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Carrying Capacity: Are We Past The Limit?

Summary

The Earth's population is rapidly increasing, to the point where many people are concerned about whether our increasing population can survive in the future, and whether we have exceeded Earth's carrying capacity. Overpopulation will lead to problems such as scarcity of resources and eventually large-scale conflicts over necessities. As such, knowledge of the carrying capacity of the Earth, i.e. the maximum population size it can sustain indefinitely, can allow us to acknowledge how much resources we should save to avoid overexploitation and what measures we can implement to increase our carrying capacity.

In this report, we identified freshwater, food, and carbon emissions as the major factors affecting carrying capacity. Next, we developed a mathematical model based on these factors, going through several stages. Firstly, we found the world's consumption or emission of the above factors, as well as the current resources available or the maximum amount the Earth can sustain. Then, using the data, we calculated the maximum population the above factors could support respectively. Finally, we took the smallest number as the real carrying capacity of Earth. We calculated both the carrying capacity under an ideal scenario (equal distribution of resources and no waste) and that of a more realistic situation (taking resource disparity and waste into account).

Through this model, we found that the carrying capacity of Earth is approximately 4.09 billion, with the limiting factor of this carrying capacity being carbon emissions. The maximum populations our freshwater and food resources can support are about 11.6 billion and 17.7 billion respectively, under a realistic situation where we take wasted food and water into account. Under an ideal situation, our freshwater and food can support about 37.0 billion people and 31.7 billion people respectively.

As such, we propose various solutions to increase our resources. One of them with the most significant impact would be switching to clean renewable energy, which can hypothetically reduce our carbon emissions to 0 and therefore increase Earth's carrying capacity, up to 11.6 billion (31.7 billion under an ideal situation), at which point the constraining factor becomes freshwater supply (or food supply for an ideal situation). Last but not least, we also would like to highlight the massive difference made by eliminating resource wastage. By cutting back on waste, we can more than double the population those resources can support.

Contents

Introduction

The carrying capacity of Earth, or the maximum population it can support indefinitely, is a concept important to understand how an increasing population will affect both human society and the planet. The carrying capacity depends on four things, availability of resources, the rate of consumption of those resources, the rate of damage to the environment, and the rate of recovery of the environment.

In the following report, we will identify the major constraining factors determining Earth's carrying capacity, calculate the carrying capacity based on our analysis, and offer suggestions with regards to increasing carrying capacity. Moreover, we will separate the problem into 2 parts: one assuming that all resources are used equally and without waste, and one assuming that the resources are used according to current habits. This will offer a clearer picture of Earth's carrying capacity.

Based on this, we will then anticipate future conditions and give suggestions as to how to increase Earth's carrying capacity. We will also analyze the feasibility of some common proposals that claim to be able to increase our planet's carrying capacity.

Last but not least, we will test the sensitivity of our model by changing the various parameters, thus allowing us to understand how our model's results will change with different data inputs.

Restatement of Problem

In this problem, we are required to do 3 main tasks:

1. Find factors that have a major impact on Earth's carrying capacity for humans
2. Create a model that can calculate the current carrying capacity of Earth for humans
3. Give suggestions for increasing Earth's carrying capacity for humans in the future

This can be further split into subtasks:

Task 1

a. Identify the basic needs of humans/human society
b. Identify factors that support those basic needs
c. Identify factors that are detrimental to humans/human society

Task 2

a. Find data relating to the factors identified
b. Calculate how many people each individual factor can support/how many people can be supported before the detrimental factor becomes too much
c. Calculate the final carrying capacity based on the individual carrying capacities calculated

Task 3

a. Predict what the future will be like based on the factors identified
b. Based on the factors identified and our predictions, come up with suggestions to increase carrying capacity

Variables

Definition of Variables

Variable	Description
K_i	Carrying capacity of Earth in an ideal situation
K_r	Carrying capacity of Earth in a realistic situation
K_{wi}	Carrying capacity of Earth in an ideal situation, based on water
K_{wr}	Carrying capacity of Earth in a realistic situation, based on water
K_{Fi}	Carrying capacity of Earth in an ideal situation, based on food
K_{Fr}	Carrying capacity of Earth in a realistic situation, based on food
K_c	Carrying capacity of Earth based on carbon emissions
N	Current population of Earth
W	Global accessible renewable freshwater, measured in km^3/year
w_i	Global consumption of water in an ideal situation (without wastage), measured in km^3/year
w_r	Global consumption of water in a realistic situation, measured in km^3/year
F	Global average food supply, measured in kcal/capita/day
F_c	Global average crop supply, measured in kcal/capita/day
F_l	Global average livestock supply, measured in kcal/capita/day
f_i	Average food required per capita in an ideal situation, measured in kcal/capita/day
f_r	Average food required per capita in a realistic situation, measured in kcal/capita/day
E	Global carbon emissions per year, measured in tonnes/year
A	Amount of carbon emissions absorbed by the Earth, measured in tonnes/year
C	Total carbon in atmosphere, measured in tonnes
t	Time

General Assumptions

Firstly, in this paper, we assume that the current conditions and technology do not change, as per the question stipulations. This implies that the production of food, withdrawal of freshwater, and emission of carbon per person will remain the same, i.e. technology or scarcity of resources will not impact the production of those resources. This is because it is too difficult to measure and quantify human behavior in such a situation.

Secondly, we assume that the usage of resources and carbon emissions are linearly related to the world's population. Since food produced is consumed by humans and humans only, it can be reasonably assumed to be linearly related to population. Water, on the other hand, is mainly consumed by humans only and can be shown to be roughly linearly correlated to human population (See Fig. 4 in Appendix). Similarly, carbon emissions roughly correlate with population, as they are approximately related to the energy use of humans (See Fig. 3 in Appendix). By assuming a linear relation among population and the 3 factors, we can obtain a useful and mostly accurate approximation of reality, without making calculations too difficult.

