In what year will the population on Earth reach 10 billion?

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Forecasting the world population by year has been a fairly common task that organizations, such as the United Nations (UN), conduct every so often. These forecasts have varied a lot in accuracy to the resolved value and forecasts that have been revised in future years are still close to the past forecasts. However, these forecasts face a number of uncertainties that we want to take into account which are not captured by the current data-driven methods of the UN.

The relationship between agriculture and population can be traced back to 11,700 years ago when the first agricultural revolution happened. A stable, healthy, inclusive, and sustainable food source is essential for a community to grow and develop. Today, 80% of the worldwide human population depends on the production from less than a dozen crop species, and many of which were domesticated many years ago (Herrera and Garcia-Bertrand 2018). A stable food source was important for a community to grow, especially in the old days. However, even today, restrictions on food production are still a limiting factor for some countries and regions to develop. For example, as mentioned by the World Bank, “Agricultural development is one of the most powerful tools to end extreme poverty, boost shared prosperity, and feed a projected 9.7 billion people by 2050.” Besides these, even the basic needs are human lives are met, malnutrition and poor diets are also the leading cause of death worldwide.

The relationship between population growth and economic growth is controversial. Many researchers draw on historical data to chart the links between population growth, growth in per capita output, and overall economic growth. Most work done supports the idea that population growth is an important factor in overall economic growth and may even contribute to increased growth in per capita output in some cases. Thus, we can infer that population growth and economic growth have strong correlation. We got data of population and GDP from The World Bank, and we noticed that the calculated R squared value between these two elements is about 0.8, which indicates that they have strong correlation. Although we note that they do not have causal relationships, they show dependence. Therefore, we can conclude that it is reasonable to use world GDP data to predict world population.

According to past data and current projections by the United Nations (2019), life expectancy is increasing steadily for all populations. In addition, the population increase trend has changed from a stage of rapid increase to stable and is projected to go into a stage of zero growth (such as trends in Denmark, Austria, and Italy) then negative growth (like Germany, Bulgaria, Japan). This means that, globally, we approach an aging population. According to the World Health Organization (2019), as the proportion of the older population increases, the expenditure on health care is increased by a hefty amount. We see this in the case in China when much of their population joined the older brackets, leading to a near double in share of global health spending.

According to the nine planetary boundaries (Rockström et al. 2009), humanity must respect the environment to keep the planet livable and habitable. If humanity exceeds the nine boundaries, then the planet would no longer be habitable. Some of the scholars have demonstrated that the exploitation of natural, mineral and energy resources, and the ability of the environment to absorb waste generated by mankind’s activities are not keeping pace with population growth (Commoner 1971; Cropper and Griffiths 1994; Demeny 1991; Myers 1997). Namely, Human activities have been impacted on the environment after the industrial revolution. Global warming and climate change are the consequences of human activities, bringing us a chain reaction rather than independent occurrences.

Based on the domain knowledge and background research, we notice that to gain a better view on world population, we need to look at the historical data of populations with agricultural statistics, GDP, life expectancy, environment, and birth and mortality rates. We’ll also look at significant events that have affected population growth significantly, such as war, pandemics, and natural disasters.

