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With asteroid mining promising vast amounts of wealth for anyone who chooses to seek it, there is a clear conflict of motivation between individual governments and private investors who seek their fortune among the stars, and the majority of people without access to the capital needed to fund such a venture. That majority though, has the United Nations Outer Space Treaty of 1967 backing them up. It promises that the exploration and use of outer space shall be carried out for all countries, and be the province of all mankind. How though, can the UN carry out it's vision of cooperative equitable use of outer space resources?

This work proposes a solution, defining and modeling equity and how it is distributed, as well as a potential future for asteroid mining. Using these models, the analysis recommends policies and strategies for the UN to effectively ensure that the resources in outer space are used equitably.

Near future asteroid mining is considered, with technologies and pricing of today. Space elevators dominate the analysis with their lower cost of transporting materials into orbit. The model is built from current estimates of costs and material prices, avoiding common pitfalls made by researchers estimating asteroid value by utilizing standard micro-economic theory. The model is kept practical by avoiding as much as possible future technologies that are unlikely to be developed.

Focusing on equity through a lens of welfare economics, a model of global equity under asteroid mining is developed and used to propose UN policies which could maximize global equity as asteroid mining becomes technologically and economically feasible. The model is a multi-agent model wherein each agent is a region capable of trading with other regions and collecting economic value from asteroid mining. It is assumed that all UN-taxed value is distributed to member regions according to population. Using net income figures for each region, global social welfare is calculated using an adapted Foster's welfare function, which accounts for total income per capita as well as income equity. Model parameters are varied to optimize the adapted Foster's welfare function, and UN policy is designed to produce optimal model parameters.

Using these models, five recommendations are made to the UN.

1. The UN should introduce a maximum proportion of asteroid-derived value that the most space-capable nations may use to further their dominance of international trade.

2. The UN should introduce a minimum proportion of asteroid-derived value that the least space-capable nations may use in global trade.

3. The UN should introduce an international tax for all member states that applies to asteroid-derived value. This value should be redistributed to member states fairly according to population.

4. The UN should aim to redistribute asteroid tax value as efficiently as possible.

5. The UN should make an effort to control space elevators, by creating or investing in them.

With these models, the UN has an excellent plan with concrete actions to take to advance global equity alongside a future that involves asteroid mining.

# Contents



# 1 What is Global Equity?

Global Equity can be framed as an extension of the concept in public administration called "Social Equity". Social Equity emphasizes the needs of the citizens, and assumes that each member of a society may need services in different measures.For example, distribution of goods not just equally, but according to the varying level of needs. Thus, the concept of global equity is social equity applied globally, to multiple societies, or multiple countries. When each country may need resources or services in different measure, global equity distributes according to that need, in a fair and just manner.

Framing the issue in terms of welfare economics, the state of global equity may be defined to be the value of a cardinal social welfare function, which is a function which takes as input quantitative representations of individual utilities and provides as output a numerical value representing social welfare. A cardinal social welfare function must satisfy six axioms:(1) monotonicity, if the utility of one individual increases while all others remains equal, the function must increase; (2) symmetry, the function must not change value if the utility profile is permuted; (3) continuity, the sets of profiles worse and better than a given profile must both be closed; (4) separability, the function is independent of individuals whose utilities have not changed; (5) independence of common scale, the comparison of two utility profiles does not change if they are both multiplied by the same scalar; and (6) Pigou-Dalton Principal, the function must prefer allocations that are more equitable [7].

Where traditional social welfare functions take individual utilities as an input and ranks societal states as better or worse, the global social welfare function (GSWF) takes regional utilities as an input and ranks global states as better or worse. Thus the fairness and justness of a given global social state, or how global resources are distributed, is determined by the welfare of each region as if it were an individual.

# 2 Measuring Global Equity

## 2.1 Model Summary

Here, a model of global equity under asteroid mining is developed and used to propose UN policies which could maximize global equity as asteroid mining becomes technologically and economically feasible. The model is a multi-agent model wherein each agent is a region capable of trading with other regions and collecting economic value from asteroid mining. Regions are groups of countries collected together to simplify the model. Economic value garnered from asteroid mining may be taxed by the United Nations. It is assumed that all UN-taxed value is distributed to member regions according to population. Using net income figures for each region, global social welfare is calculated using an adapted Foster's welfare function, which accounts for total income per capita as well as income equity. Model parameters are varied to optimize the adapted Foster's welfare function, and UN policy is designed to produce optimal model parameters.

Analysis finds that income benefits a given region and its surrounding region with the greatest effect on the given region.

## 2.2 Reasoning and Justification

Given the lack of a formal welfare function of every country on earth, a common substitution would be a country's GDP. GDP is a measure of the market value of all goods and services produced over a given time, and is often used to measure a country's prosperity or development. This choice, however, is a misguided one. GDP is a poor approximation of a country's social welfare function, as individual welfare does not map proportionally to national production. To quote Robert F. Kennedy,

> "Gross National Product counts air pollution and cigarette advertising, and ambulances to clear our highways of carnage. It counts special locks for our doors and the jails for the people who break them. It counts the destruction of the redwood and the loss of our natural wonder in chaotic sprawl. It counts napalm and counts nuclear warheads and armored cars for the police to fight the riots in our cities...it measures everything in short, except that which makes life worthwhile."

In short, a high GDP indicates the presence of wealth, but does not indicate that that wealth is benefiting all members of a society. More rigorously, GDP does not satisfy the Pigou-Dalton Principal, making it unsuitable as a welfare function. A more apt welfare function must prioritize equity, but cannot neglect total income. To illustrate this point, consider the limit case in which all individuals have no income. While this case has optimal equity, it is unfavorable for all individuals, so total income clearly must be considered. Here, an established welfare function which rewards both high income and high equity between individuals is adapted used as a GSWF. Using this metric of equity, policy-controllable parameters like trade volumes and tax rates to inform UN policy decisions.

## 2.3 Assumptions

1. Global trade is well-approximated by a handful of 'regions'
2. The trade profile of each of these regions is well-approximated by the profile of the most economically powerful country included in the region
3. The welfare of a region corresponds to the welfare of its citizens
4. Welfare increases with equity and with income
5. The mineral and monetary benefits of asteroid mining may be reduced to a single economic value.
6. UN may tax materials mined on asteroids, and revenues are redistributed according to population.
7. Asteroid-derived resources will be exported by each region according to the distribution of total exportation for all goods now.

## 2.4 Model Construction

### 2.4.1 Foster's Welfare Function

In order to develop a GSWF which reflects the total world income from asteroid mining as well as inter-regional equity, metrics of total income and equity individually must be established. For total income, this is straightforward. Simply let $\overline{Y}$ be the mean income:

$$\overline{Y} = \frac{1}{N} \sum_{i=1}^{N} Y_i,$$

where $Y_i$ is the income of the i-th agent and $N$ is the number of agent.

Establishing a metric for equality is more difficult. One approach is to use the Theil index, which is a measure of economic inequality based in information theory. The Theil index is defined to be the difference between the maximum possible and observed Shannon entropies of the income-per-agent distribution [6]. The Theil index may be derived from information theoretic principles and is stated:

$$T = \frac{1}{N} \sum_{i=1}^{N} \frac{Y_i}{\overline{Y}} \ln\left(\frac{Y_i}{\overline{Y}}\right),$$

where $N$ is the number of agents, $\overline{Y}$ is the mean income, and $Y_i$ is the income of the i-th agent.

Foster's welfare function is a social welfare function calculated as the product of the exponentiated, negative Theil index and the mean income:

$$W_F = \overline{Y} e^{-T}.$$

Foster's welfare function satisfies the social welfare function axioms and will be adapted to serve as a GSWF for this analysis.

