2019 International Math Modeling Competition

Earth's Carrying Capacity

9372

Summary

Tackling the question of the carrying capacity of the world's human population is a difficult one. There are many variables that can be taken into account, such as agricultural capacity, water supplies, and physical space, and as a result, no mathematical model can be created that factors in that many variables to individualized degrees.

In this situation, we decided to observe human behaviors, as opposed to tangible resources and other variables that can be seen as direct corollaries to human population. Since food and many other resources are taken into account when people decide to reproduce, human behavior and specifically fertility, can handle the parsing of many environmental variables and situations, as individuals will decide based on their personal circumstances whether having a child is a good idea or not.

We set population as our independent variable and fertility rates as our dependent. This is because population dictates the availability of resources and the overall living conditions of the average person at a given time period. It's these conditions and variables that dictate whether or not a person will try to reproduce or not, and this reproduction rate is directly linked to the next generation's population.

We used various sources outlining the population changes in the past few years, alongside the fertility rate changes, to solidify the correlation between the two and plot them against each other, removing the unnecessary time variable. This allows for a relationship between the two variables without an external variable.

Through this method, we can effectively calculate the carrying capacity of Earth's human population. Since people will stop reproducing when there is not enough resources to support having children, the absolute minimas of the fertility rate over time represent the maximum population at which humans can use their resources around them to sustain themselves indefinitely (otherwise known as the carrying capacity). Using this model, we arrived at an answer of **10.2 billion people** as the Earth's maximum carrying capacity under current conditions.

In order to increase our maximum carrying capacity, the most important thing we have to do is maximize how effectively we use our resources. We waste many of our resources so the best way to have an impact **right now** is to make sure we are using all of the resources available to us in a sustainable manner in order to support as much life as we can. In order to do this, we applied an industry grade deep neural that had a 92% accuracy in order to rapidly analyze large amounts

of satellite images and return whether or not a land patch was fit for cultivation and whether the resources (such as trees and forests) were at risk of being overused.

Part I: Most Important Factors

When considering the individualized needs of each person to survive, as well as the requirements to keep the human race going, there are a lot of factors to consider. On the individual scale, each person requires food, hydration, and protection of some sort from the environment. When we scale this up to the general population, this becomes problematic because of how much of each resource or security is needed per person.

As for if we look at the largest possible scenarios for human population, there is the limiting factor of surface area of the Earth. We simply do not have enough room on the planet to fit an infinite number of people such that disease does not spread rapidly enough to wipe out entire populations, considering a sizeable portion of the Earth's surface area is water.

Even our societal views heavily shape the next generation of humans. Some countries, such as China, may limit the reproduction of their citizens, and some generational trends, such as depression in the current adolescent generation, can cause fluctuations in predictable populations and thus carrying capacities. As humans, one of our innate skills is to find a solution to any and every problem. It is highly likely that if population were to have a sizeable increase overnight, there would be precautionary measures enacted that we could not accurately predict at the current moment.

There's simply too many factors that play into account when calculating the maximum carrying capacity of the Earth, because of how complex and varied human civilization has become. It's no longer just about the bare necessities of a person, but also about the governmental stability, social stability, and many other factors that play into account in our everyday lives.

To put this into perspective, many previous papers have attempted to put factors such as agricultural capacity into account. However, this analysis is difficult for many reasons. First, this problem is attempting to deal with the carrying capacity from a global perspective. However, in order to do this, we need data from all across the world in order to fully encompass how the rest of the world acts and how agriculture affects their population. One of the best ways to analyze this is through looking at price because they are a good way to model the supply and demand of goods. However, many countries do not have historical prices of key food items such as bread and water available because they have not had the resources to collect this data and publish it online. As a result, many comprehensive datasets only provide data from the 2000s which is not enough to fully analyze trends. Due to this issue, we run into problems where problems fluctuate so much from year to year because of war and internal issues that it becomes difficult to accurately model.

Part II: Modelling

One approach to model the Earth's carrying capacity may be to analyze one or several of the variables/factors mentioned in Part 1. However, as mentioned previously, the actual carrying capacity of the Earth is influenced by so many factors. As such, even under a multivariate analysis there will always be missing holes and inaccuracies due to some factor that was not accounted for, and trying to include all of the factors would prove to be an extremely complex and convoluted problem indeed.