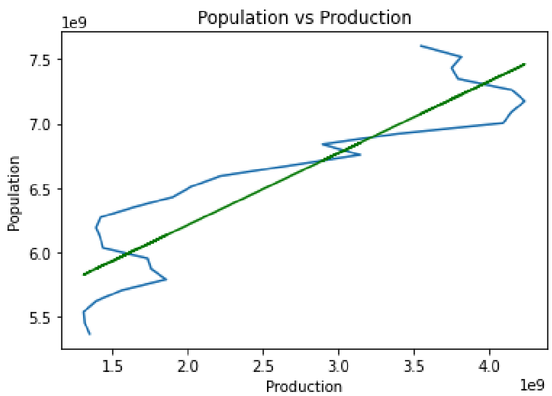
Agriculture

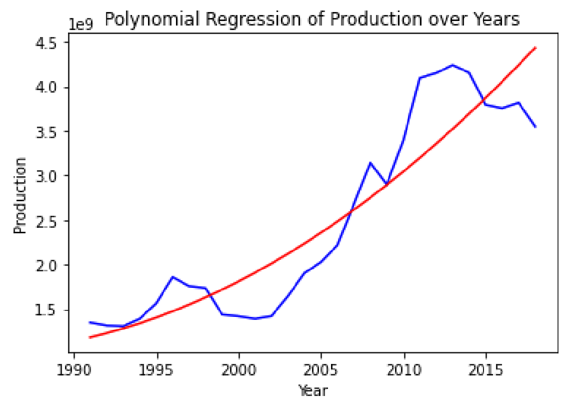
First, since the first agricultural revolution started about 11,700 years ago with transition to settled agriculture, the second agricultural revolution happened between 1600s to 1800s which corresponds to the doubled population growth in England and Wales within 100 years (Richards and Hunt 1995), and the third agricultural revolution happened in 1930s to 1960s using research such as chemical fertilizers to facilitate cultivation, our first assumption is that the next large agricultural revolution will not happen before population on earth reaches 10 billions. Using zeroth and first order forecasting, we derive the gap between each 10,000 years and 245 years respectively. Considering we are only 77 years away from the green revolution, both zeroth order and first order differencing gives us a value beyond the length of major forecasts. So, it is reasonable to assume that the next technology advancement will not occur in the scope of these questions, and thus we can follow the trend of current data.

Second, looking at the relationship between population and agriculture, we get a correlation of 0.9042767101953659, meaning that our data has a strong positive correlation. Looking closer at the linear regression result, we get:

$$\hat{Population} = 0.55746183 \cdot Production + 5098266052.721117$$

Therefore, using the linear equation, we need world agriculture production to reach 170238981115.53214, which corresponds to 31.49 years.





Therefore, the estimated year for the population to reach 10 billion is *2035*. Introducing confidence intervals into my estimation, I get *[2034, 2036]* years.

GDP

Here, we use GDP per capita to predict population instead of GDP because GDP per capita determines a country's standard of living. Conceivably, a larger population almost always results in a larger aggregate economy. More workers, more consumers, and more government spending lead to a larger GDP (Peterson 2017). But the standard of living in a country is determined by GDP per capita, not the overall size of the economy. GDP and population show dependence because GDP impacts standard of living, and so the birth rate and death rate will change.

As expected, the r-squared value between GDP per capita and population is higher, which is 0.877. We got an equation that shows the relationship between these two variables. However, we can not simply use this equation to do prediction because we need to take the Great Recession that occurred globally between 2007 and 2009. We noticed that the GDP per capita in the past decade fluctuated around $10500, while the GDP per capita from 2000 to 2008 increased sharply. It does not mean the economy is stagnant in recent decades. The period from 2010 to 2020 saw the longest economic recovery on record. After economic recovery from the Great Recession, the economic growth will turn back. Therefore, we use the equation between GDP per capita and population from 2010 to 2020 to get the lower bound of GDP per capita when the world population reaches 10 billion.

GDP per capita (2010 to 2020):

$$1.24 \times 10^{-6} \times x + 1591 \text{ (x:population)} \Rightarrow 1.24 \times 10^{-6} \times 10\, billion + 1591 = \$13991$$

$$\text{GDP: } \$13991 \times 10\, billion \approx \$140\, trillion$$

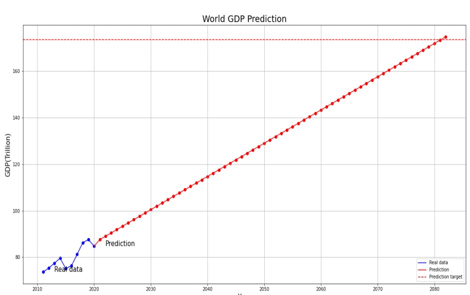
The upper bound of GDP per capita is about $16000. The increase of GDP per capita in the economic recovery period (2010-2020) is about $2000. The growth rate in the next few decades should be between the growth rate from 2000 to 2009 and from 2010 to 2020 because of COVID 19, a global severe infectious disease. The world needs time to recover from the pandemic, so it can not grow as quickly as the period from 2000 to 2009.