For the purposes of this analysis, the world will be divided into $N$ 'regions.' Each region will be treated as an agent in social welfare analysis but, unlike in traditional social welfare analysis, it would not be equitable if each region received the same income, because they are not equally populous. In order to achieve maximal equity, global regions would not need to achieve equal income, but instead would need to achieve equal income per capita. This is because a given level of income in one region does not contribute to welfare the same as that same level of income in a more or less populated region. For this purpose, income expressions in both mean income and Theil's index must be adapted to income per capita. This gives the following formulation:

$$\overline{Y}' = \sum_{i=1}^{N} \frac{Y_i}{P_i N}$$

$$T' = \frac{1}{N} \sum_{i=1}^{N} \frac{Y_i}{\overline{Y} P_i} \ln\left(\frac{Y_i}{P_i \overline{Y}'}\right)$$

$$W_F' = \overline{Y}' e^{-T'}.$$

For the purposes of this model, economic value derived from asteroid mining will be considered as income while all other forms of monetary value are neglected. This is in keeping with the United Nations' Outer Space Treaty of 1967, which requires that the exploration of outer space specifically must benefit all countries. Just as Foster's welfare function rewards high income and high equity between agents, with a higher weighting of low-income agents, this formulation, which will be called the adapted Foster's welfare function, rewards high income per capita and high equity of individuals in a system where the agents are regions of variable population.

### 2.4.2 Validation

This model of global social welfare will be validated on a simple toy example where the appropriateness of the model's predictions will be evident. Consider two regions: A and B. Suppose region A has a population one fifth that of region B (without loss of generality, suppose region A has a population of one and B a population of five). The adapted Foster's welfare function is in this case a function of two variables: $Y_1$, the income of region A, and $Y_2$, the income of region B. These arguments are passed into the $W_F$ function as $W_F(Y_1, Y_2)$. Observe that

$$W_F(10, 10) = 4.71 \text{ and } W_F(20, 20) = 9.42,$$

so increasing the income of all regions increases welfare, as expected. Also observe that

$$W_F(10, 10) = 4.71,\ W_F(20, 10) = 7.46, \text{ and } W_F(30, 10) = 10.11$$

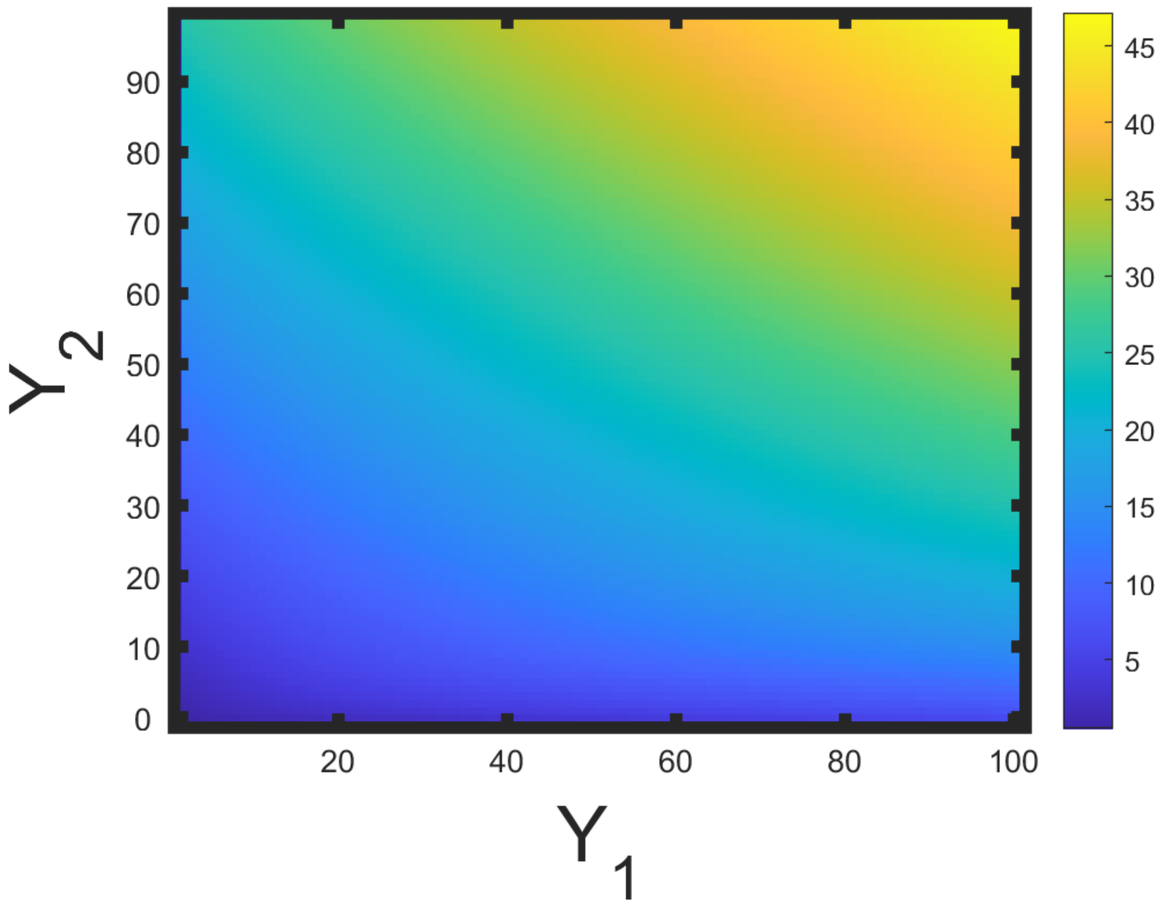


Figure 1: Heatmap illustrating the behavior of the adapted Foster's welfare function as the incomes of region A ($Y_1$) and region B ($Y_2$)) are varied. No unexpected behaviors are observed.

$$W_F(10, 10) = 4.71, \; W_F(10, 20) = 6.37, \; \text{and } W_F(10, 30) = 7.7513,$$

so increasing the income of one region increases welfare, but is more impactful in Regions with a lower population, as expected. A heatmap of welfare values for a range of income levels to both regions shows that the expected behaviors persist across the domain (Figure 1).

The adapted Foster's welfare function performs well on this example, is based on well-known methods from information theory and economics, and can be derived from a small number of robust assumptions. These elements together confirm the validity of the adapted Foster's welfare function as a GSWF.

# 3 A Future of Asteroid Mining

## 3.1 Background

Facing limited access to valuable resources hear on earth, and the prevalence of valuable materials in asteroids, humanity often looks to asteroids for the resources we need. Asteroid mining is currently theoretical, and limited largely by economic and technological factors.

Asteroid mining studies have often focused on rocket based designs, where the cost of getting into and out of orbit is expensive. This leads those studies to focus on high value materials in asteroids, such as platinum, to offset the transportation cost. Some other studies propose keeping mined materials for use in space to reduce that cost, such as using water for rocket fuel.

## 3.2 A Possible Future

The analysis suggests that the most likely future for asteroid mining will be high volume mining of minerals whose value on average is fairly low. A conservative estimate for maximum profit is in the range of tens of billions of dollars per year. With this, the quantity of materials mined would be in the range of $10^{10}$ kg per year. Additionally, the scale of costs and profits suggest that this would be feasible for private or national enterprises. International enterprises are possible, but are not necessary and as such are not as likely.

## 3.3 Assumptions

1. Space mining operations will be driven by profit. Specifically, mining operations with larger profit margins are more likely to occur.
2. All materials transported to and from earth incur the same cost each way.
3. Costs for an operation are within an order of magnitude of previous estimates.
4. Demand for metals mined is similar to that of the current demand for metals.
5. Space elevators are a feasible technology given development time and funding.
6. Given investment, electricity costs can be reduced large amounts by creating infrastructure.
7. A space elevator, or multiple, are capable of transporting high volumes of material given development time.

## 3.4 Reasoning and Description

Assuming profit driven mining operations, a function can be constructed to determine the relative likelihood of a given mining operation based on it's profit margin. First, a mining operations' profit will be determined by its revenue minus its expenditures.

$$P = R - C \tag{1}$$

An operations revenue can be simply modeled, as a mining operation it can be determined by quantity of the resources it extracts multiplied by their prices.