Thirdly, we will not consider the effect on the economy or society. Even though an increase in population would lead to economic and social breakdown long before we reached the carrying capacity, leading to an effective decrease in resources (as they will cease to be exploited), we assume this to not be the case, as again it is too difficult to quantify human behavior in such a scenario. Predicting the global economy and social condition is out of the scope of this question.

Fourthly, we will not take astronomical time spans into consideration, i.e. we assume that "indefinite" does not refer to time scales of billions of years or more. This is because the Sun will eventually burn out and the universe will eventually experience an end of some sort. If we consider time scales of this magnitude, the carrying capacity will be zero, because the planet cannot support any population indefinitely. Therefore, we will assume this to not be the case.

Last but not least, we will assume that all the planet's accessible resources will be used to support a hypothetical "maximum population". This includes untapped potential for renewable energy sources and uncultivated arable land. This is because at present technology, we are capable of utilizing these resources, but we are unwilling to do so because of their relatively large cost. When calculating the carrying capacity, these resources/potentials should also be taken into account, as they represent resources that are accessible "at current conditions".

Crucial Factors

We went through multiple factors that we considered important for humanity's continued survival, including space, energy, water, food, carbon emissions, and environmental damage.

Space, while being an important factor for humanity's survival, was ultimately considered to be in relative abundance and therefore not a limiting factor. Similarly, while our energy mostly comes from non-renewable fossil fuels nowadays, present technology has the capability to replace them with renewable energy sources. The only reason why this has not been carried out is monetary cost, not engineering limitation thus is not a limiting factor as well.

In the end, we identified 3 main factors that have a significant impact on the carrying capacity of Earth, namely freshwater resources, food, and carbon emissions. We chose them based on their relative scarcity (abundance for carbon emissions) and significance to humans' survival. The first 2 factors are basic necessities that are required for survival; as such, there is a limit on how many people these resources can support. The final factor is a detrimental one that will totally alter the climate and make the whole Earth unsuitable for living. It increases with population, i.e. the more people there are, the more carbon will be emitted and thus the more the planet will heat up, which places a limit on how many people there can be. These factors can be used to calculate the carrying capacity of Earth.

Water is an extremely important resource. From the World Health Organization (n.d.), the minimum amount of water required for a human's daily needs is 20 L[35]. Moreover, water is used in agriculture and other industries. In order for our consumption of freshwater to be sustainable, our annual consumption of freshwater w must be less than or equal to the annual amount of accessible freshwater that is renewed W.

Moreover, food is essential for continuing a person's biological processes. The average human being needs at least 2000 kcal to maintain current body weight and thus survive. (World Health Organization, 2018)[34] As above, the consumption of food f should be less than or equal to the global food supply F, so that enough food can be produced for everyone.

Last but not least, a high concentration of carbon dioxide can threaten human lives. According to Kunzig, R. (2013), the carbon dioxide concentration must be kept under 450 ppm to avoid serious consequences for the planet[17]. Too much carbon would aggravate the situation of global warming and lead to a series of other climate and environmental impacts. Eventually, the planet would become unsuitable for living due to all the extreme weather conditions and overheating, and thus wouldn't be able to support any human beings. This limit must eventually be breached as long as there is a net emission of carbon, as opposed to absorption. Therefore, the environment can only be sustainable if the carbon emission rate E is less than or equal to the absorption rate A.

Analysis and Calculations

Food

Assuming food consumption is linearly related to population N, we can see that $\frac{f_r}{F_c+F_l} = \frac{N}{K_{Fr}}$, i.e. $K_{Fr} = N(\frac{F_c+F_l}{f_r})$. Similarly, $K_{Fi} = N(\frac{F_c+F_l}{f_i})$.

From the Food and Agriculture Organization of the United Nations (2013), there were 2370 kcal/capita/day of agricultural products and 514 kcal/capita/day of livestock, with a total of 2884 kcal/capita/day[5]. The population of 2013 was about 7.21 billion (Worldometers, n.d.) [36]

However, we must also consider that in 2015 only 36% of all cultivable land was used, amounting to 1.5 billion hectares, or 15 million square kilometers, of arable land in use. (Food and Agriculture Organization of the United Nations, 2015)[7] If the unused arable land is cultivated, there will be about 2.78 times the current arable land. Assuming that this land is similarly productive and produces similar crops as the present, this means that there will be a similar increase in the production of agricultural products.

Thus, if the planet operates at carrying capacity, with full utilization of its resources, we can estimate that agricultural products can give about 6583 kcal/capita/day. Therefore, the combined food supply will be 7097 kcal/capita/day.

If the world continues to consume food at present rates, then we can see that **the carrying capacity based on food resources under a realistic situation (with waste and overconsumption)** K_{Fr} **would be about 17.7 billion.**

However, according to Lipinski B. *et al* (2013), about 24% of all food calories produced is wasted[19]. Extrapolating to the increased production of food, this means 1703/kcal/capita/day is wasted. Also, an average human only needs 2000 kcal/day to meet their basic needs. (World Health Organization, n.d.) **Therefore, the carrying capacity under an ideal situation** K_{Fi} **is about 31.7 billion.**

Freshwater

Similar to the above, we can derive that $K_{wr} = N(\frac{W}{w_r})$ and $K_{wi} = N(\frac{W}{w_i})$.