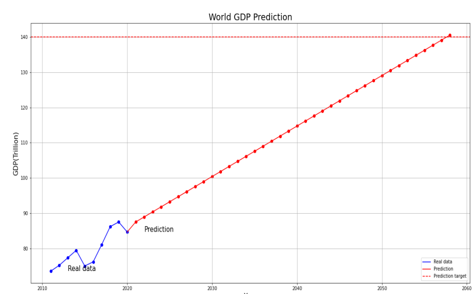
GDP per capita (2000 to 2020):

$$3.8 \times 10^{-6} \times x - 17301 \Rightarrow 3.8 \times 10^{-6} \times 10\, billion - 17301 = \$20699$$

$$\text{GDP : } \$20699 \times 10\, billion \approx \$207\, trillion$$

$$(\$140\, trillion + \$207\, trillion)/2 = \$173.5\, trillion$$



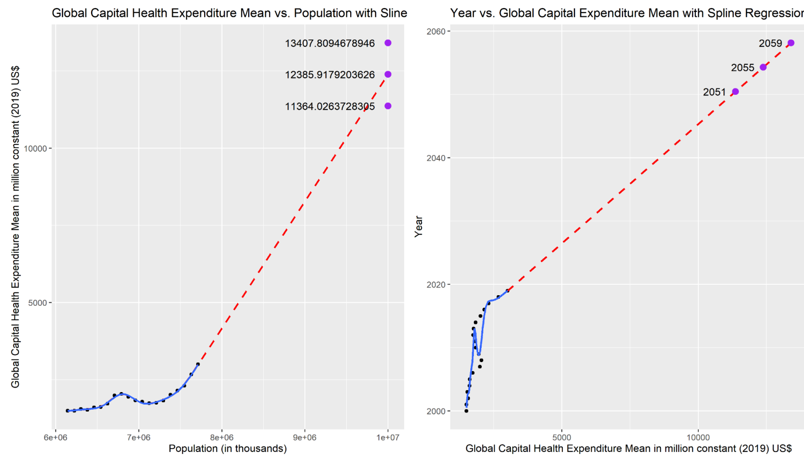


This is the linear regression model that shows the prediction of GDP in particular years. Our lower bound of GDP when population reaches 10 billion is $140 trillion and the upper bound is $173.5 trillion. The red dashed line shows the targets which are 140 and 173.5. The blue part is the real data, and the red part is the prediction. From the two figures, we can see that GDP is expected to reach $140 trillion and $173.5 trillion in the year of 2057 and 2081, respectively:

	Year	GDP
46	2057	139040418490897.36
70	2081	173348711420288.7

Therefore, the output yields an interval of *[2057, 2081]* and *2069* point estimate.

Life Expectancy



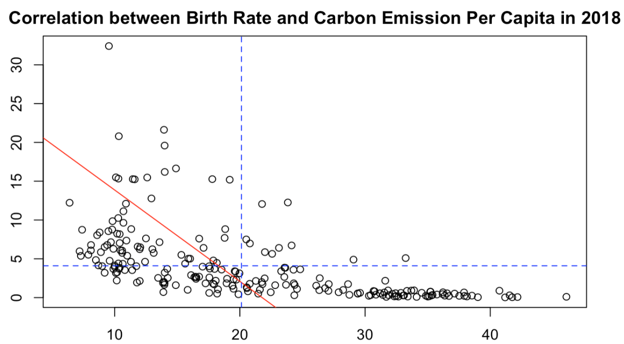
Informed by the high correlation in the transition to an aging population and health expenditure, we will use capital health expenditure and population trend to predict a year. To limit the scope and complexity of this prediction, we obtained just the yearly mean of global capital health expenditure in million constant (2019) US$ from The World Bank. Combined with yearly population estimates from the United Nations World Population Prospects, a natural spline regression model (*df* = 7) with $r^2 \approx 0.9933$ was fitted. Using the extrapolated trend from the model, at 10 billion population, global capital health expenditure has a 80% prediction interval of [11364.03, 13407.81] and 12385.92 point estimate.

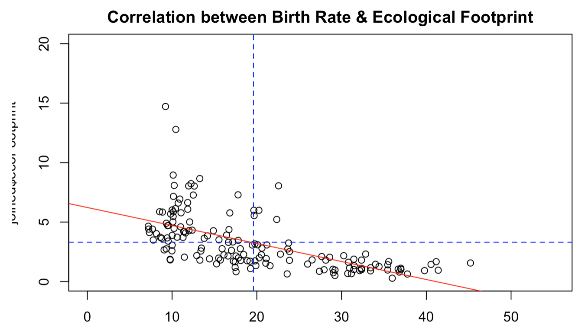
Then to predict the year based on our estimate of global capital health expenditure, another natural spline regression model (*df* = 11) with $r^2 \approx 0.8952$ was fitted. This time, the prediction interval and point estimate from the previous model was used to predict the year using this new model. The output of the point estimates using that interval and point estimate yielded an interval of *[2051, 2059]* and *2055* point estimate (rounded because of discreteness of years).