Costs can be separated into orbital costs (transporting materials and equipment to and from earth), operations cost (cost of resource extraction), development costs (creating new technologies and infrastructure).

$$P = \sum_{material_i = material_0}^{n} (price_i * quantity_i) - (C_{orbital} + C_{operations} + C_{development}) \tag{2}$$

### 3.4.1 Orbital Costs

Orbital costs are often measured in dollars per kilogram, and current cost estimates are for cost of getting materials into orbit. There are several proposal for methods of returning mined materials from orbit, including thermal concentrators, mass drivers, rotary launchers. These methods are highly theoretical, and have not yet been shown to be possible. For returning materials through rocketry, especially reusable rockets, it makes sense to assume cost for returned materials is the same as the cost as for returned materials, as for a space mining operation rockets will necessary carry down disproportionately more than they bring to orbit. This means that the same operational costs, rocket refurbishment, and fuel costs will be needed to bring materials back down. Similarly, for a space elevator the amount of energy is the primary cost, and space elevator climbers would climb up and down, expending the same costs for bringing materials up as down. Thus this model assumes an equal cost of getting materials back to earth safely.

Current costs for rocket material transportation to low earth orbit average about $12,000 per kilogram with a minimum of about $2,700 for the reusable Falcon 9. [4]

Cost estimates for space elevators are about $220 per kg to geostationary orbit, based on power beaming and electricity prices[3]. However, with increases in power beaming efficiency and/or powering the system through solar power could reduce that cost of electricity, making the trips far cheaper.

Orbital costs largely determine what materials are viable to mine and transport to earth, as paying thousands to transport raw iron to sell it for tens of dollars will never be economical. However, some materials are valued for their use in space, where orbital costs play a much smaller factor. Water, for example, could be used in space to create rocket fuel. However, because of the focus on impact on earth this model focuses on mining operations that profit primarily from bringing metals back to earth.

### 3.4.2 Operations Costs

Operations costs are dependent on the type of operation chosen. Mining, refinement, and production could all take place in space, only bringing materials down for final consumption. One estimate for operational cost is $5.7M.[5]

The NASA GRC COMPASS team estimated the full life-cycle cost of an asteroid capture and return mission at $2.6B.[8] This is another possible operational cost, as capturing and returning asteroids could make it easier to build reusable operations infrastructure.

Ultimately, operations costs can vary largely depending on the method of mining chosen. Additionally, it's hard to predict because of the new technology necessary to mine and process asteroids in space. This is accounted for by taking past estimates as a starting point, and analyzing using a range around them to account for actual cost differences.

### 3.5 Development Costs

Development costs depend on mining strategy, and on any given estimate. In addition, development cost is in practice hard to predict. To mitigate this, development cost is modeled with a wide range of possible values. Referencing earlier estimates for reusable spacecraft mining, a development cost estimate range is from $75M to $818M.

For space elevators, initial development of the elevator is estimated to cost $15B.[3] Development costs for a space elevator are notably high, but a one time cost. For analysis, this cost is spread out over ten years of mining to reduce the impact on current profitability.

### 3.6 Revenue

A robust model of the long term value of asteroid mining can be constructed by estimating supply and demand curves. Asteroids often contain a specific subset of materials, and are classed into several types. For this model, we consider the average of valued materials over a range of asteroids, labeled material $m$. This material's price will be labeled $p$, the cost producers are willing to extract material for, and the price consumers are willing to pay. Following supply and demand curve tradition, the quantity will be labeled $q$.

So, given a supply function on price, $S(p)$, and a demand function on price, $D(p)$ the model predicts the expected price and quantity of material, and thus revenue for a given time period.

### 3.7 Total Profit

Using the costs detailed above, we can predict the percent return on investment for a given cost and quantity.

$$\frac{R-C}{C} = \frac{P \cdot Q}{C_{orbital} + C_{operations} + C_{transit} + C_{development}} \tag{3}$$

This works well for the producer end, for modeling how profitable a given venture will be given a cost and quantity. However, it is important to consider the demand for materials created from space mining. This however, is challenging to predict. In 2019, 457 tons of platinum were mined, with approximately 13 billion in value[1][11]. It would not be realistic to assume mining the same amount of platinum would give that same price, but to expect a drop in price given an increase in supply without a matching increase in demand. This is similar for many of the precious metals contained in asteroids. High volume metals such as iron (3 billion tons mined in 2019[1]), would have a much more stable, but much lower price. An additional confounding factor is the increase in demand caused by new uses of various materials. If asteroid mining produced a surplus of nickel as a byproduct of mining for the higher valued platinum, the value of nickel could increase as more uses for cheaper nickel could be found. To avoid over-optimistic estimates, the supply curve is estimated to be at a value based on current market rates, and current quantities mined.

To start, the model's space of possibilities includes prices from that of iron, currently at around $60 per kg to that of platinum, around $26 million[11]. The model will consider mining from 1 ton of material, to double the worlds current supply of metals, about 6.4 billion tons. Using this in combination with costs, the model can estimate how profitable a given venture can be depending on price and quantity.

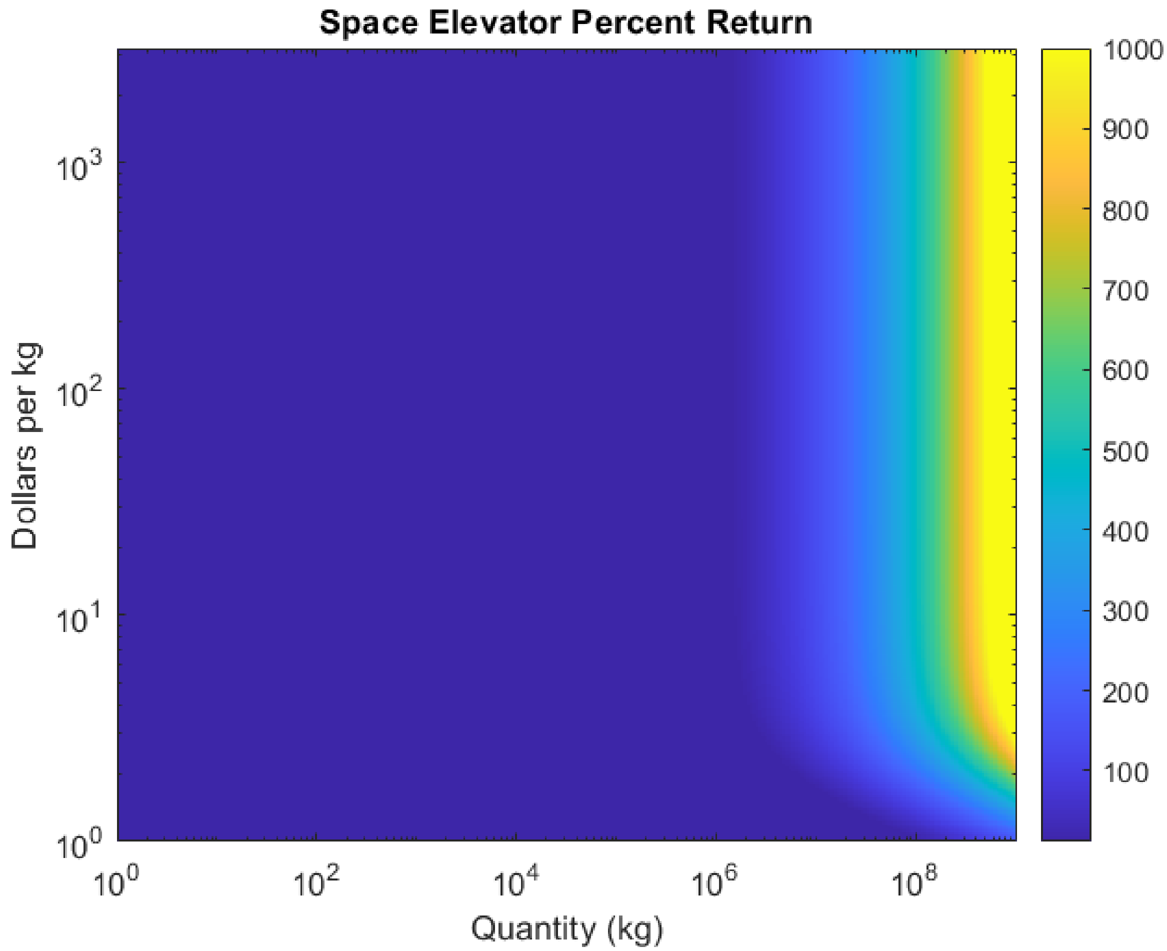


Figure 2: Percent return on mining ventures given quantity and price. Many of these may not be viable due to the demand curve.

