Statistical Analysis of Human Overpopulation and its Impact on Sustainability

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Abstract

In this project, I examine the relationship between population size and resource use, with particular emphasis on carbon emissions. I use a combination of time series methods and regression analysis to obtain forecasts for global carbon emissions and energy use to the year 2060, taking into account population growth and economic development. In general, my predictions are consistent with predictions already made by different experts, though mine tend to be slightly more pessimistic. I end by addressing some potential ways to decrease population growth rates.

1 Introduction

In the twentieth century, human population nearly quadrupled from 1.6 billion to 6.1 billion. Over that same period of time, global carbon consumption increased by a factor of twelve [1]. Population growth has begun to slow, especially in developed countries, but global population is not expected to reach peak levels for at least thirty years [2][3].

In light of these trends, a natural question to ask is whether the Earth can support these kinds of increases in both population and per capita consumption. The population aspect of this is important because if we assume that available resources are finite, then a smaller population size may not solve the problem of overconsumption but it will slow demand for resources and give us more time to develop sustainable long-term solutions.

Despite the intuitively clear relationship between population and resource consumption, the issue of overpopulation is one that has been largely ignored in scientific circles since the 1970s [4]. In this project, I seek to examine the effects of current population growth patterns on resource consumption. In Section 2, I will describe in greater detail the environmental impacts of population growth, as well as the ethical and cultural considerations that come into play when discussing issues of overpopulation. Section 3 gives the results of a country-by-country regression analysis used to model carbon emissions and energy use as a function of population and economic development. These models are then used to forecast global carbon emissions and energy use until the year 2060. Some methods for slowing population growth are discussed in Section 4.

2 Background and Related Work

2.1 Environmental Impacts of Population Growth

Population size has an impact on all aspects of sustainability. Between 1950 and 1990, global population doubled while the global economy grew by 15 times, cars by 16 times and fertilizer use by sixfold [5]. All this consumption requires a host of natural resources, from petroleum to land for agriculture. Scientists have identified nine biophysical "planetary boundaries" which humanity should avoid transgressing, or risk irreversible environmental damage [6]. Increasing populations and affluence are putting more and more pressure on the environment in many different ways [7], and edging humanity closer to – and, in at least three cases, over [6] – these planetary boundaries.

In addition to dire biophysical consequences, overpopulation can have strongly negative social impacts. An overpopulated society risks becoming *demographically entrapped*, which occurs as a result of an unfavourable combination of the following three variables [4]:

1. A circumscribed ecosystem which has exceeded its carrying capacity
2. Lack of adequate opportunities for migration out of the ecosystem
3. The inability of the economy within it to produce the necessary exports, and therefore obtain necessary imports – especially food

When a population becomes strongly entrapped, they may suffer widespread starvation, disease or warfare [8]. It has been postulated that the 1994 Rwandan genocide occurred partly as a result of demographic entrapment [9]. At the time of the genocide, Rwanda was the most densely populated country in Africa and its economy depended almost exclusively on its primary production. The price of its most important export, coffee, had declined steeply just before the genocide [10]. The country's limited agricultural capacity forced many young men into Kigali, causing a concentration of young men with few prospects other than what might be gained through violence.

2.2 Ethical and Cultural Considerations

Despite an obvious relationship between world population size and various environmental concerns, discussion of overpopulation has fallen out of favour, both within the scientific community and among the general population [11]. This has been named the *Hardinian taboo*, and it refers to the self-inflicted thought process by which people refuse to contemplate world overpopulation as a problem [4].

There are many reasons for this taboo. One is the fear of censure; specifically, in discussing overpopulation – and population control in particular – one risks unfavourable comparisons to eugenics [12].

Closely related to this are our current notions of human reproductive rights: we believe that family size is an intimately personal decision, and are vigorously opposed to the idea of any legislation that would restrict our freedoms in this matter.

Furthermore, religious attitudes play an important role. The Catholic Church is opposed to nearly all methods of family planning, and this has had a strong cultural impact in many countries [13]. In addition to this, the Catholic Church and many other religions are strongly opposed to abortion.

Finally, the idea that overpopulation exists and is a problem challenges the increasing resource use of the developed world. If we assume that the problem of global poverty can be addressed through foreign aid and policy changes alone, it is possible to justify our own consumption. There is no need for us to live more sustainably if all poorer countries can and will experience the kind of development seen in wealthy nations. However, if we were to accept the premise that there are not enough resources to give everyone a “first world” standard of living, then it becomes clear that we are consuming far more than our fair share of resources.