Environment

Climate change has been discussed over the past decade. Carbon neutralization is a reach goal for most countries to ensure the continuation of the human population. Diving into how environmental factors affect population growth, we consider four perspectives that are essential and crucial for human beings: water, land, air and ocean. Environmental factors are difficult to quantify, and it is an ongoing debate in human society. We consider Environmental (Planetary) capacity and map it onto population growth. Generally, we form an intuitive prediction based on the global carbon emission and modify the prediction by the other three perspectives. The following paragraph further justifies our method of prediction:

Some scholars measure climate change by using carbon emission and ecological footprint. An ecological footprint measures *"how much nature we have and how much nature we use,"* according to Global Footprint Network (GFN). Based on data, ecological footprint has a negative correlation with the crude birth rate and ecological footprint is strongly correlated with the GDP per capita. More developed countries produce more ecological footprint, however, there are outliers such as Qatar, Saudi Arabia, and Iran etc. Living in a fossil-fuel based world, the calculation of the ecological footprint is determined by carbon emission. Price has always been a swaying factor affecting global energy. In the face of rising energy prices and geopolitical risks, oil and gas prices hit a record level while the cost of clean energy continues to fall. In order to reduce dependence on a single country and energy source, the development of renewable energy can lessen the share of fossil fuel usage to a certain extent and further promote energy diversification to cope with the energy crisis. Most emissions come from a few countries and these major trends are likely to continue.

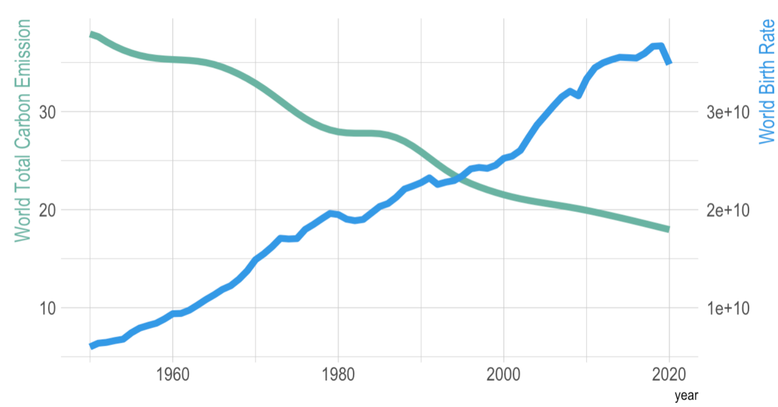




Formula: Contribution to the global carbon emission × Projected renewable energy in 2050

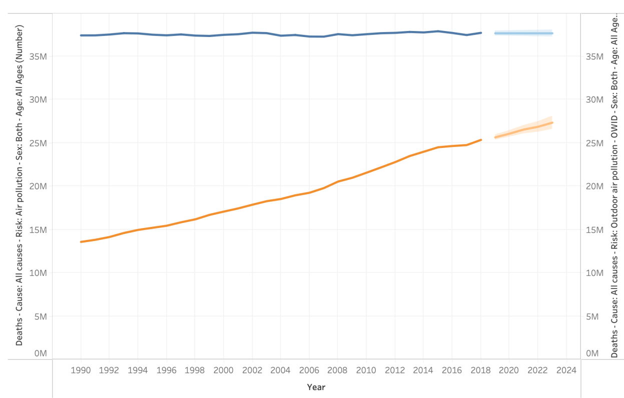
China: 30% × 50% = 15%	EU: 18% × 60% = 10.8%
US:14% × 66% = 9.24%	India: 10% × 60% = 6%.