Many of the higher return values are unrealistic, as described previously 6.4 billion tons of gold would not be able to sell for the current cost of gold in a given year. To clarify what a realistic mining venture would look like, the model considers current prices and quantities of commonly cited asteroid-mineable metals.

| Common Asteroid Metal Quantities and Prices[1][11] | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Iron | Aluminum | Manganese | Nickel | Cobalt | Gold | Platinum |
| Price per kg (Dollars) | 0.09 | 2.64 | 2.06 | 19.93 | 33 | 57,058 | 27,392 |
| Yearly quantity mined (Metric Tons) | 3.04 B | 62.9 M | 56.6 M | 2.7 M | 123 k | 3.3 k | 457 |

This gives a logarithmic line of best fit.

$$p = e^{-0.8451q+9.3664} \tag{4}$$

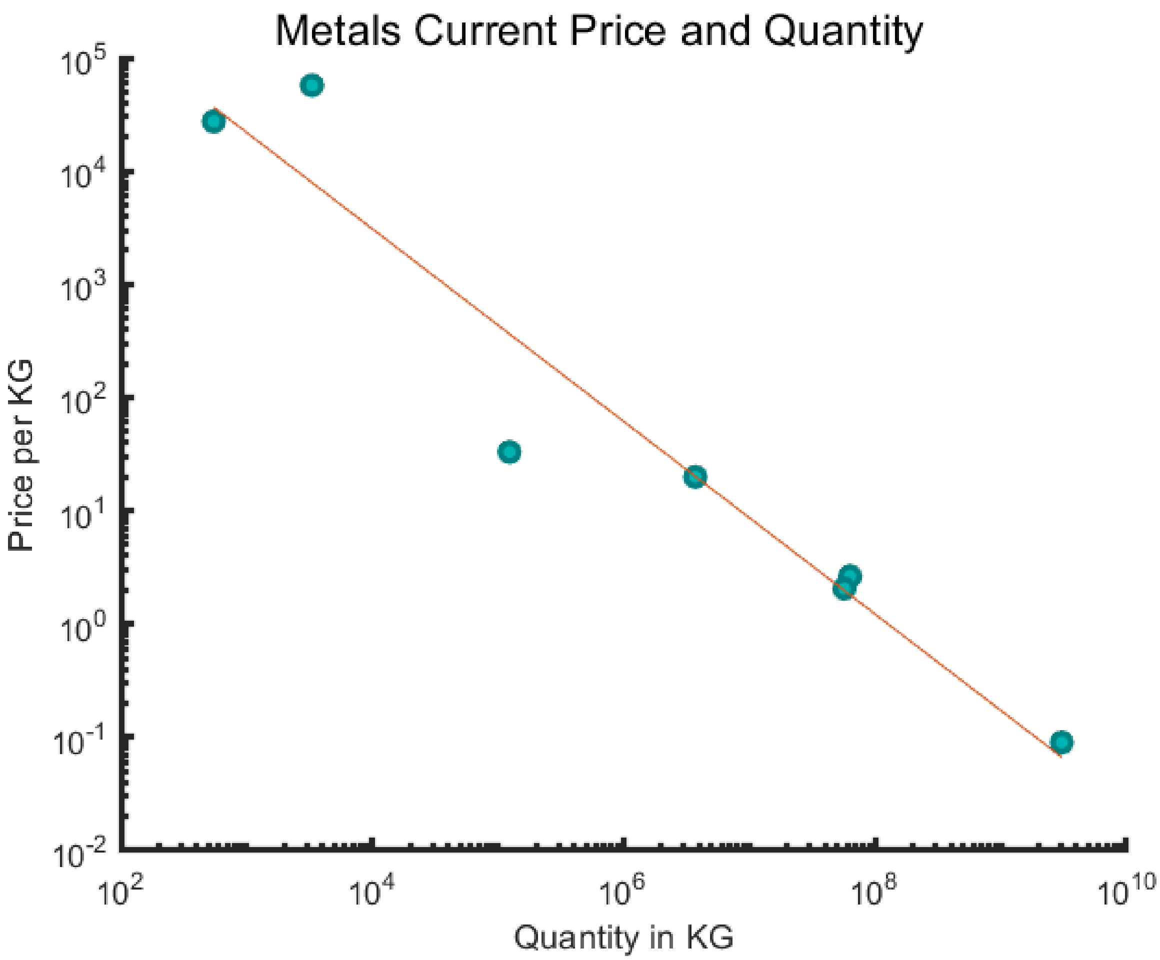


Figure 3: Asteroid metal quantities and prices, with logarithmic line of best fit.

Using these metrics, for what realistic supply looks like and what profitable ventures look like it becomes possible to find the most profitable, and therefore most likely, venture. In addition, it can be calculated what the scale of that profit is. The first notable result is that using even the most optimistic development and operational costs (1 million each) and current orbital costs no profitable rocket based operations can be found. In part this is due to conservative price estimation, however, in a venture with so many unknowns this is a good strategy. Thus, the analysis chooses to focus on asteroid mining involving a space elevator, and thus lower orbital costs.

For a space elevator with operational costs of 5.7 Million, no development costs, and orbital costs of $220 per kg, no profitable operations can be found. However, if the operational costs decrease to 1 Million a venture with a 25% return on investment can be found. This is a very optimistic scenario, where the space elevator is developed independently but can be used as part of the mining operation. Because of the unlikeliness of an independently developed space elevator that also happens to work well for mining, the analysis chooses to focus on another scenario.

For a space elevator with the same operational costs, a development cost of $15 Billion spread over 10 years, and exceptionally low orbital costs ($0.1 per kg), there are many many profitable scenarios. The low orbital costs are a primary factor, leading to large scale sales of metals at lower prices. The remarkably low orbital costs are justified by renewable sources of electricity built out in the initial stage of space elevator development, reducing the primary driver of orbital cost in a space elevator scenario. In this scenario, profit begins at around \$4.5 per kg of orbital cost. Analysis will go from there, to around \$0.05 per kg of orbital cost.

| Most Profitable Asteroid Mining Operations | | | | |
|---|---|---|---|---|
| Orbital Cost (\$ per kg) | Max Percent Return | Total Profit | Price (\$ per kg) | Quantity (kg) |
| 4.5 | 0.07 | 2.84 M | 7.108 | $10^{8.762}$ |
| 4 | 7.8 | 321 M | 6.806 | $10^{8.814}$ |
| 3 | 29.3 | 1.2 B | 6.143 | $10^{8.935}$ |
| 2 | 67.2 | 2.75 B | 5.287 | $10^{9.112}$ |
| 1 | 159 | 6.55 B | 4.091 | $10^{9.416}$ |
| 0.5 | 302 | 12.4 B | 3.178 | $10^{9.715}$ |
| 0.1 | 1014 | 41 B | 1.759 | $10^{10.41}$ |
| 0.05 | 1627 | 66.6 B | 1.366 | $10^{10.71}$ |

Results from this analysis are a conservative estimate for maximum profit levels for an asteroid mining operation are around 66.6B. Feasible operations should focus on minimizing orbital costs, as maximum profit comes from reduced orbital cost. This analysis focused on the most well researched form of that reduction, through space elevator development, and this is currently the most feasible option for mining. In addition, to avoid saturation (and thus devaluing) of valuable minerals, high volume mining is recommended. In addition, this scale is suited for private or national enterprises, as profits and costs are in the $10^{10}$ range.