3 Data Analysis and Forecasting Results

This section describes the techniques used to model the relationship between population and resource use, as well as the use of population and economic forecasts to predict future carbon emissions and energy use. Linear regression models are used to fit each country’s resource use to its population and per capita GDP over time. Then, population and per capita GDP are forecasted up to the year 2060 using a Holt-Winters exponential smoother [14]. These forecasted values are then used in the regression model to predict future resource use.

3.1 Population Forecasts

Before describing the results of the regression analyses, I will discuss the results of the population forecasts. For this project, I have used the Holt-Winters method to forecast population for each country. The reason for using this technique rather than using more complete demographic models is that I wanted to have a population forecast for every country in the world, and to ensure that consistent methods were used for all the predictions.

It should be noted that the lack of demographic information present in the modelling is an important consideration in assessing the validity of these models. However, in comparing the results of the Holt-Winters forecasts with more sophisticated demographic models, it becomes clear that the Holt-Winters estimates are, at the very least, reasonable.

Let us focus first on global population estimates. The United Nations predicts that in 2050 the global population will be between 7.4 and 10.6 billion, with the most likely value at around 9 billion [2]. The Holt-Winters method, on the other hand, gives a confidence range between 9 and 10.8 billion, with the mean prediction value at 9.6 billion. So, my forecasts are higher than those given by the United Nations, but not dramatically so. It should be noted that population forecasting is always highly uncertain – other models have predicted that population will reach 11 or 12 billion by 2050 (though this considered a less likely outcome)[5]. Furthermore, the UN's 1995 estimate for world population in 2050 was 7.8 billion, which we are now virtually certain to exceed within 15 years [11].

To obtain an understanding of how Holt-Winters compares to the demographic models for individual countries, let us first consider the examples of the United States and India. For the United States, the American Census Bureau predicts that the population in 2060 will be 422 million people [15], while the Holt-Winters model predicts 430 million. For India, the UN predicts a population of 1.89 billion by 2060 [16] where Holt-Winters predicts 1.98 billion.

In most cases, the Holt-Winters method gives somewhat higher predictions than the demographic models. This is likely because fertility rates in most countries are expected to fall in the next few decades. There is, however, one case in which Holt-Winters gives considerably lower estimates than demographic models, and this is in the case of the poorest, least developed nations. The Holt-Winters forecast for the 2060 population of sub-Saharan Africa is 2 billion, compared to a UN estimate of 2.4 billion [2]. These poorest countries are the ones expected to experience the most rapid growth, as they are the only countries where population growth is actually expected to accelerate, rather than slow down [17].

3.2 Regression Models

Now, we focus on modelling each country's carbon emissions as a function of its population and per capita GDP. The regression model is then used in conjunction with population and GDP forecasts to obtain a carbon emissions forecast to the year 2060. This was done for every country in order to obtain a global model, but in this section the focus is on three example countries: the United States, a developed country; India, a developing country; and the Central African Republic, an impoverished country where development is stagnant [18].

Forecasts for US population and per capita GDP are shown in Figure 1. Carbon emissions data from 1960 to 2010 [18] was then fitted to the population and GDP data over that same time period using a linear regression. The R^2 value for the model is 0.92. A comparison of the regression model's predicted emission values and the observed emission values is shown in Figure 2.

Combining the forecast data and the regression model, we obtain a forecast for American carbon emissions (Figure 3).