According to the Food and Agriculture Organization of the United Nations (2014), the world withdrew 3760 km^3 of water in 2014, 69% being used in agriculture[6]. Moreover, according to Postel, S. L., Daily, G. C., & Ehrlich, P. R. (1996), there was 12500 km^3 of accessible renewable freshwater per year in 1996, with the amount being estimated to be 13700 km^3 per year in 2025[26]. The population in 2014 was approximately 7.30 billion (Worldometers, n.d.) [36]

As expressed previously, we also need to account for increase in arable land and thus crop output. Of the global freshwater supply, about 8% is used for livestock (Schlink, A., Nguyen, M., & Viljoen, G., 2010), which means about 61% is used for crops[28]. By adjusting the amount used for crops according to the data we used in the food section, we can calculate that the total amount of water withdrawn for agriculture will be about 6677 km^3 per year. Thus, the total amount of freshwater used at carrying capacity should be around 7844 km^3 per year. **As a result, the realistic carrying capacity K_{wr} is about 11.6 to 12.8 billion people.**

Moreover, 50% of all water used in agriculture is wasted due to inefficient irrigation methods. (Reig P. , 2013)[27]. This implies that about 3339 km^3 of water will be wasted every year if we use all arable land for crops. In addition, about 24% of all water used in agriculture was wasted due to food wastage in 2013. (Lipinski B. *et al*, 2013) [19]. Extrapolating this to the increased amount of water used at the carrying capacity, this means an additional 1602 km^3 per year will be wasted. In total, this means about 4941 km^3 per year of freshwater will be dumped unused. As such, if no water is wasted, the amount of freshwater used in agriculture would be about 1736 km^3 per year.

According to the World Health Organization (n.d.), each person needs at least 20 L of water per day to meet their basic needs[35]. Thus, the minimum global domestic water use per year should be 0.146 km^3 for a population of 7.30 billion. Assuming that the water needed for industry per year remains roughly unchanged, i.e. 734 km^3 (Food and Agriculture Organization of the United Nations, 2014) [6], the total amount of freshwater used per year at carrying capacity should be around 2470 km^3.

Therefore, we can calculate the ideal carrying capacity K_{wi} to be about 37.0 to 40.5 billion people.

Carbon Emissions

Only when all human carbon emissions are matched by the carbon absorbed by the Earth, can we ensure that the Earth will not become overheated someday in the future. Assuming that the carbon emissions are linearly related to the population and that the rate of carbon absorption of plants is independent of it, we can conclude that $\frac{E}{A} = \frac{N}{K_c}$, or $K_c = N(\frac{A}{E})$.

According to the CO2.Earth, n.d., around 26% and 30% of total carbon emissions were absorbed by the oceans and land respectively in 2014[3]. Therefore, only 56% percent of the total population in 2014 can be supported by the Earth without risking the warming up of the globe. Since the world population in 2014 was 7.30 billion (Worldometers, n.d.) [36], **the carrying capacity of Earth based on carbon emissions is around 4.09 billion people.**

We can also note that there is no split between an ideal and realistic scenario for carbon emissions, since unlike the other factors, carbon emissions are evenly distributed across the globe once emitted and will not be "wasted" as they are not resources.

Carrying Capacity

The carrying capacity of the Earth K should be the smallest carrying capacity calculated from the various factors, as that number represents the point at which one of the factors begins to run out (or in the case of carbon emissions, become too high). Thus:

$$K_r = min\{K_{Fr}, K_{wr}, K_c\}$$
$$K_i = min\{K_{Fi}, K_{wi}, K_c\}$$

By incorporating the equations derived above, we arrive at:

$$K_r = min\{N(\frac{F_c+F_l}{f_r}), N(\frac{W}{w_r}), N(\frac{A}{E})\}$$
$$K_i = min\{N(\frac{F_c+F_l}{f_i}), N(\frac{W}{w_i}), N(\frac{A}{E})\}$$

We can conclude from the above calculations that both the carrying capacity under an ideal situation and one under a realistic one would be the same, namely, **4.09 billion people**, which is the carrying capacity based on carbon emissions. We have found that carbon emissions are the primary limiting factor that impacts the Earth's carrying capacity. Our current population is about 7.7 billion (Worldometers, n.d.)[36], which means that we are already operating above our planet's carrying capacity. This is evidenced by the fact that our planet is experiencing global warming and rising carbon concentration levels, which should not happen under an indefinitely sustainable environment.

Anticipated Future Conditions

As mentioned above, carbon emissions are the primary limiting factor for our planet's carrying capacity. However, even when operating above carrying capacity, carbon emissions will take a long time to build up, and thus initially their impact will not be as pronounced. Even so, the United Nations (2018) estimates that surface temperatures will rise for more than 3 degrees Celsius by the end of the century, and that average sea levels will rise by 40 - 63 cm in 2100, if no intervention is made[30].