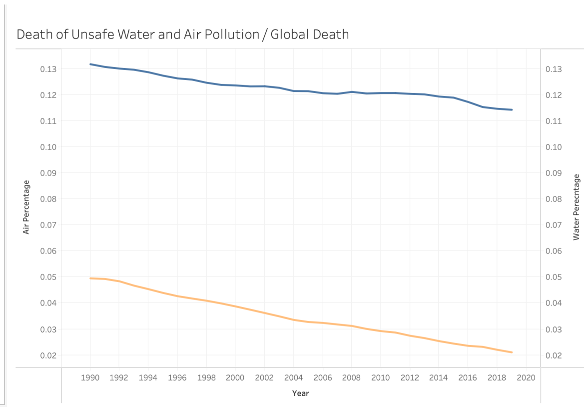
It comes up with 41.04% out of the 72% of global emissions. We optimistically estimate that at least 50% of the energy generation comes from renewable and clean energy by 2050 which means global emission will be halved to 2019 level to attain the 1.5°C goal. We could remove the outliers while estimating the birth rate since clean energy is going to play the dominant role in the energy sector. According to the Environmental Kuznets Curve, environmental quality tends to deteriorate as per capita income increases, and only after per capita income reaches a certain level does environmental quality begin to improve, with the curve of environmental quality changing in an inverted U-shape as per capita income increases. "*This reveals that while different development paths may relate to relatively small differences in the environmental output intensities, it may produce rather large differences in actual forest loss, air quality and carbon emissions depending on the scale of the economy*" (Andrée et al., 2019). Worse scenarios may in fact be considered as relevant possibilities by major carbon emitters adopting carbon-negative policy or delay in progress. This is in line with our result that continuing current development on the linear-log model puts the world on emissions that keep rising associated with a 4.9°C pathway in 2100. As the population continues to grow, humans will need access to more demand in limited resources to survive. In other words, the cost of living will increase by resource justice, and this will drive down the willingness to have children and the fertility rate implicitly.



Water covers 70% of the Earth's surface. However, the accessible freshwater resources are limited. Water scarcity comes up with the crucial factor affecting human population. Nearly four billion people experience water scarcity. According to the reports of WHO, nearly 1.2 million people die from unsafe water. For the issue of drinking water resources, both developed and less developed countries around the world are facing a growing water shortage. However, for the improvement of water resources, developed countries and most developing countries are improving year by year. The issue of unsafe sanitation is therefore one which is largely limited to low and lower-middle income countries. Death rates are much higher in low-income countries, especially for African countries. However, in some low-income countries and in Africa, the problem is growing, and they are also the countries with potentially high birth rates in the next decade. The number of deaths by unsafe water has declined from 2.44 million in 1990 to 1.23

million in 2019. The significant decline accounts for the improvement of water sanitary from economic development. ***"****Global water demand has increased by 600% over the past 100 years.5 This corresponds to an annual increment rate of 1.8%"*" (Boretti & Rosa 2019). Increasing water demand follows population growth, economic growth. We estimate the global water demand for all purposes will increase 20%-30% by 2050 and the number of deaths will be between 1 million to 1.5 million. Even though the mortality rate is declining, water sanitation cannot keep up with population growth and demand growth, especially in low-income countries and water-scarce countries.





Environment as a constraint to stack down the population growth. With the development of technology, death tolls tell a very clear story: people are safer from climate-related disasters than ever before. However, extreme weather due to climate change. For example, extremely high and cold temperatures. Although we could not find the dataset for report death, according to Professor Yumin's report, nearly 5 million people die every year due to abnormal temperatures. This number will continue to grow since climate change is an emerging and accutte issue. Natural disasters are more like random and stochastic processes. The relationship between temperature and mortality is roughly U-shaped, meaning that the risk of death increases sharply for every 1°C increase in average daily temperature at the extreme heat that people are not used to. The estimation we formed is that the death from abnormal weather would double from every 1°C global temperature within the 4°C range (See Appendix). The global average temperature increased 0.26°C yearly over the decade. In short, it is indelible to blame population growth instead of taking action of strictly environmentally friendly and sustainable policy.

Diseases

Another important factor to consider is the probability of future pandemics that could lead to a decrease in population. Based on past records, the rate of major outbreaks, with a death toll of at least 10 million, is approximately once per century, which translates to 0.28 times per 28 years, and if we estimate the occurrences with a Poisson distribution at this rate, the probability of a major pandemic by 2050 is about $0.28e^{-0.28} \approx 0.212$. Since the world population and level of medical care vary in different eras, the measure we picked to estimate the impact is the percentage of population loss resulting from past major pandemics. By averaging, it is expected that this potential outbreak will cause a decrease in population, in the year it is predicted to happen, by roughly 6.4. Based on this forecast, the population loss is estimated to be about 640 million. Assuming a population growth rate of 1.05%, which was the historical average, we could calculate the number of years it would take to recover by solving for t in $9.36(1+\frac{1.05}{100})^t = 10$.This gives us a little above 6 years, and we adjusted our upper bound accordingly.