There is a much more effective alternative. By selecting and analyzing a variable in a model that encapsulates many factors, the modeling process will be greatly simplified and accuracy improved. According to the definition of carrying capacity provided, for a population to be classified as under the threshold of the carrying capacity, humans must be able to sustain themselves indefinitely in an environment given the resources available in their environment. Instead of looking at the factors that affect the resources available to humans, we can instead go to the other side of the pipeline and look at the behaviour of humans when they are and when they are not able to sustain themselves using the resources around them.

The human behaviour that this model chose to analyze was human fertility rates. The behaviour of human reproduction fits the definition of carrying capacity perfectly. If members of a population will feel that there are enough resources available in the environment to sustain both themselves and their offspring, they will reproduce and create the next generation of the population. However, if resources are scarce due to dangerously high population numbers, members of a population will either not have enough resources to sustain themselves, or they will choose to not reproduce because there are not enough resources to support their children. So, that population at its capacity will not be able to sustain itself indefinitely because it cannot reproduce and create the next generation.

Thus, the point at which fertility rates become dangerously low is the maximum carrying capacity: the maximum population at which humans are able to sustain themselves using what is available to them, as well as where humans are able to keep the population going indefinitely by reproducing.

This approach not only simplifies the process by analyzing only one variable but it also greatly increases the practicality of the model. By looking at the decisions that humans actually make given the circumstances of their environments, we do not make any assumptions about the theoretical “perfect” distribution of resources, or make any assumptions that humans will act rationally to aid other humans. For example, although it might be possible for well-off countries to start administering unprecedented amounts of aid to poorer countries in an effort to increase the poorer countries’ populations, this series of events would almost never take place in the real world due to the fact that countries generally act in their own self-interests. Another model that analyzes agricultural production capacity might end up making this flawed assumption (that richer countries can theoretically donate large amounts of food that they waste to poorer countries) and would thus inflate their carrying capacity to theoretical figures that lack meaning in a practical sense.

One important thing to consider when analyzing historical fertility rate data is the presence of contraceptives. Contraceptives make it significantly easier for humans to align their intentions of making offspring with what actually ends up happening. Since our model assumes that humans have some control over creating offspring and use their surroundings to make a decision as to whether or not make offspring, it is convenient for our model to analyze fertility rates when humans have more control over their reproductive abilities. Thus, our model will only look at fertility rates after the invention of and relatively-wide adoption of contraceptives, which we chose to be after the year 1950. Additionally, for both historical population figures as well as historical fertility rate figures, we used data that applied to the entire globe.

First, our model regressed upon time (x) versus population (y) (Figure 1) to predict the future population based on historical data. The type of regression used was logistic because although population does grow quickly initially, as time goes on, the resources dwindles until the population’s growth slows and approaches its carrying capacity. Then, our model regressed upon time (x) versus fertility rates (y) (Figure 2) in order to project the future fertility rate. The type of regression used was logistic to comply with the type of regression used for the time v. population regression: if population and fertility rates are related, then they should exhibit a similar curvature and behavior. Then, our model eliminated the common parameter of time and combined our projections for both population and fertility rates into one convenient model (Figure 3). Since overpopulation will tend to limit resources, which will influence human decisions to reproduce, which will affect fertility rates, it is clear that population should be the independent variable that affects the dependent variable of fertility rates.

When performing the regressions, we used the general form of a gaussian curve:

$$\frac{a}{e^{\left(-\frac{(x-b)^2}{c^2}\right)}} + D$$

It is similar to a logistic curve but the gaussian curve approaches its asymptote and limit faster than a logistic curve.[1] This is helpful when dealing with especially small datasets.

Analyzing figure 3, the fertility rate begins to level when the population is at around **10.2 billion**, and thus that is our model's output for our current carrying capacity. We conducted this analysis by taking the first and second derivatives to see the inflection points and see the rate at which the population growth changes and when it starts to approach 0.

There are a few ways in which this model can be improved. First, an analysis of each country could have been done, and then the carrying capacities of each country could have been summed up for a final global carrying capacity. This approach may have been more accurate because it would have respected the individual circumstances that make each country unique. Among many circumstances, some may include: varying exposure to contraceptives depending on their economic status, or choosing to make slightly different reproductive decisions based on their culture.