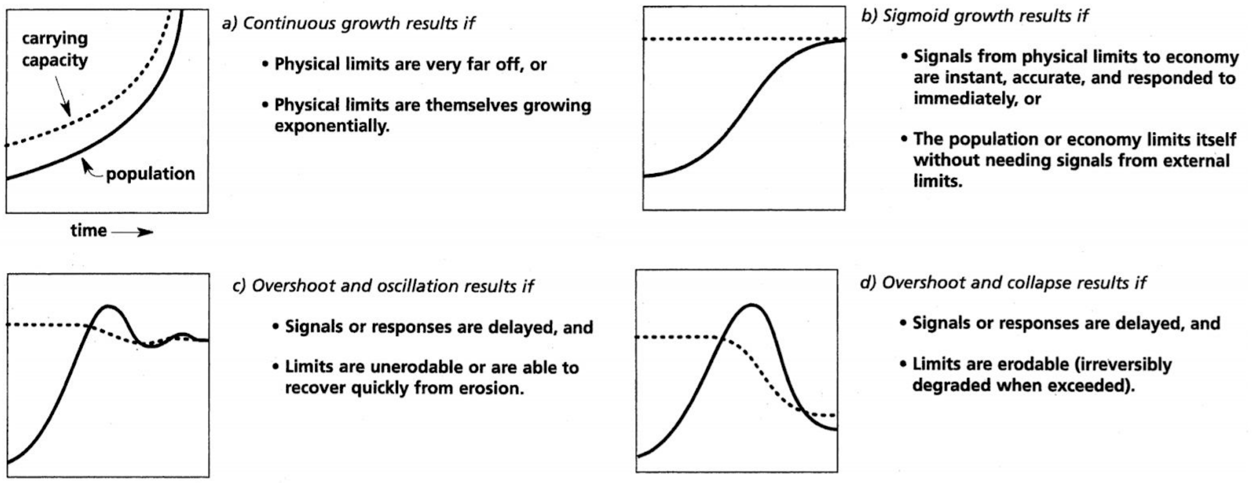

Fig. 1: Different scenarios when population reaches carrying capacity.
Note. Reprinted from *The Limits to Growth: The 30-Year Update* (p. 168), by Meadows, D.H., Meadows, D. L., Randers, J., 2004. White River Junction VT: Chelsea Green Publishing Company. Copyright 2004 by Meadows, D.[22]

The slow-acting nature of global warming and carbon emissions also means that it will take very long for carbon in the atmosphere to be reabsorbed. This means that even when population begins to decrease, the Earth will continue to warm up. As seen from Fig. 1, this most closely matches scenarios (c) and (d), with delayed responses/signals. Moreover, the increase in carbon emissions may possibly heat up the planet to the point where the ability of our planet to absorb carbon is overwhelmed (due to ecological damage). This means scenario (d) is entirely possible, i.e. the human race may be wiped out before the carbon levels return to normal and the planet cools back down. As such, one of the most important measures to take in order to increase our planet's carrying capacity would be to lower carbon emissions, the details of which will be discussed later.

The second limiting factor is water. As Earth's population continues to increase in the future, we foresee that demand for water will increase. Moreover, since worldwide living standards will gradually increase, freshwater consumption will increase along with them. In our previous calculations, we assumed that the population continued to consume at current conditions and habits, but in a future situation, this would most likely not be the case. Therefore, our previous projections of 11.6 to 12.5 billion people may be too high, if living standards increase beyond the current global average. We expect that the problem of water shortage will continue to worsen in the future as our population approaches 11 billion or more, leading to a global water crisis.

Thirdly food will also limit Earth's carrying capacity. In our current state, only 36% of arable land is being used. (Food and Agriculture Organization of the United Nations, 2015)[7] Again, as living standards increase, demand for food will also increase, which was not considered in our previous model. In addition, the problem of desertification will mean that more and more arable land will be lost as time goes on, decreasing agricultural productivity. Moreover, with increasing global temperatures due to carbon emissions, it will be more and more difficult to grow crops successfully. Therefore, food scarcity will continue to worsen, necessitating new solutions to be developed.

However, the predictions we just mentioned have not accounted for a significant factor: human behavior. As food and water gets more scarce, people will conserve on the resources and consume less. This may help mitigate the impact of resource scarcity. In addition, as we mentioned in our general assumptions, the world may be willing to devote more resources to excavate water and increase food supply when scarcity becomes more apparent, which may also increase food and water supply. Unfortunately, since the effects of carbon emissions are less obvious and less immediate, we also expect that comparatively less effort will be made towards reducing carbon emissions.

Another mitigating factor is the increase in technological level. As time goes on, our technology is expected to increase. This implies that new methods to increase agricultural output, extract water, or absorb carbon may be developed. Therefore, we expect the situation in the future to be somewhat soothed by increases in technology.

Solutions and Suggestions

Carbon Emissions

Clean renewable energy

By transitioning to clean renewable energy sources, we can theoretically reduce our carbon emissions to zero. This means that after phasing out fossil fuels and using renewable energy sources without carbon emissions, we can technically increase Earth's carrying capacity from 4.09 billion to the next limit, which is 17.7 billion (constrained by food supply).

Since the production of biofuel would consume food and lead to competition on food resources, it is not a very ideal mean of renewable energy source. For nuclear power, concerns about the safety of nuclear energy have arisen, leading countries such as Germany, Switzerland and Japan to cut down their nuclear power production. There was a sharp fall in nuclear energy production from 10 GW to 3.6 GW in 2017 (International Energy Agency, 2019)[13], so the future development of nuclear power is under question and thus it is also not considered as a feasible renewable energy source in this report.

Currently, wind power, solar panels and hydroelectric power generates 5.08 million GWh energy per year (International Energy Agency, 2018)[12], contributing to 3% of the total energy supply with the global energy consumption being 158 million GWh (Enerdata, 2018)[4]. Among these, solar power generation occupies the least land and is the cheapest kind of renewables, while HEP is on the other hand the most expensive and land-consuming. However, solar power is highly dependent on the presence of light, and according to Baker, A. (n.d.), daylight available each day is only approximately 7 hours[2] and there might be a lack of sunlight during the rainy seasons. This makes it a less stable energy supply. HEP and wind power, in contrast, are very consistent despite their higher costs, since wind is often present and the water used in HEP is from reservoirs and can be renewed frequently. One more point to note is that the area of "land" required for HEP stations also includes the reservoirs and rivers, which is not available for a lot of other essential purposes (e.g. agriculture, afforestation). The actual area of usable land used for HEP dams is therefore much smaller than estimated in the appendix. (Please see Appendix **Table 8** for more data.)

However, the change in carrying capacity have to take place over a long period of time: as of 2014 there was 545 gigatonnes of carbon in the atmosphere. 30% of 2014's emissions were absorbed by the land and 26% by the ocean, which is about 5.5 gigatonnes of carbon in total. (CO2.Earth, n.d.)[3] Using the equation $t = \frac{C}{A}$ and assuming the rate of absorption to stay roughly constant, this means if we stopped emitting carbon in 2015, it would still take more than 99 years to return Earth's carbon cycle to an equilibrium.