# 4 How Does Asteroid Mining Impact Global Equity

## 4.1 Multi-Agent Model

For the purposes of this analysis, the world will be divided into five regions: (1) Americas, (2) Europe, (3) Asia, (4) Africa, and (5) Oceania. This indexing scheme (1-6) will be used to arrange regional data into vectors and matrices throughout this section. These regions were selected because they align most closely with the availability of useful demographic data. The regional populations (in billions) are summarized [10]:

$$P = \begin{pmatrix} 1.0228 \\ 0.7476 \\ 4.6411 \\ 1.3406 \\ 0.0431 \end{pmatrix}.$$

Regional space exploration spending as a proportion of global space exploration spending, which is assumed to be indicative of future asteroid-mining capability is also summarized [9]:

$$S = \begin{pmatrix} 0.5393 \\ 0.2383 \\ 0.2152 \\ 0.0070 \\ 0.0002 \end{pmatrix}.$$

The distribution of exported economic value from the most economically powerful country in each region, which is assumed to be reflective of the region as a whole is also summarized [2]. $T_{ij}$ is the proportion of exports from the j-th region which are imported by the i-th region. The economic power of a country was assumed to be fully described by GDP, so the six regions are represented in exportation by (1) USA, (2) Germany, (3) China, (4) Nigeria, and (5) Australia.

$$T = \begin{pmatrix} 0.43 & 0.12 & 0.26 & 0.069 & 0.066 \\ 0.23 & 0.67 & 0.21 & 0.39 & 0.084 \\ 0.31 & 0.19 & 0.47 & 0.34 & 0.8 \\ 0.015 & 0.016 & 0.043 & 0.19 & 0.008 \\ 0.019 & 0.0082 & 0.024 & 0.0065 & 0.037 \end{pmatrix}.$$

The model will consider each region as a single entity which collects resources from asteroid mining and exports those resources to other regions as outlined above. These resources will necessarily be brought to Earth inequitably, but the UN requires that all regions benefit equitably from them, so, to the end of motivating future UN policy, the model assumes that some proportion $U < 1$ of all asteroid-derived value is 'taxed' by the UN and redistributed to all regions such that they all make the same income per capita. This redistribution will necessary have a sub-ideal taxpayer return on investment, so only a proportion $E < 1$ of redistributed wealth will actually be redistributed, with some value being lost. This scheme allows for regional incomes to be calculated as a vector:

$$Y = (1 - U)AS + (1 - U)(T - I)AS \circ Q + E\left(\sum UAS\right)P,$$

where $A$ is the total rate of value acquisition from asteroids, $I \in \mathbb{R}^{5\times5}$ is an identity matrix, and $Q$ is a vector whose i-th entry is the proportion of its asteroid resources (after UN tax) that region i chooses to export. $\circ$ denotes the Hadamard product. Because each term of this expression contains $A$, the income of each region per unit asteroid harvesting rate may be derived:

$$\frac{Y}{A} = (1 - U)S + (1 - U)(T - I)S \circ Q + EU\left(\sum S\right)P,$$

which may be easily normalized for population by dividing element-wise by $P$.

This model of the distribution of asteroid-derived resources is parameterized by $Q$ and $U$. The model produces regional incomes per capita which may be used alongside the adapted Foster's welfare function to evaluate the equity of a given combination of $Q$ and $U$. Because $Q$ and $U$ reflect trade dynamics and UN taxation respectively, both of which may be regulated, using the adapted Foster's welfare function as an objective function to optimize these values will yield motivated UN policy suggestions.

## 4.2 Our Future of Asteroid Mining's Impact on Global Equity

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All analysis uses $A = 1$, so incomes are incomes per arbitrary unit asteroid mining rate. Our potential future does not incorporate UN taxation and redistribution of minerals mined on asteroids. Selecting an intermediate, uniform trading proportion of $Q_i = 0.2$ for all regions, welfare may be calculated as a function of UN tax rate $U$ for a representative sample of UN tax return on investment

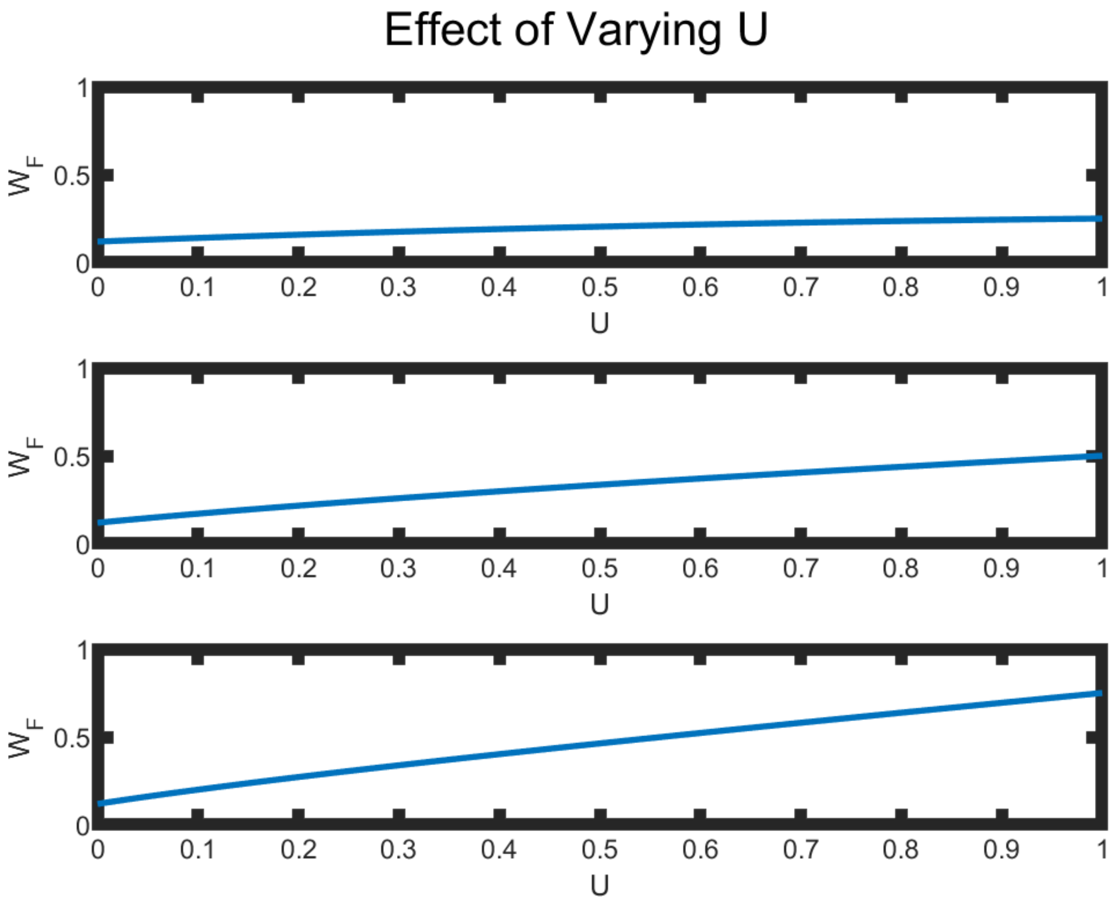


Figure 4: Welfare as a function of degree of resource distribution at $E = 0.25$ (top), $E = 0.5$ (middle), and $E = 0.75$ (bottom). Welfare values are calculated as if 1 arbitrary unit of value is gathered from asteroid mining per time unit.