Analyzing death rates would also be another way to further bolster confidence for this model. This is because we only analyzed the derivatives of the fertility rates in order to calculate our carrying capacity. However, if we analyze the death rates, we can check this carrying capacity by looking at when the fertility rates drop below the death rate and when this happens, this is often a good sign that the carrying capacity has been reached assuming that a problem such as war or disease does not come up.

Part III:

In order to raise the carrying capacity, the most important thing to do is to maximize how effectively we use our resources. Humans are terribly inefficient at using their resources. For example: a ⅓ pound-burger requires nearly 660 gallons of water[2], and nearly ⅓ of global food supply gets either wasted or lost.[3]

As a result, we have utilized an industry grade deep neural network in order to analyze satellite images and return if that patch of land is good for agricultural. Using a dataset of satellite photos

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[1] NG, A. Y., & Jordan, M. I. (n.d.). On Discriminative vs. Generative classifiers: A comparison of logistic regression and naive Bayes. Retrieved from http://ai.stanford.edu/~ang/papers/nips01-discriminativegenerative.pdf

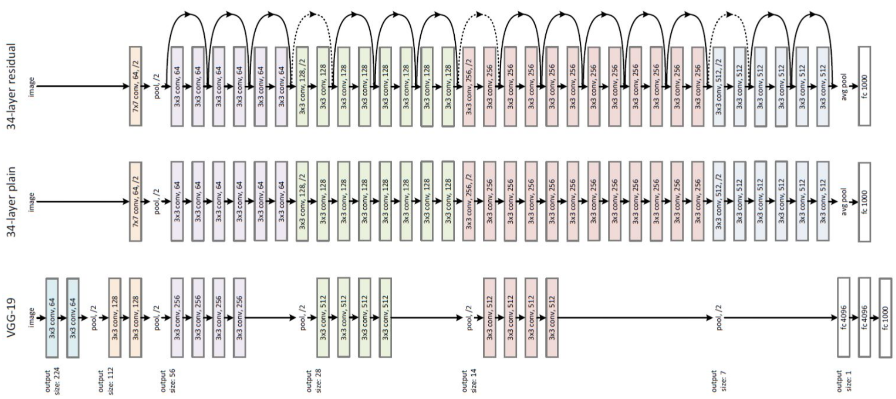
[2] https://www.latimes.com/food/dailydish/la-dd-gallons-of-water-to-make-a-burger-20140124-story.html

[3] Key facts on food loss and waste you should know! (n.d.). Retrieved from http://www.fao.org/save-food/resources/keyfindings/en/

that describe the quality of land in a region from PLANET, a satellite technology company, we took in photos such as these:



And then we outputted labels for each image such as forest health (if there is one), is the land fit for cultivation, is there a river present in the photo, and what structures are present in the photo (in one case, we had an artisanal mine in our photo). Using an industry grade deep learning model, Resnet 34, we were able to achieve a 92% accuracy on our multi-label image classifier.



[4]

The implications for this deep learning model are immense. Not only can we rapidly analyze millions of satellite photos in order to understand whether land is healthy for cultivation and consequently be able to utilize all the land we can in order to maximize food production but we can also analyze where rivers are in the world in order to find new water sources and expand trade routes. Additionally, we can analyze tree health across the world in order to curb rapid deforestation by notifying lumber companies when they are removing trees too quickly. This helps with combating climate change by increasing the number of carbon sinks we have.

Another action that we can take to improve our global carrying capacity is to fund education worldwide. Education is generally known to increase employment opportunities in any nation, and if employment and population grow closely together, then some of the negative effects of overpopulation can be mitigated or delayed.

