ, the only Nash equilibrium is that player 1 contributes $\log \lambda p/\lambda$ and player 2 contributes zero because $\log \lambda \delta p/\lambda < \log \lambda p/\lambda$.

Taking the partial derivative of the total utility of player 1 and player 2 with respect to $c_1 + c_2$, it can be shown that the aggregate contribution to the fund would always be lower than the socially optimal level, because $\log \lambda \delta p/\lambda \leq \log \lambda p/\lambda < \log \lambda(1+\delta)p/\lambda$ always hold.

$$(c_1 + c_2)^* = \frac{\log \lambda(1+\delta)p}{\lambda}$$

4. Discussion

The model analyzed in this paper suggests that a collective fund for the protection of the global commons, including outer space, is unlikely to attract the optimal level of total funding, which is consistent with earlier studies that predicted that collective action would yield suboptimal results. Furthermore, this papers' findings reveal a unique Nash equilibrium under such a mechanism when benefits are asymmetric, whereby the actor receiving the relatively higher benefit makes the entire contribution to the fund while the other actor contributes nothing. The intuitive explanation for this result is that, as the actor receiving the higher benefit would contribute a greater amount than is optimal for the actor receiving the lower benefit, regardless of the amount that the latter contributes, they will always be better off contributing less.

This result implies that a collective fund for the protection of the global commons would face significant difficulty in enticing contributions from actors who derive relatively fewer benefits from the commons. In practice, such asymmetry may arise when access to the commons is subject to technological constraints, as is the case for outer space. It may be predicted from the model that the initiative to create a collective fund for space debris mitigation would inevitably have to be led by a group of technologically advanced countries that benefit most from the utilization of outer space and that the funding would predominantly, if not entirely, come from these countries.

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