War

We have also included the possibility of war, and in order to apply the same method of estimating the probability with a Poisson distribution, we picked the start year to be 1364 since it was the time when the first use of firearms was recorded, and besides *WWI* and *WWII*, we assigned Cold War half the weight because even though there was no significant casualties during the Cold War, it was considered as the global tension that almost led to a worldwide nuclear war; therefore, we would get a rate of $\frac{5}{47}$ per 28 years, and this gives the result that with probability $\frac{5}{47}e^{-(\frac{5}{47})} \approx 0.096$, there will be a war similar to *WWI* and *WWII* before 2050.

The consequences of such war will be significantly more disastrous than all the previous world wars due to the existence of modern weapons; therefore, we believe that our forecast of the probability of a world war before 2050 could be numerically less meaningful than the previous estimates because of the extremities of a world war in this era. The probability that the world population will peacefully and gradually achieve 10 billion is extremely high; however, in the unlikely event that a world war happens by 2050, the consequence will likely to be close to the level of human extinction, and in the case, we find it necessary to estimate the amount of time needed for humans to repopulate the Earth.

Assuming that the population loss of the unlikely future world war is about 95% and that it happens at a point where the population reaches 9.9 billion, we get a remaining population of approximately 495 million. The highest rate of population growth ever recorded was 2.2% in the 1960s, and the doubling time T could be obtained by $T = \frac{\ln(2)}{\ln(1+\frac{r}{100})}$, where r is the growth rate; therefore, optimistically, if we use this maximum as the population growth rate, we would get a doubling time of roughly 32 years, and based on this, we found that it would take only slightly fewer than 160 years for a human population of 495 million to repopulate the Earth back to 10 billion; however, if we choose to use the historical average population growth rate as mentioned above, over 330 year would be needed.

Other Options

Some additional possibilities that might make our forecast way off include the discovery of habitable planets that are capable of hosting and promoting the developments of technological species. A particularly useful reference here is the *Drake Equation* that is used to probabilistically estimate the number of active, communicative extraterrestrial civilizations in the Milky Way Galaxy, and it suggests that on the pessimistic side, we could be alone in the observable universe, but changing the parameters of the equation to achieve a maximum suggests that there are roughly 15.6 million civilizations. Although the probability of such habitable zone is extremely low if we consider the Earth as the only case since civilization does not guarantee habitability, this factor could affect our forecast because a successful discovery before the world population reaches 10 billion would mean that some will move to the new planet; therefore, the year that the world population reaches 10 billion will be pushed back, but at the same time, in the foreseeable future, population on Earth would reach 10 billion before 2060, and the costs as well as the time required are unimaginable because it is certainly not the case that one day we would suddenly be able to transfer half of the population on Earth to a new planet.

Additionally, "*molecular nanotechnology weapons have topped the Humanity Institute's list because they have the potential to be both lethal and widespread*". Future warfare involving unstoppable and possibly self-replicable weaponized MNT could be catastrophic and swiftly lead to human extinction. As scientific advancements become increasingly rapid, one of its potential product, a super-intelligent and self-conscious artificial intelligence has been rising in popularity in discussions and leading to concerns about human decimation due to a potential loss of control on such AI; however, as we have predicted in "*Forecasting AI*" , with high confidence, the year that the population on Earth is expected to reach 10 billion will be way before the year that AI will be able to perform essentially all tasks that humans can do. Therefore, the probability of the occurrence of any of these events before the world population reaches 10 billion is extremely low, and we decided not to include these considerations in adjusting our confidence intervals.