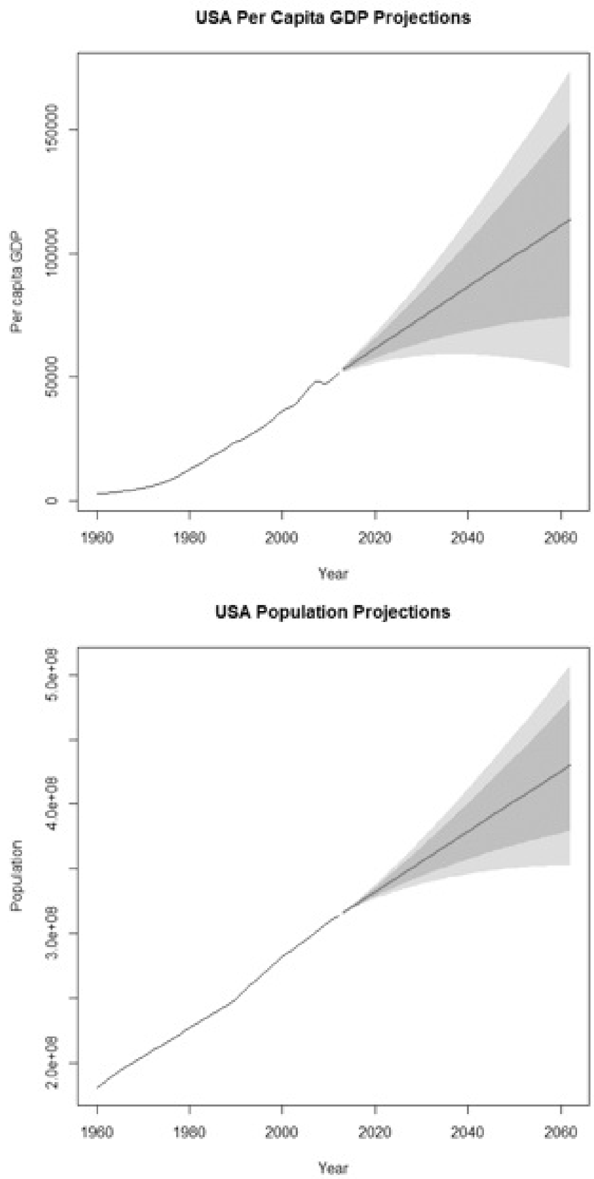


Figure 1: Forecast data for American population (top) and per capita GDP (bottom). 80% and 95% confidence intervals are shown in grey

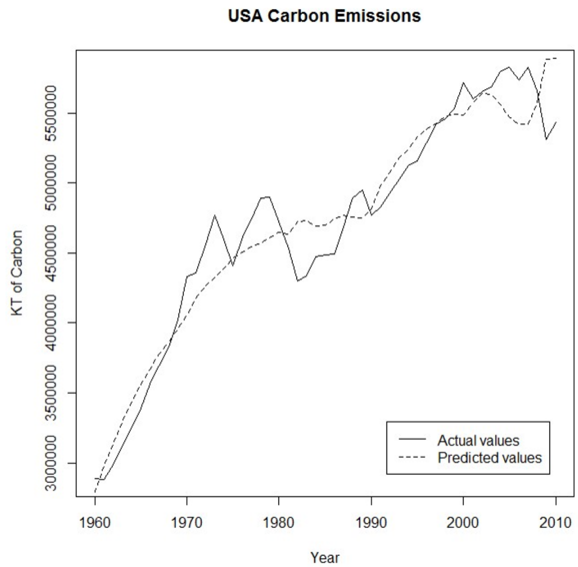


Figure 2: Regression model predictions for USA carbon emissions data

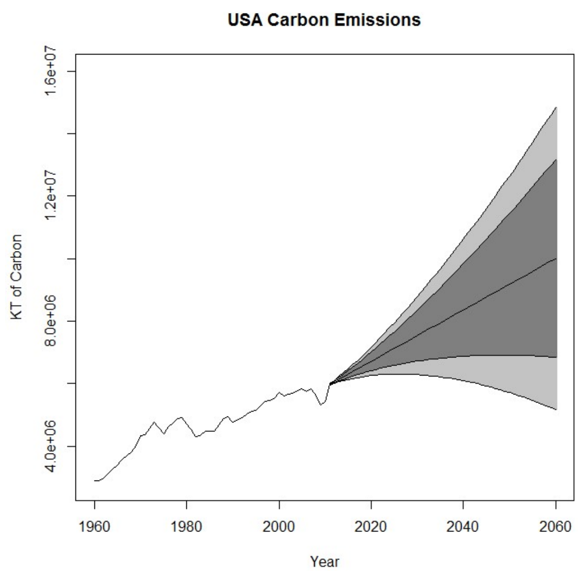


Figure 3: Forecast for USA carbon emissions. 80% and 95% confidence intervals shown in grey

In the case of India, we observe a rapidly increasing population size with slower corresponding growth in per capita GDP (Figure 4). In this case, the linear regression provides an excellent fit for the carbon emissions data ($R^2 = 0.97$); population is a strongly significant factor in carbon consumption ($p < 2e^{-16}$), whereas GDP is only slightly significant ($p \approx 0.1$). Due to the strong effects of India's rapidly growing population, we obtain a very narrow confidence band for India's future carbon emissions (Figure 5).