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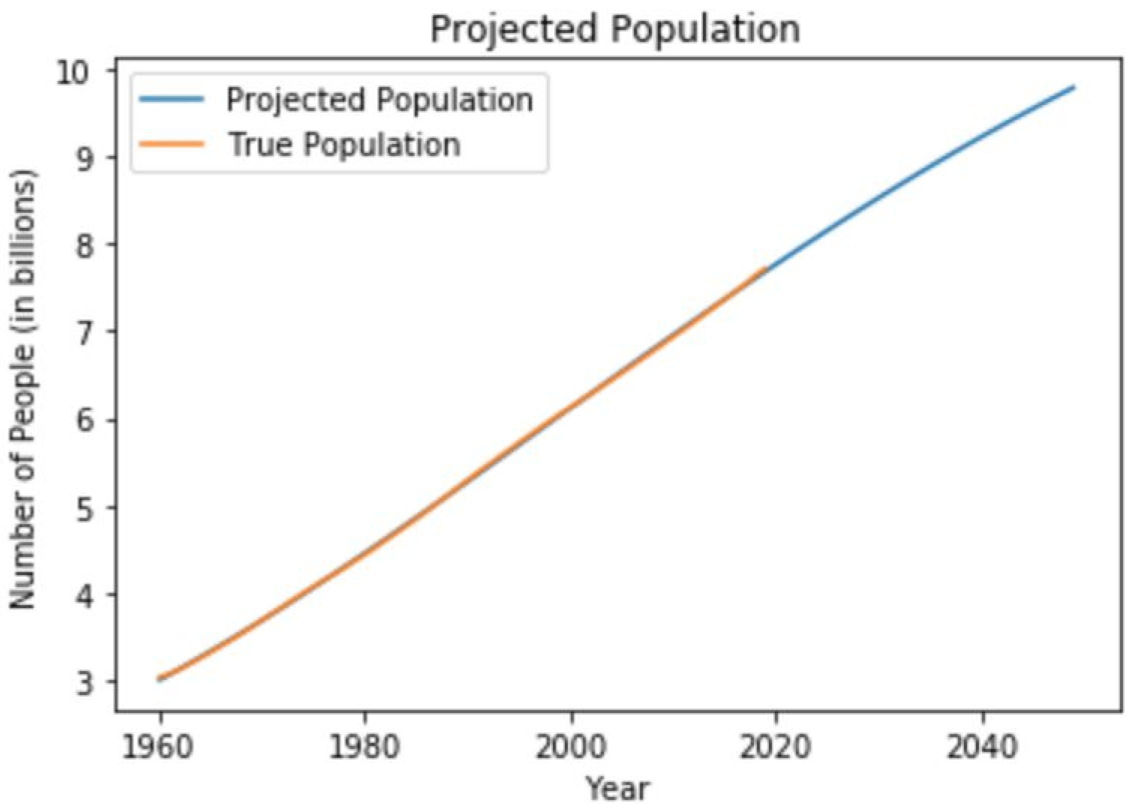
[4]He, K., Zhang, X., Ren, S., & Sun, J. (2015, December 10). Deep Residual Learning for Image Recognition. Retrieved from https://arxiv.org/pdf/1512.03385.pdf