Combining Forecasts

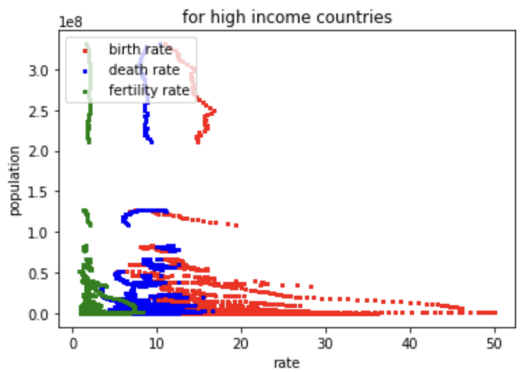
Out final model consists of 3 parts:

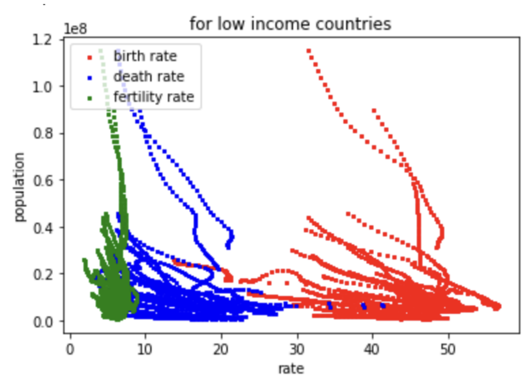
1. Combined forecasts from agriculture, GDP, and health care
2. The prediction based on birth rate and death rate
3. The modifiers introduced by environment and the other option.

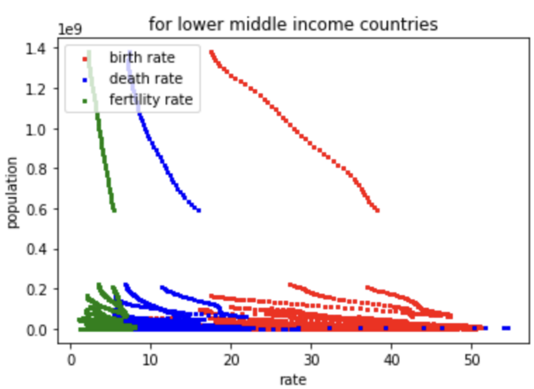
First, combining the forecast from agriculture, GDP, and health care, the confidence interval becomes *[2047.33, 2058.67]*.

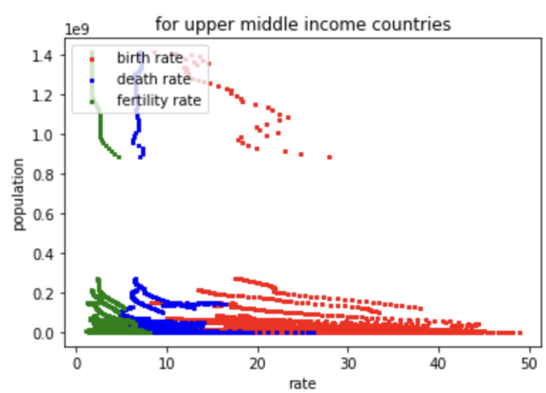
Second, we viewed the data based on birth rate and death rate. According to the World Bank Analytical Classificer, we can classify all the countries into low income (L), lower middle income (LM), upper middle income (UM), and high income (H). Then, we grouped countries into each income group and created models based on its birth rate and death rate for each country. Then, we combined the 4 models for each classifier and predicted the year in which the human population on earth would reach 10 billion.

We can see the birth rate, death rate, and fertility rate for each country is different. Using the birth rate and death rate for each income group, we will adjust our confidence interval by 5 years. Therefore, the final confidence interval is *[2042.33, 2063.67]*









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Appendix

Name	Year	Total Number of Death	Death from air pollution	Death from unsafe water
World	1996	51689048	6528219	2203646
World	1997	52030524	6547192	2171865
World	1998	52361735	6525727	2140947
World	1999	52679836	6522139	2099432
World	2000	52978353	6548091	2049815
World	2001	53249602	6562169	1994001
World	2002	53489264	6593796	1934978
World	2003	53696120	6588013	1873268
World	2004	53871987	6541469	1805631
World	2005	54016094	6556779	1767662
World	2006	54128359	6528813	1752216
World	2007	54218245	6527585	1722904
World	2008	54299904	6576417	1694361
World	2009	54388442	6554957	1635490
World	2010	54498936	6576174	1592303
World	2011	54644548	6593948	1566354
World	2012	54836846	6600712	1504617
World	2013	55088432	6619746	1461535
World	2014	55412196	6612532	1406151
World	2015	55822989	6638067	1363038
World	2016	56331837	6605030	1327637
World	2017	56935173	6564255	1319414
World	2018	57625149	6605560	1270273
World	2019	58394378	6671740	1230154