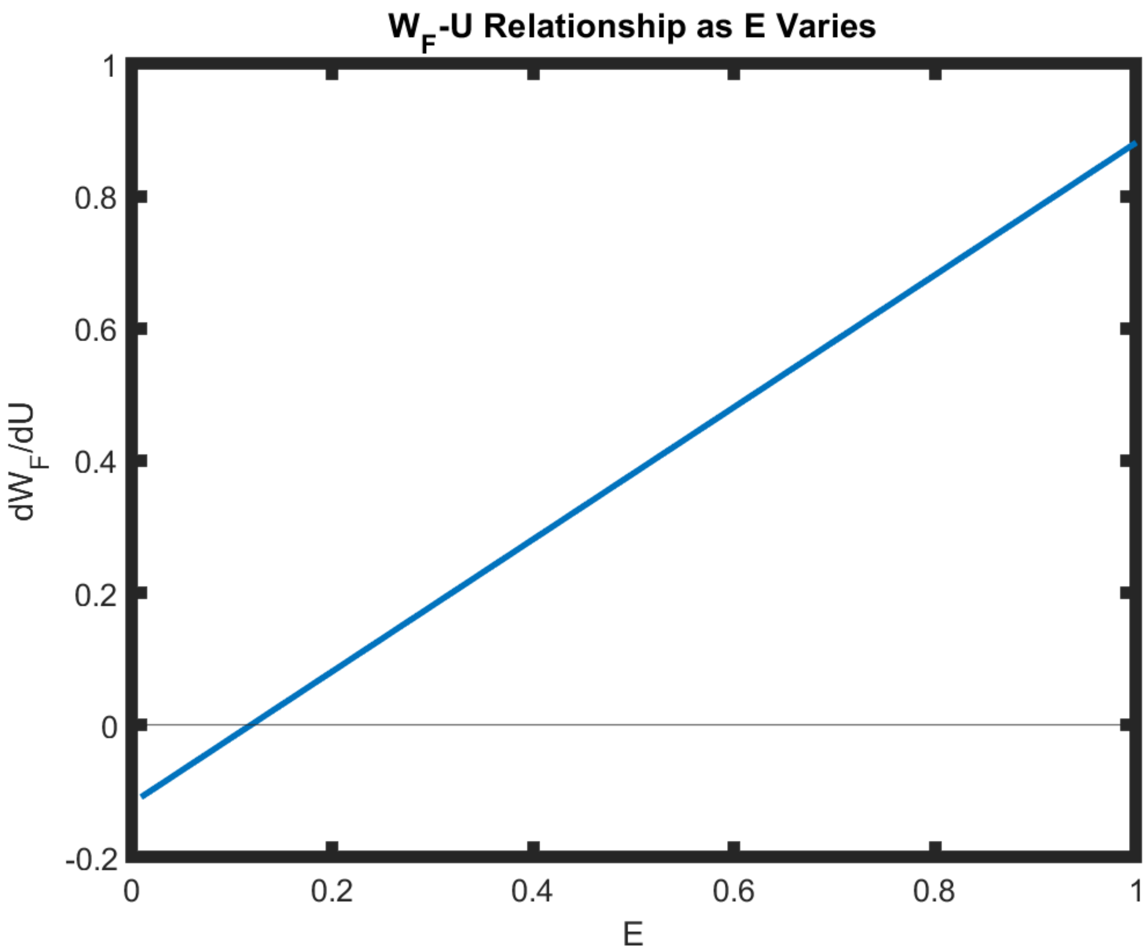


Figure 5: Rate of change of welfare with respect to degree of redistribution as redistributional efficiency varies. At $E = 0.12$ welfare is not affected by redistribution.

values $E$ (Figure 4). As expected, welfare increases as the degree of resource redistribution increases and the effect is more drastic when redistribution is more efficient.

Within this framework, the UN would best achieve their goal of equitable distribution of the benefits of space exploration by seizing all asteroid-derived value and redistributing it. Importantly, this result indicates that mean income per capita, which is also a factor of $W_F$, is not decreased enough with the considered redistribution efficiencies to overcome the welfare benefit of equitable distribution. These results also suggest that welfare increases monotonically with with the efficiency of resource distribution.

Calculation of $\frac{dW_F}{dU}$ for a range of $E$ values reveals that welfare transitions from decreasing as $U$ is increased to increasing with $U$ around $E = 0.12$ (Figure 5). The UN would need to evaluate its own efficiency in resource redistribution in a pilot study of some kind prior to establishing policy in this case.

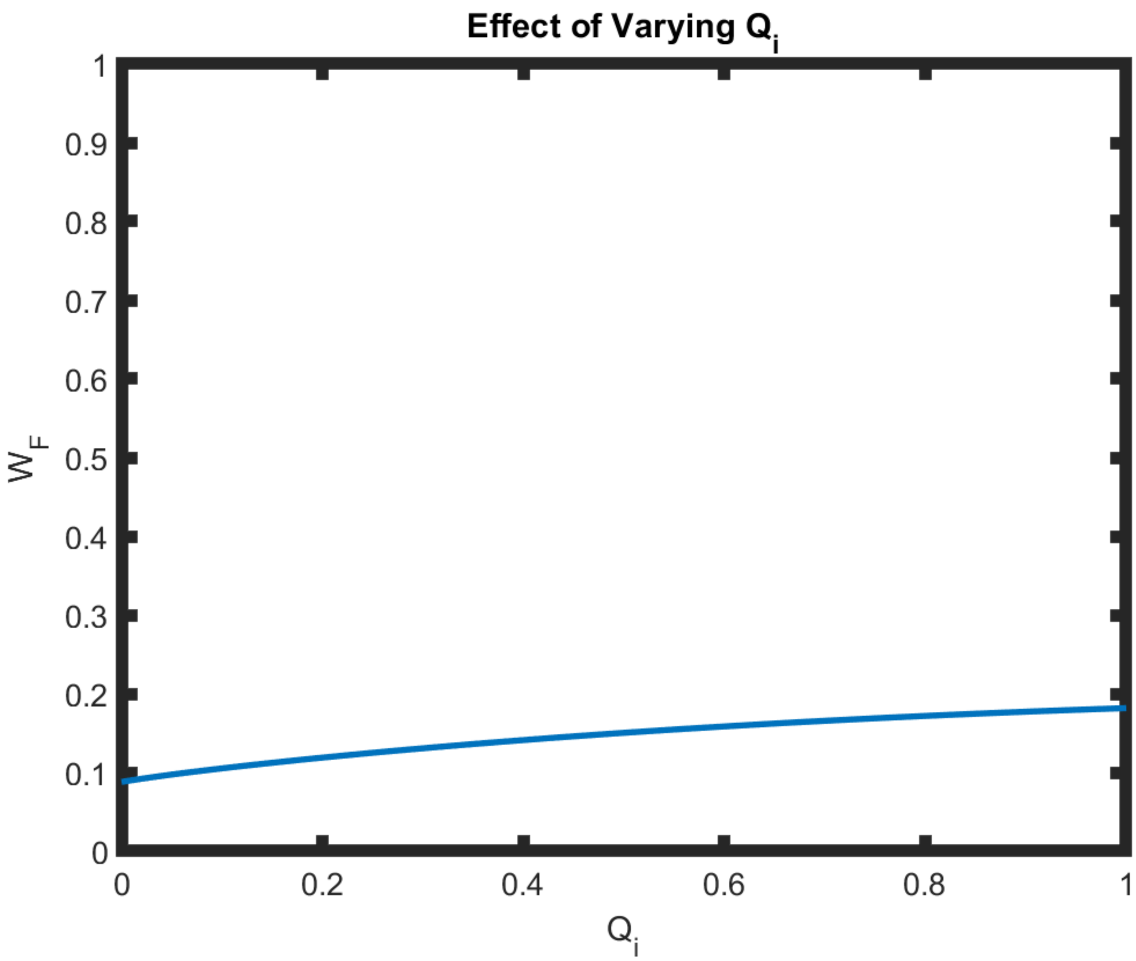


Figure 6: Global social welfare of the single export rate model as that rate varies. $Q_i$ represents that single rate.