Considering that it may take a lot of time to transition to clean energy, methods of removing carbon other than natural absorption of carbon by the planet may be needed to speed up the process. These methods will be discussed and reviewed below.

Afforestation/Planting trees

Planting trees has been cited as a common method for absorbing carbon emissions from the atmosphere. According to One Tree Planted (2014), a tree can absorb up to 48 pounds, or about 21.7 kilograms, of carbon dioxide each year[24]. This is equivalent to about 0.013 tonnes of carbon. From our equations above, $K_c = N(\frac{A}{E})$. Thus, $\frac{dK_c}{dA} = \frac{N}{E}$, or for every additional tree, the increase in carrying capacity is equivalent to $\frac{0.013N}{E}$.

From CO2.Earth (2014), there were 9.795 gigatonnes of carbon dioxide released in 2014[3]. Moreover, there were about 7.30 billion people in 2014. (Worldometers, n.d.)[36] We can then find that each additional tree increases the carrying capacity based on carbon emissions by approximately 0.00976 people on average. In other words, it would take at least 103 trees to increase the carrying capacity by 1 person. To increase our carrying capacity to the current population of 7.7 billion (Worldometers, n.d)[36], we will need to plant about 400 billion trees.

Therefore, we can see that it is not very feasible to rely on planting trees to increase the planet's carrying capacity. As such, we must look into other methods to remove carbon.

Synthetic Trees

A new method to remove carbon from the atmosphere is the usage of synthetic trees to absorb carbon. According to Leach (2009), a single synthetic tree is about 1000 times more effective at absorbing carbon, meaning a synthetic tree can increase the carrying capacity by more than 9 people[18]. By this measure, 40 million synthetic trees will need to be created to increase the carrying capacity to 7.7 billion, which is more feasible to implement, though it is still not very possible unless radical changes in technology make them much cheaper to produce.

In addition, from previous calculations, we know $t = \frac{C}{A}$. From this, we can see that $\frac{dt}{dA} =- \frac{C}{\sqrt{A}}$. This means that each synthetic tree will reduce the time taken to return to carbon equilibrium by 0.00000232 years, or that we need about 430000 synthetic trees to reduce the time taken by one year. Keeping in mind that this is assuming that we have stopped producing carbon emissions after 2015, we estimate the real number needed to be much larger in the future. Again, although synthetic trees are a lot more efficient at absorbing carbon than normal trees, we still need huge amounts of them to make a significant difference. Therefore, we recommend using a multi-pronged approach to solving the problem of carbon emissions, so as to maximize the efficiency.

Other methods to remove carbon

According to Mcrae (2019), Australian scientists have developed a method to convert carbon dioxide into carbon by stripping oxygen ions from it[21]. In addition, according to Perasso (2018), Icelandic researchers have been able to convert carbon dioxide to rock by mixing it with water and injecting it underground, where natural processes mineralize the solution[25]. Unfortunately, since these methods are relatively new, no consistent data can be obtained as to how effective they are. Nevertheless, they are promising solutions to the problem of carbon emissions.

Water

Reducing waste and overconsumption

As demonstrated by our previous calculations, the population our freshwater resources can support differs by more than 20 billion people between an ideal and realistic scenario. This is due to the large amount of water wasted per year in both agricultural and domestic use. In addition, there is overconsumption of water.

If everyone only consumes enough water to meet their own basic needs, and does not waste water, the world's water resources could support more than 37 billion people. Naturally, it is impossible to not waste water at all, but if we decrease our water consumption and waste by half, we could still support an extra 11 billion people.

Methods to decrease water wastage in agriculture include implementing drip irrigation and deficit irrigation. Drip irrigation is an irrigation method where water is administered drip by drip to the crops, so as to minimize water loss by evaporation. Deficit irrigation, on the other hand, is a method in which just enough water is applied to the plant such that water loss by transpiration is minimized. According to Wu and Gitlin (1983), deficit irrigation efficiency can reach as high as 100%, meaning no water is wasted during irrigation[37].

New methods to regulate irrigation have also been proposed, such as the use of artificial intelligence to control how much water each plant gets, based on factors such as soil, humidity, temperature, and plant growth. However, since it is a relatively new method, data relating to its efficiency is inconsistent.

Moreover, huge amounts of domestic water is wasted due to leaky faucets and other similar problems. According to the United States Environmental Protection Agency (n.d.), about 900 billion gallons, or more than 3.4 km^3 of water, is wasted per year in American households due to household leaks[31]. By educating people on the importance of water saving, more domestic water could be saved.

We expect that the use of the above methods can successfully minimize water waste and thus increase the carrying capacity based on water greatly.

Desalination

A promising way to increase water supply is desalination of seawater. Using this method, we can create freshwater from previously unusable saltwater.

The effectiveness of desalination to increase freshwater supply has been acknowledged in recent years. According to the Voutchkov, N.(2016), there were approximately 18000 desalination plants worldwide in 2015, with a combined production capacity of 86.55 million m^3 per day[32]. This means on average, each desalination plant produced 4808 m^3 per day. From the equation outlined previously, $K_{wr} = N(\frac{W}{w_r})$. This means $\frac{dK_{wr}}{dW} = \frac{N}{w_r}$, i.e. each desalination plant can add about 1700 people to the realistic carrying capacity based on water, or about 5300 people to the ideal carrying capacity based on water.

Moreover, according to Advisian (2017), the cost of desalination has dropped significantly over the past years, with the cost of Multi-Stage Flash Distillation having dropped 20% from the years 2000 to 2017 and the cost of desalinating brackish water dropping by 50% in the past 20 years.[1] This would make it relatively affordable.