Lastly, the Central African Republic is experiencing rapid population growth and very slow economic development (Figure 6). For the Central African Republic, as well as for other impoverished countries such as Niger and Malawi, population is a significant factor in predicting carbon emissions while GDP has almost no effect. In addition, the linear regressions are not a good fit in these cases (typically, $R^2 \approx 0.6$), so the emissions forecasts (Figure 7) should be taken with a grain of salt.

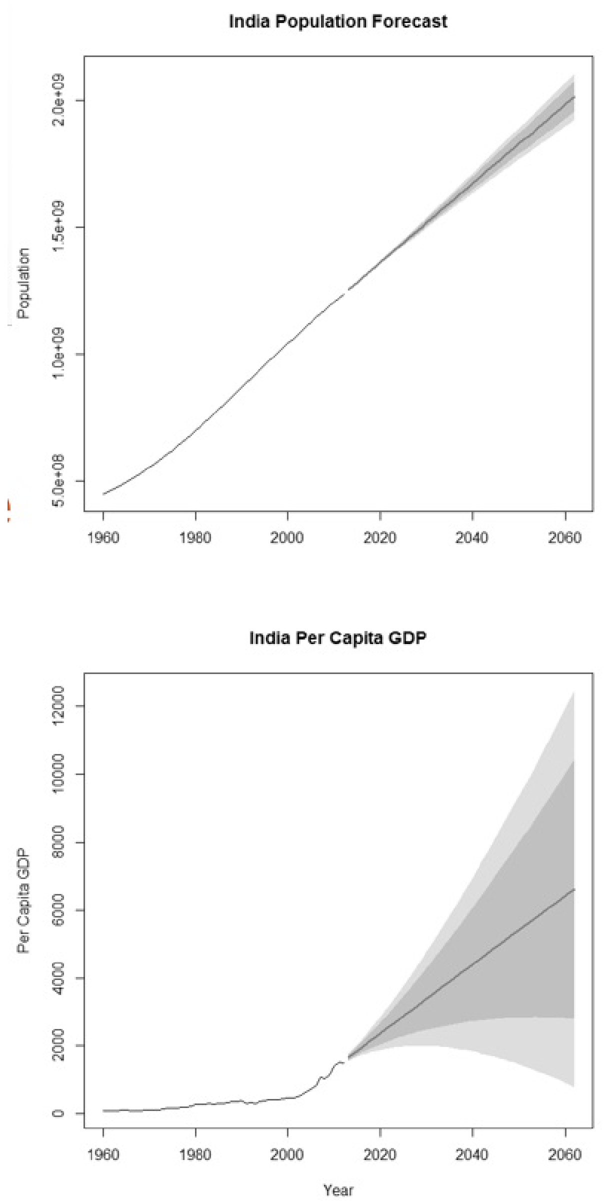


Figure 4: Forecast data for Indian population and GDP

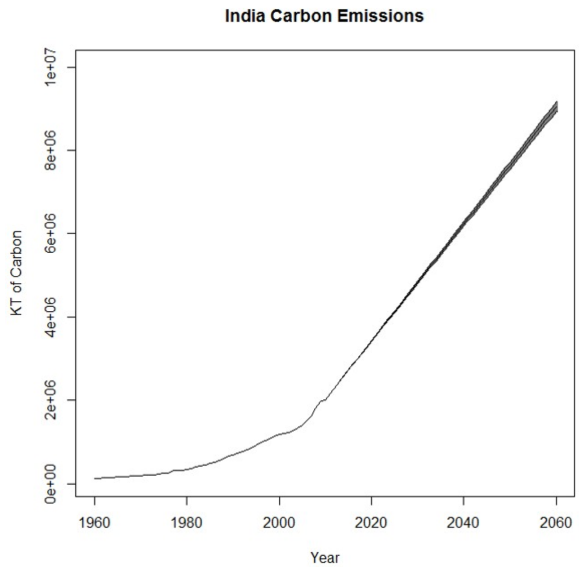


Figure 5: Forecast for India carbon emissions

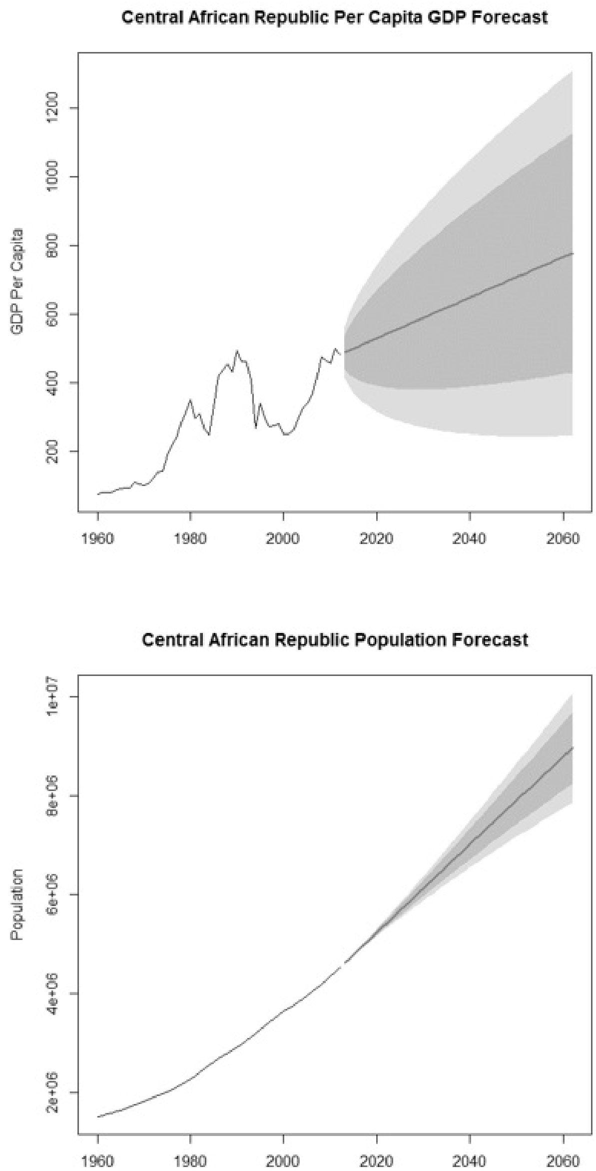


Figure 6: Forecast data for CAR population (top) and per capita GDP (bottom)

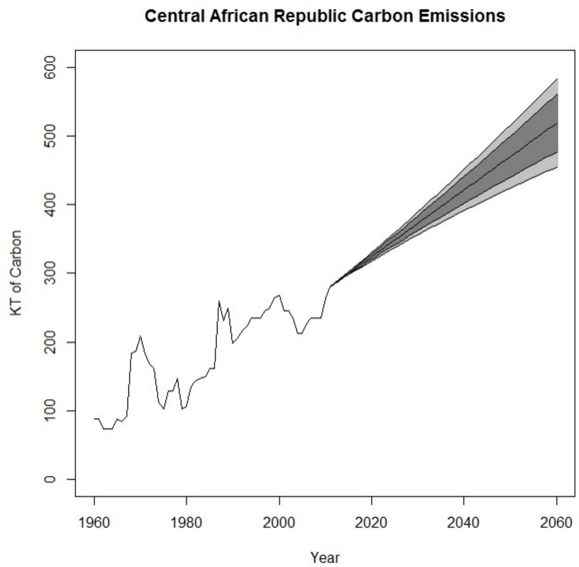


Figure 7: Forecast for CAR carbon emissions

3.3 Global Forecast Results

The forecast for global carbon emissions is obtained by adding together the individual forecasts of each country. There were 22 countries with insufficient data to obtain a forecast, so for these cases I classified the country as either low-, medium- or high-income and assumed that per capita carbon emissions would be consistent with the average per capita emissions of the other countries of that income level. Fortunately, the countries with missing data all have small populations, so the global estimates of carbon emissions in 2010 obtained using this extrapolation method were very close to the true global carbon emissions [18]. A plot of the global carbon emissions forecast can be seen in Figure 8.

Scientists have warned that, if humanity wants to avoid disastrous climate change, cumulative carbon emissions need to be limited to one trillion tonnes [19]. Current predictions are that the trillionth tonne will be emitted by 2040, though they do not state whether population size is explicitly modelled as a factor. My own forecast is somewhat more pessimistic: using the assumption that oceans and terrestrial ecosystems will absorb half of all emissions [19], my prediction would be that the trillionth tonne will be emitted in 2032. My model's prediction for cumulative carbon emissions by 2040 is 1.3 trillion tonnes.