Appendix

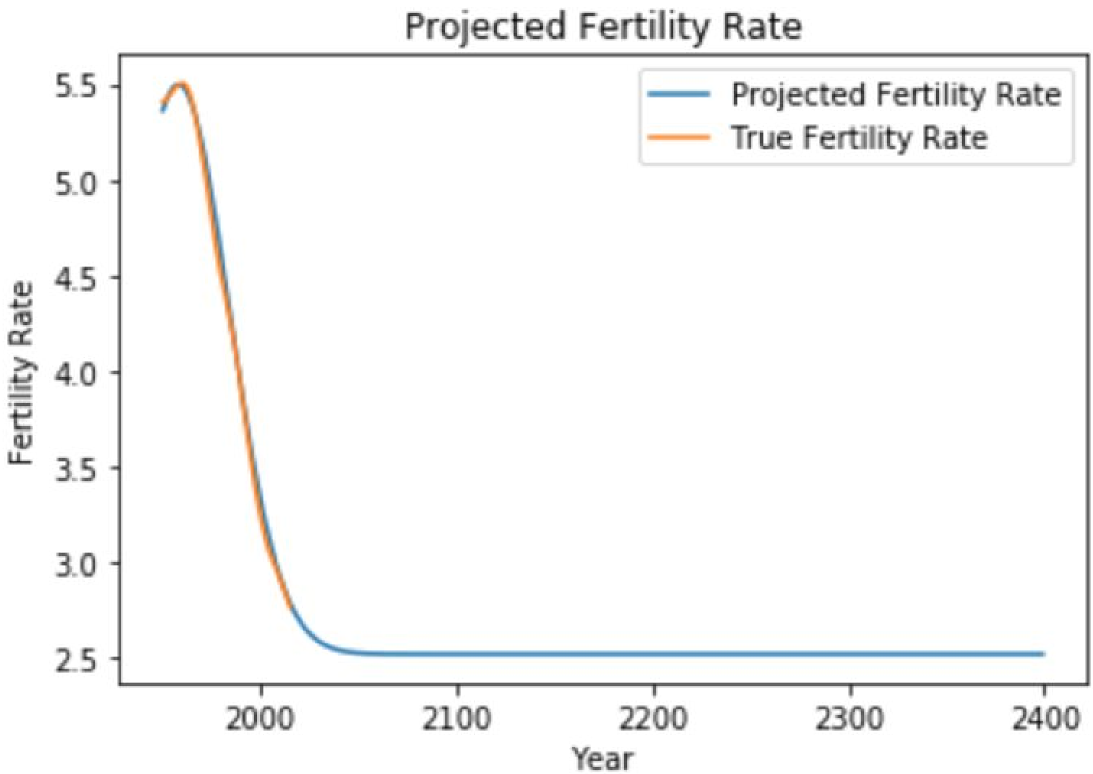
Figure 1



Root Mean Squared Error: *0.01450*

Logistic coefficients (constants correspond to the equation described in the paper):
A: -11.06947879,
B: -41.40888421,
C: -112.45742534,
D: 12.66845678

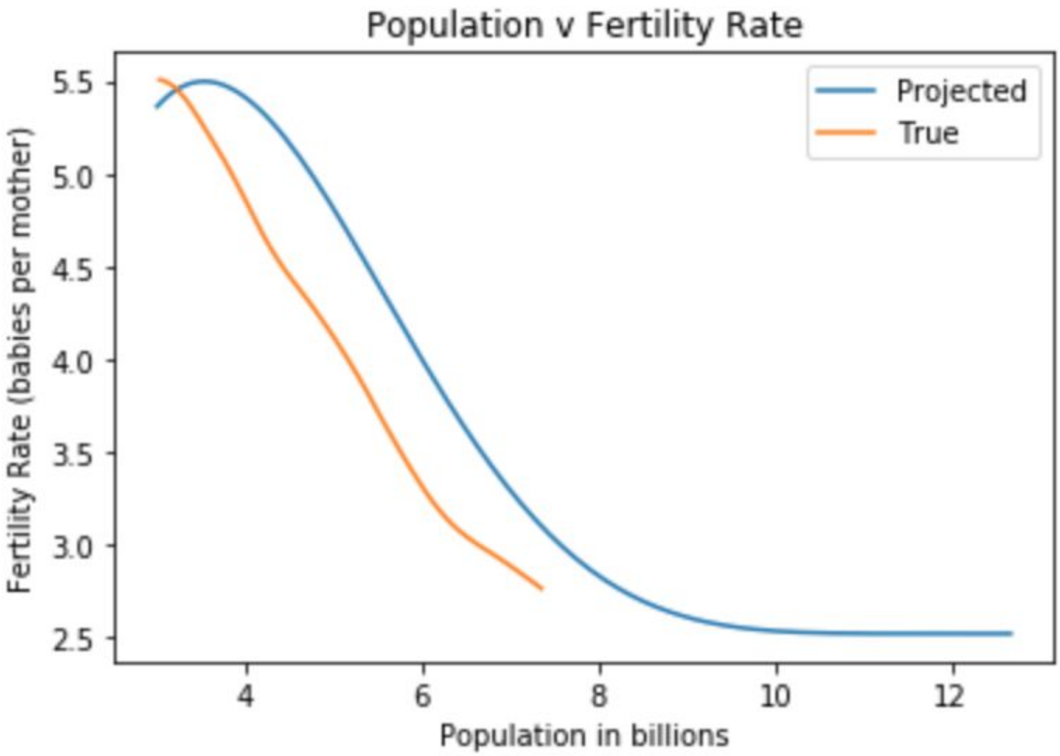
Figure 2



Root Mean Square Error: 0.03641

Logistic coefficients (constants correspond to the equation described in the paper):
A: 2.97466196,
B: 7.92488637,
C: 36.75981589,
D: 2.52164397

Figure 3


Population v Fertility Rate
Projected
True
Fertility Rate (babies per mother)
Population in billions
5.5
5.0
4.5
4.0
3.5
3.0
2.5
4
6
8
10
12