As such, we see desalination plants to be a relatively effective and useful method to increase the global freshwater supply.

Other methods to increase water supply

Currently, there are about 38.7 million km^3 of freshwater (Nieman, 2014)[23], but only about 12500 km^3 of freshwater is accessible. (Postel *et al.*, 1996)[26] This is because most of the water is locked in ice caps, glaciers, and extremely deep groundwater. In order to increase water supply, we suggest funding attempts to drill deep into the earth for this groundwater, or to “mine” glaciers and ice caps for additional freshwater. These endeavors could be able to make better use of the freshwater on Earth, thus increasing the planet’s carrying capacity.

Food

Reducing waste and overconsumption

The problem of food shortage is in a very similar position to water shortage. If food waste is eliminated and everyone only consumes just enough to meet their basic needs, the carrying capacity based on food will increase by about 12 billion.

Ways to decrease food waste include levies on food waste, which can give people an incentive not to waste food. We can also reduce food waste by giving everyone more equal access to food resources, which can ensure that everyone can consume at least enough food to meet their basic needs.

Much of the effort towards decreasing food waste hinges on individual efforts, however, which means that worldwide governments will have to increase their citizens' understanding of the importance of food conservation through methods like education and advertising.

Cultivating more land

As we mentioned previously, only about 36% of all arable land is currently in use. (Food and Agriculture Organization of the United Nations, 2015)[7] Although the uncultivated land was also incorporated into our calculations of Earth's maximum carrying capacity, the land is not in use as of now, and thus will require cultivation to reach the 17.7 billion figure (31.7 under an ideal scenario) we previously calculated. Without additional land, the carrying capacity of our planet is essentially our current population - 7.7 billion. This is under a scenario with waste and overconsumption; in an ideal situation, the figure would be about 12.5 billion, which is still lower than 17.7 billion.

Countering land degradation

If nothing is done about land degradation, much of our current arable land will be lost. According to the United Nations (2010), 24% of land in use was in the process of degradation in 2010, with 20% of that being cropland and 20-25% being rangeland[29]. This means if we assume food production and agricultural land to be roughly linearly related and if the degrading land used for food production was fully degraded, it would reduce the carrying capacity of Earth based on food by about 200,000 people (about 3,350,000 people in an ideal situation without food waste). Countering land degradation requires the adoption of sustainable agricultural methods, which can be achieved by educating farmers to avoid overgrazing or over-irrigating, as well as protecting vegetation cover to prevent soil erosion.

Other ways to increase food supply.

Genetically modified (GM) food can potentially increase food supply in the future. According to Klümper and Qaim (2014), GM crops have increased crop yields by 22% on average[16]. This is because GM crops can be modified to grow faster or survive better in certain environments, enabling them to vastly increase food supply. They are also not very costly to implement, and in fact can increase farmers' profits by 68%. (Klümper and Qaim, 2014)[16] The consumption of insects to provide additional protein has also been proposed, though data on this is inconsistent.

Analysis of Our Model

Sensitivity Analysis

We performed a comprehensive sensitivity analysis on our model, such that we could test how it responded to changes in data. The results are as below:

	Normal ($W =$ 12500 - 13700 km^3/yr)	$W =$ 7500 km^3/yr	$W =$ 17500 km^3/yr
K_{wr}	11.6 - 12.8 billion	7.0 billion	16.3 billion
K_{wi}	37.0 - 40.5 billion	22 billion	51.7 billion
K	4.09 billion	4.09 billion	4.09 billion

Table 1: The calculated carrying capacities after changing the accessible water supply W .

	Normal ($w_r =$ 7844 km^3/yr)	$w_r =$ 5000 km^3/yr	$w_r =$ 10000 km^3/yr
K_{wr}	11.6 billion - 12.8 billion	18.3 - 20.0 billion	9.13 - 10.0 billion
K	4.09 billion	4.09 billion	4.09 billion

Table 2: The calculated carrying capacities after changing the realistic water consumption w_r .

	Normal ($w_i =$ 2470 km^3/yr)	$w_i =$ 1000 km^3/yr	$w_i =$ 3000 km^3/yr
K_{wr}	37.0 - 40.5 billion	91.3 - 100 billion	30.4 - 33.3 billion
K	4.09 billion	4.09 billion	4.09 billion

Table 3: The calculated carrying capacities after changing the realistic water consumption w_i .

	Normal ($F =$ 7097 kcal/capita/day)	$F =$ 5000 kcal/capita/day	$F =$ 9000 kcal/capita/day
K_{fr}	17.7 billion	12.5 billion	22.5 billion
K_{fi}	31.7 billion	22.3 billion	40.2 billion
K	4.09 billion	4.09 billion	4.09 billion

Table 4: The calculated carrying capacities after changing the food supply F .

	Normal ($f_r =$ 2000 kcal/capita/day)	$f_r =$ 1000 kcal/capita/day	$f_r =$ 3000 kcal/capita/day
K_{fr}	17.7 billion	35.4 billion	11.8 billion
K	4.09 billion	4.09 billion	4.09 billion

Table 5: The calculated carrying capacities after changing the realistic food consumption f_r .

	Normal ($f_i =$ 2000 kcal/capita/day)	$f_i =$ 1000 kcal/capita/day	$f_i =$ 3000 kcal/capita/day
K_{fi}	31.7 billion	63.4 billion	21.1 billion
K	4.09 billion	4.09 billion	4.09 billion

Table 6: The calculated carrying capacities after changing the ideal food consumption f_i.

	Normal ($\frac{A}{E} =$ 56%)	$\frac{A}{E} =$ 50%	$\frac{A}{E} =$ 60%
K_c	4.09 billion	3.65 billion	4.38 billion
K	4.09 billion	3.65 billion	4.38 billion

Table 7: The calculated carrying capacities after changing the percentage of carbon emissions absorbed $\frac{A}{E}$.