## 4.3 Other Futures' of Asteroid Mining's Impact on Global Equity

The previous subsection considered all regions to export the same proportion of their after-tax asteroid resources. The effect of varying this single export rate on adapted Foster's welfare may be determined in the absence of any UN redistribution (Figure 6). This reveals that, in the single export rate model, trade does promote welfare, but not as efficiently as UN redistribution and with diminishing returns.

It is also interesting to consider a two-rate model of exportation, wherein regions with relatively high space exploration capacity (Americas, Europe, Asia) have exportation rate $q$ and regions with relatively low space exploration capacity (Africa, Oceania) have a complementary rate of exploration $1 - q$. The effects of varying $q$ in this model are summarized (Figure 7). This analysis reveals that welfare is maximized when less space-capable participate much more in trade than more space-capable regions.

Further analysis shows that this relationship persists as the degree of UN redistribution is varied (Figure 8).

The dichotomy of more space-capable regions and less space-capable regions produces a more

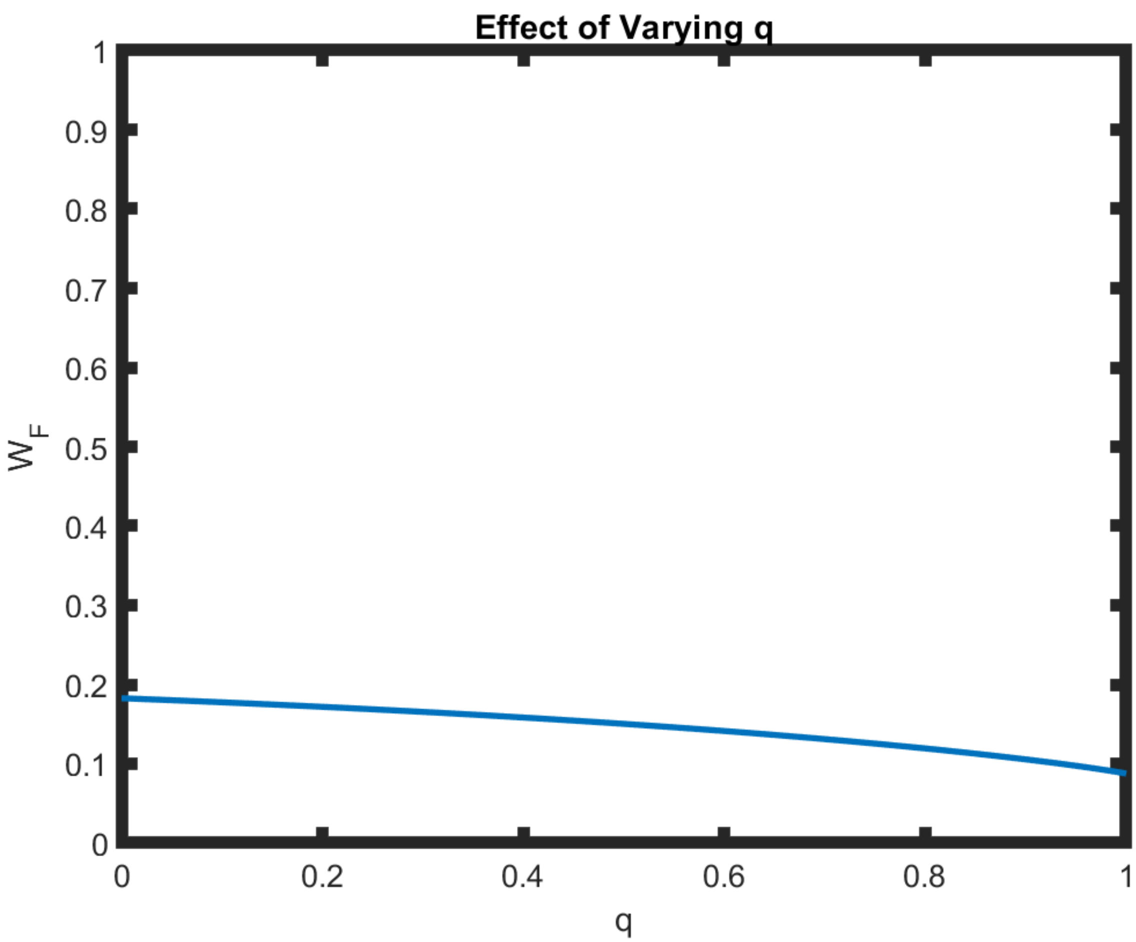


Figure 7: Global social welfare of the two export rate model as that rate varies. $q$ represents the rate at which the Americas, Europe, and Asia export while $1 - q$ represents the rate at which Africa and Oceania export.

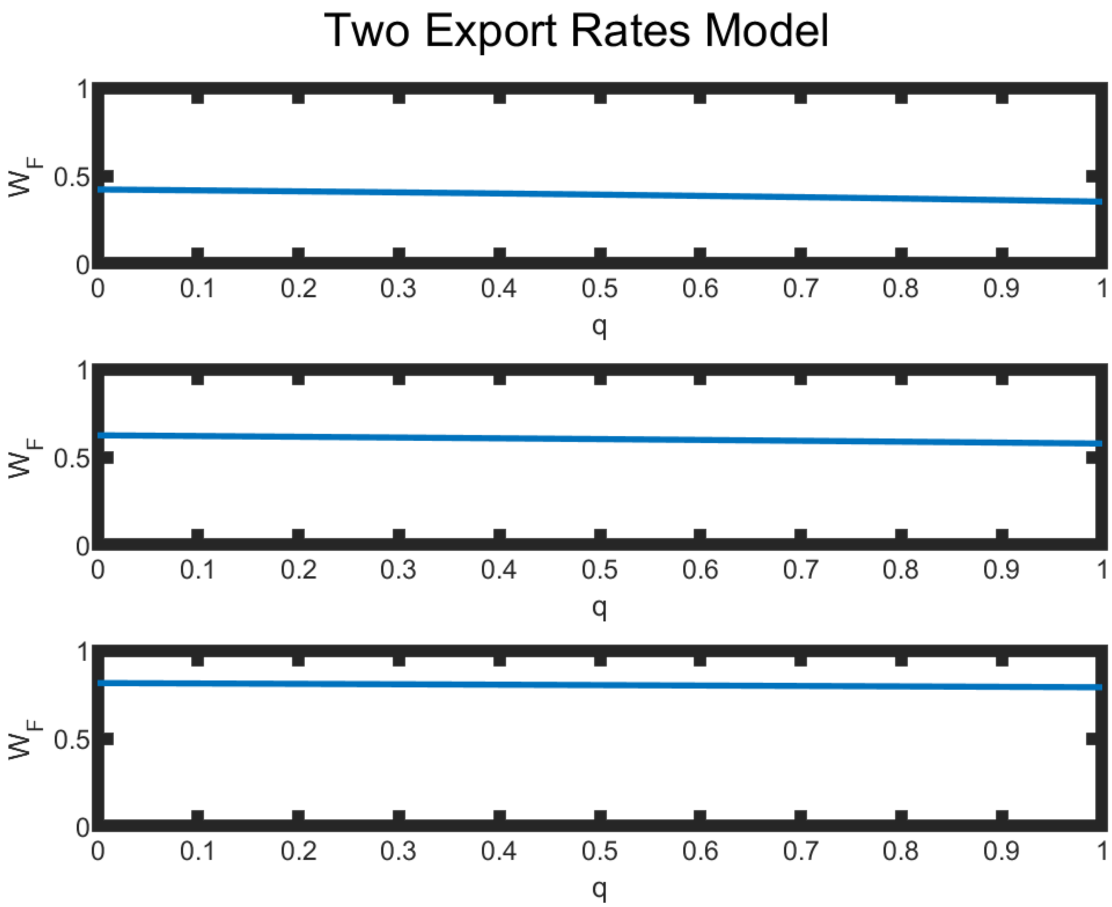


Figure 8: Effect of varying $q$ in the two export rates model for $U = 0.25$, $U = 0.5$, and $U = 0.75$. For these results, redistribution was 100% efficient.

realistic and therefore useful model because it captures the complexity of international trade with slightly more granularity than the single-rate model. For this reason, the two-rate model will be used to justify UN policy decisions moving forward.