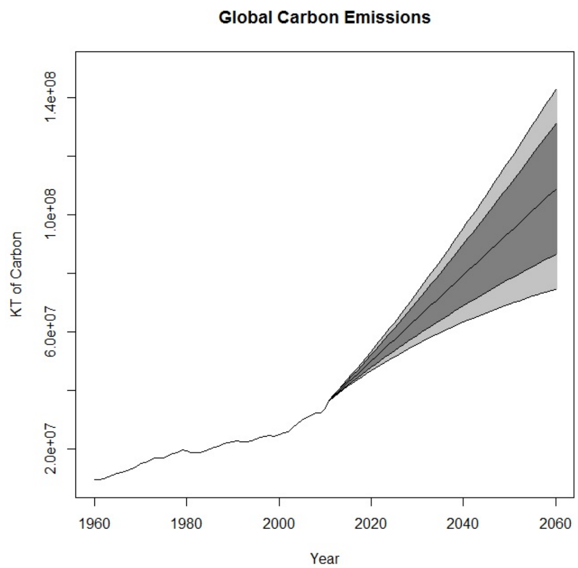


Figure 8: Forecast for global carbon emissions

3.4 Energy Use Forecast

I have used the same regression and forecasting method to create a forecast for global energy use to the year 2060. Qualitatively, the patterns are all quite similar to those observed in the analysis of carbon emissions. Figure 9 shows the forecast for global energy use, in kilotonnes of oil or equivalent.

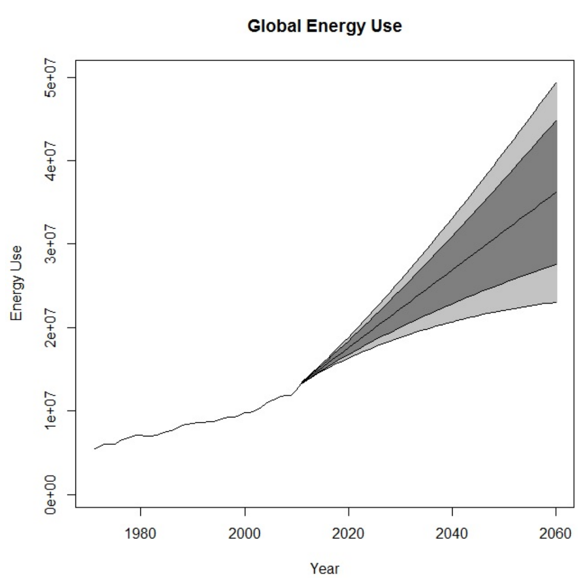


Figure 9: Forecast for global energy use (primary, before transformation to other end-use fuels)

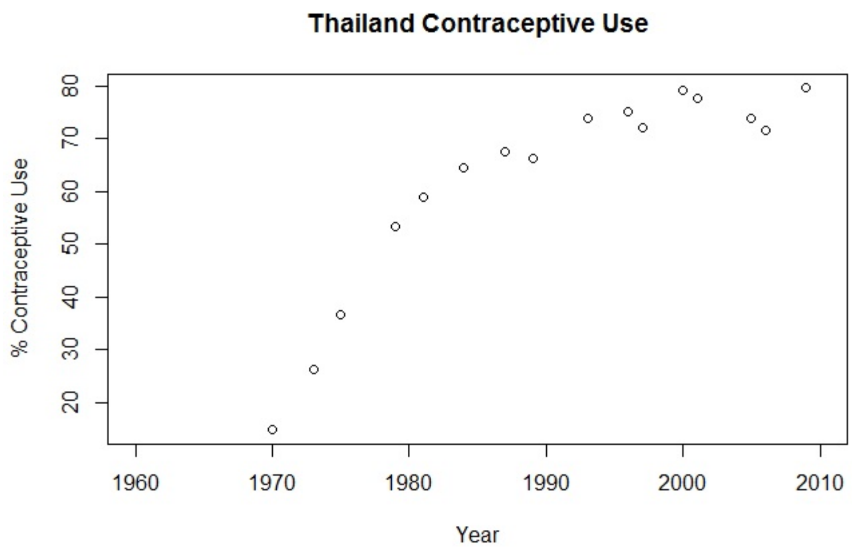
4 Overpopulation Solutions

The only palatable solutions to overpopulation problems are certain methods to lower birth rates. One of the best ways to do this is to elevate the status of women [20]. Education, economic opportunities and access to family planning for women are all strongly linked with decreased fertility. In section 4.1, I address the problem of unmet need for contraception worldwide, and use the regression models found in section 3 to examine the impacts of increasing availability of family planning methods in developing countries. In section 4.2 I discuss the impacts of reducing gender inequality on population growth.