As seen from the tables above, our model is fairly robust against changes to its parameters, with only changes to the percentage of carbon emissions absorbed $\frac{A}{E}$ having a measurable impact on the final calculated carrying capacity.

Strengths

- Our model is relatively insusceptible to changes in the parameters, meaning it is less prone to error due to faulty data. When changed, all parameters except carbon emissions absorbed did not change the carrying capacity calculated.
- Our model considers the most important factors that affect the carrying capacity of Earth, including freshwater, food, and carbon emissions, allowing it to accurately estimate the carrying capacity.
- Our model takes resource waste and overconsumption into account, giving estimates for the carrying capacity in both a realistic and ideal situation, which allows for a more comprehensive outlook on Earth's carrying capacity.
- Our model is not very computationally intensive and can arrive at the estimated carrying capacity without requiring large amounts of time.

Limitations

- Our model assumes population to be linearly related to freshwater/food consumption and carbon emissions, which may be inaccurate. However, since our model is not very sensitive to changes in the parameters, this will not affect the results dramatically.
- Our model does not consider the economic, social or behavioral effects of an increasing population, as it is difficult to quantify the effect of population on these factors.
- Our model does not take astronomical time scales into consideration, as at these timeframes the planet would not be able to support any population size indefinitely.
- Our model assumes that all available resources will be used to support the human race regardless of cost, which may not entirely reflect real life.

Conclusion

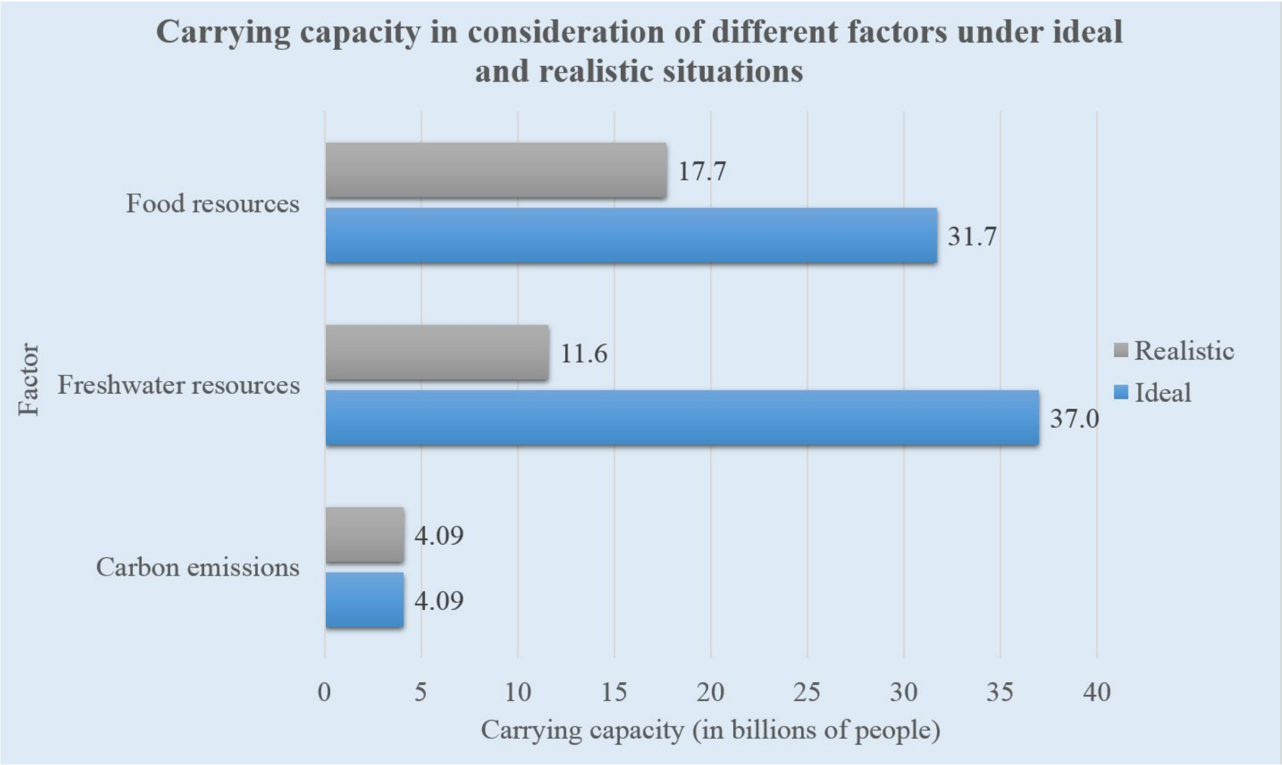

Fig. 2: Carrying capacity as calculated based on different factors.

The above figure is a summary of our calculated results. Using our mathematical model, we found the carrying capacity of our planet to be about 4.09 billion people. The main constraining factor is how much carbon our planet can absorb. As of now, our population has already exceeded Earth's carrying capacity. Although this seems paradoxical, it is actually possible, because the negative impact of carbon emissions takes a long time to be felt, and thus our population may continue to exceed its limit for a long time. Nevertheless, the fact remains that Earth's carrying capacity has already been exceeded and that our carbon emissions are too much for the planet to absorb.

Based on our calculations, we proposed various measures to increase the carrying capacity of our planet.

For carbon emissions, much more research is needed to help increase our planet's carrying capacity. Present methods are not very effective, as we have demonstrated. As such, we recommend increased funding for research into this matter. At present, we also suggest using a combination of renewable energy, synthetic trees, and converting carbon dioxide into other chemicals to reduce carbon emissions and even absorb additional carbon from the atmosphere, so as to increase our carrying capacity. We conclude that from what we've analyzed, phasing out fossil fuels and using renewable energy sources remains to be the most effective solution.