## 4.4 Strengths and Weaknesses of This Approach

The modeling method here has several strengths:

- It is simple to understand and implement;
- It produces an single-value estimate of welfare that is easy to interpret;
- It parameterizes welfare on a small number of policy-controllable factors, making the effects of policy easier to probe;
- It is very computationally efficient;
- It is not difficult to add additional model granularity by incorporating data for more, smaller regions.

It also has several weaknesses:

- The reduction of entire continents to a single region is reductive, especially using the trade data for a single country as was done here;
- It assumes all regions mine asteroids as much as they are able to, regardless of economic incentive;
- It assumes all global trade occurs at a static rate;
- It assumes that the distribution of asteroid-derived value in global trade is reflective of the aggregate of all global trade;
- It does not consider the unequal distribution of wealth within regions, instead considering only the distribution of wealth between regions;
- It does not incorporate important elements of welfare such as systemic inequality along racial, national, or gender lines or the effect of the asteroid mining industry on the environment;
- It assumes that all benefits of asteroid mining (minerals, monetary value, scientific value) can be summarized by a single monetary figure;
- It neglects the existence of states which are not members of the UN.

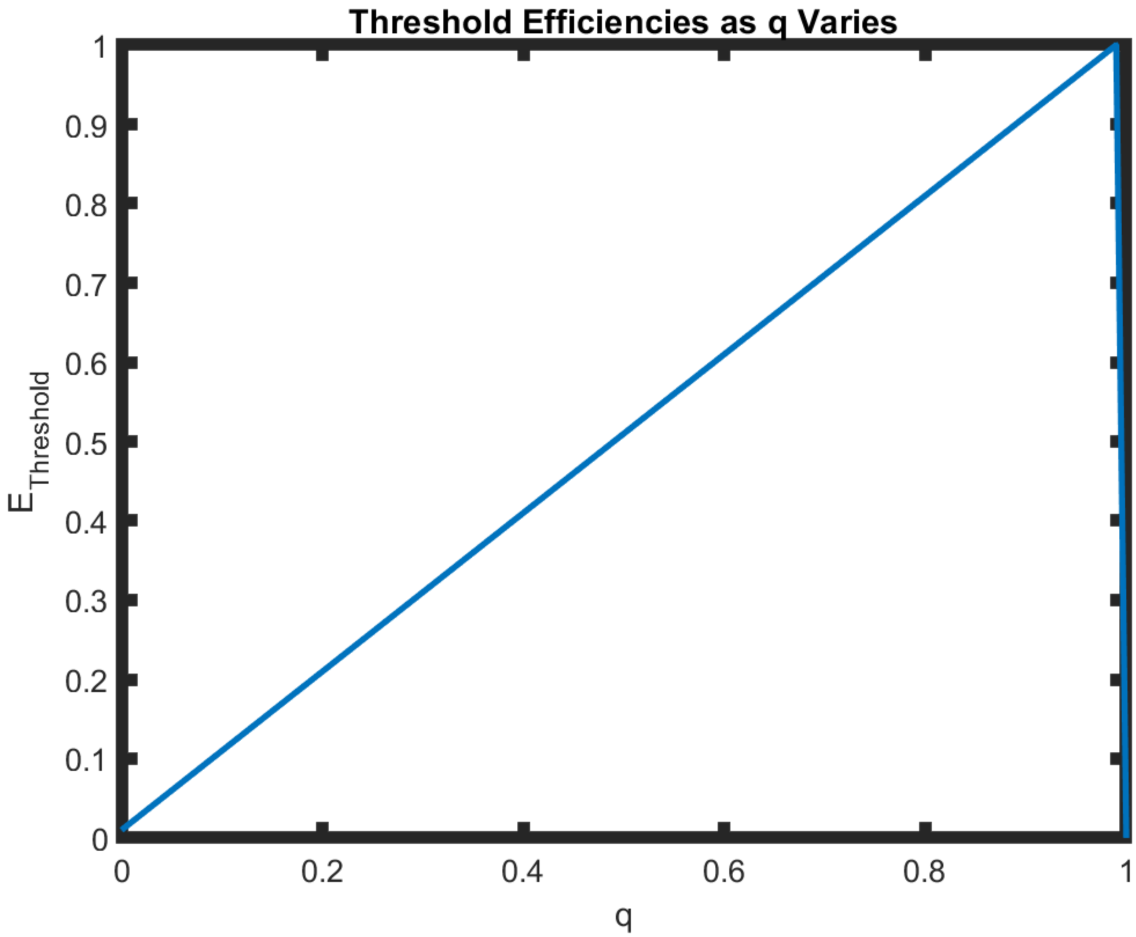


Figure 9: Threshold redistributional efficiency at which UN redistribution of asteroid-derived value becomes favorable as $q$ varies in the two export rate model.

## 4.5 Optimization of Global Equity

The above analysis of the two export rates model reveals that regions with reduced access to space (in this model, Africa and Oceania) should participate the most actively in trade with the value they gain through asteroid mining and regions with improved access to space should internationally less with the value they gain through asteroid mining.

Figure 5 illustrates that, in the single trade rate model, there is a threshold efficiency at which UN redistribution switches from being unfavorable to being favorable. Further analysis shows that such a threshold value exists in the two export rates model and increases linearly with $q$ (Figure 9). It is favorable for the threshold efficiency to be minimized so that the UN may beneficially redistribute value more reliably, so it is preferable for $q$ to be small, as was determined by analyzing the effects of trade (Figures 7,8).

These results, taken together, suggest that the adapted Foster's welfare function, a reasonable measure of global welfare, is maximized under asteroid mining when the most space-capable regions participate least in international trade and the least space-capable nations participate the most, when the UN collects and redistributes a large proportion of all value derived from asteroid mining, and when the UN does so with the highest possible resdistributional efficiency (or taxpayer return on investment).

# 5 UN Asteroid Mining Policies to Optimize Global Equity

These findings suggest that the UN could promote the vision of the Outer Space Treaty within an asteroid mining paradigm by producing policy that achieves the ends outlined above.

Firstly, the UN should introduce a maximum proportion of asteroid-derived value that the most space-capable nations (USA, Russia, China, France, India, etc...) may use to further their dominance of international trade. The model presented here suggests that this maximum should be made as small as possible, but model assumptions may break down as this value approaches zero. This figure is largely dependent on the costs involved with asteroid mining, and because of the lack of knowledge, a specific recommendation should only be made once asteroid mining has been proven.

Secondly, the UN should introduce a minimum proportion of asteroid-derived value that the least space-capable nations (primarily the global South) may use in global trade. Similar to the previous piece of policy, the model suggests that this value should be made as high as possible, but further knowledge is needed to recommend a specific rate.

Thirdly, the UN should introduce an international tax for all member states that applies to asteroid-derived value. This value should be redistributed to member states fairly according to population. The model suggests the size of this tax should be maximized, but the model neglects the decrease in asteroid mining which would occur should all financial incentive be removed. A maximum realistic tax rate depends largely on the minimum orbital costs of operating a space elevator, as before.

Fourthly, the UN should aim to redistribute asteroid tax value as efficiently as possible. This could be achieved by requiring that value be used for high return-on-investment projects like academic research, public housing, or infrastructure. The UN should also avoid using any asteroid-derived value to enrich the organization, instead distributing all value to member states.

Fifth, the UN should make an effort to control space elevators, by creating or investing in them. As they are a large part of the predicted future of asteroid mining, UN control over a space elevator could lead to more mining, with lower costs for mining corporations, and more funds for the UN to redistribute.

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