For freshwater, the most effective method is to reduce water waste through more efficient irrigation systems and educating people on reduction of water waste. Another effective methods to increase the carrying capacity based on freshwater is desalination, which is getting cheaper due to improvements in technology and has the potential to provide additional freshwater at a relatively low cost in the future. Last but not least, Earth's remaining freshwater resources that are currently inaccessible could be tapped. However, this would require huge costs in technology, which means improvements in technology must be made before this practice becomes affordable. More research would be required to carry this out effectively.

For food, one of the most effective ways is to increase the number of people it can support would be to reduce food waste. This could be achieved through increased education and more equal access to food resources. We also propose to cultivate remaining arable land such that it may be used, which could more than double food production. In addition, we consider countering land degradation to be of paramount importance. Ways to do so include increasing vegetation cover and teaching sustainable agricultural practices to farmers. Moreover, the use of GM crops may be able to increase food production by allowing crops to thrive in different environments. Last but not least, insects are also good ways to increase the protein supply in the future, though the cultural negativity towards eating insects will need to be dealt with.

In the course of humanity, we have raised our carrying capacity again and again by improving our technology, all the while pushing through limiting factors such as food resources and energy resources. While our planet's carrying capacity is only an estimate and cannot accurately predict the future, it does offer a glimpse of what needs to be done to avoid reaching the tipping point. From our analysis, it is clear that there is no single silver bullet that can solve the problem of increasing carrying capacity. However, through multiple efforts aimed at decreasing carbon emissions, increasing exploitation of resources, and decreasing wastage of resources, we can increase Earth's carrying capacity by a huge amount, expanding our planet's ability to support humanity.

Appendix

	Land (acres/GWh/year)	Cost ($/GWh/year)
Solar power	2.8-3.8[11]	114,155[20]
Wind power	14.6[9]	148,402-251,142[33]
HEP	69.1[15]	188,356[14]

Table 8: Comparison of different kinds of renewables in terms of land used and costs per GWh per year**. (Sources:** Hardesty, L., Garfield, L., International Water Power & Dam Construction, Marsh J., Windustry, International Renewable Energy Agency)

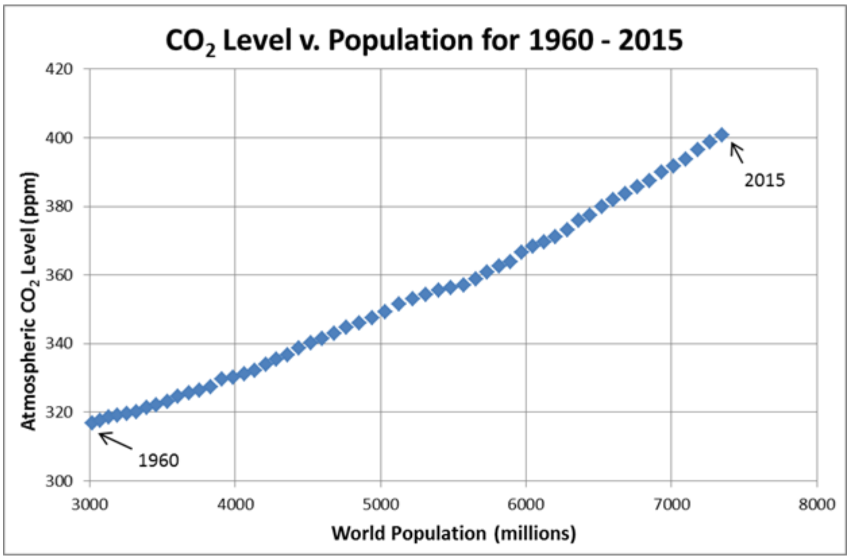

Fig. 3: Global population compared with CO2 Level.
Note. From "The Correlation between global population and global CO2," by Graves, R., 2016 (https://wattsupwiththat.com/2016/05/17/the-correlation-between-global-population-and-global-co2/). Copyright 2006-2019 by Anthony Watts.[10]

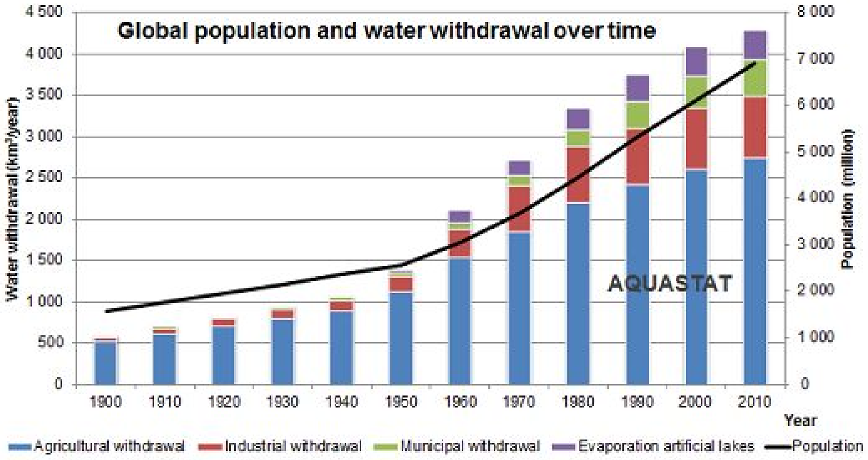

Fig. 4: Global population compared with water withdrawal/consumption.
Note. From "AQUASTAT" by Food and Agriculture Organization of the United Nations(FAO), 2016 (http://www.fao.org/nr/water/aquastat/water_use/index.stm). Copyright 2016 by FAO.[8]

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