4.1 Addressing Unmet Need for Contraception

According to the UN, there are an estimated 222 million women worldwide with an unmet need for contraception [21]. I decided to try to predict the impact on carbon emissions if we were to address some of this unmet demand. I thought that modelling this within the framework of the simple linear regression models would work because: (a) unlike methods such as educating women, contraceptive use has a direct and immediate impact on fertility, and (b) we could reasonably expect that a given increase in the rate of contraceptive use would have roughly the same effect on birth rates in all countries.

To investigate the latter claim, I examined some countries which have had large but fairly steady increases in contraceptive use since 1960 [18]. Examples include Bangladesh, Thailand, Peru, Nepal and the Philippines. As expected, contraceptive use is strongly correlated with decreased birth rates, and the impact is roughly the same in all countries: in each case, the relationship was modelled with a linear regression, and in all cases the factor by which contraceptive use rates impacted birth rates per 1000 people was between -0.38 and -0.43. In other words, when an additional 1% of women of reproductive age use contraceptives, there are approximately 4 fewer live births per 1000 people. For an illustration of this relationship in Thailand, see Figure 10.



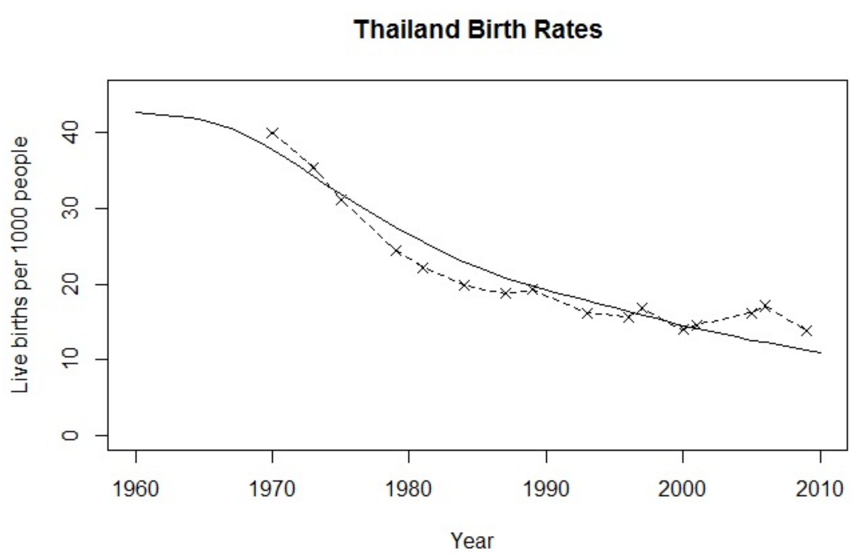


Figure 10: Thailand contraceptive use rates (top) and crude birth rate (bottom). Birth rates predicted by the regression model are denoted by the dashed line

There is insufficient data on contraceptive use to be able to predict the global impact of increased contraceptive availability, so instead I shall focus on Uganda as a case study. Uganda has a current contraceptive use rate among women ages 15-49 of 30% [18], and its unmet need for contraception (defined as the percentage of women ages 15-49 who are sexually active, express an interest in preventing or delaying pregnancy and do not have access to family planning) is 34% [21]. Thus, if we could instantly fulfill all Ugandan women's unmet need for contraceptives, use rates would go up to 64%.

To examine the impacts of this, we construct an approximate linear regression model for Uganda's birth rate as a function of contraceptive use rates. For the model slope, we use the value -0.4 (the approximate average of the slopes of the other countries' models), which, examining the historical data for Uganda, would give us an intercept of 47.794. Thus, with contraceptive use rates of 64%, Uganda would have an approximate birth rate of 22.194 per 1000 people per year, compared to the current figure of 43.624. This information is used to forecast Uganda's population to the year 2060, using the simplifying assumptions that birth rates would remain constant after an instantaneous increase in contraceptive use rates and that trends in population growth from death and migration would not change. The impact of this on Uganda's population is shown in Figure 11, while the potential impact of this on Uganda's carbon emissions is shown in Figure 12.

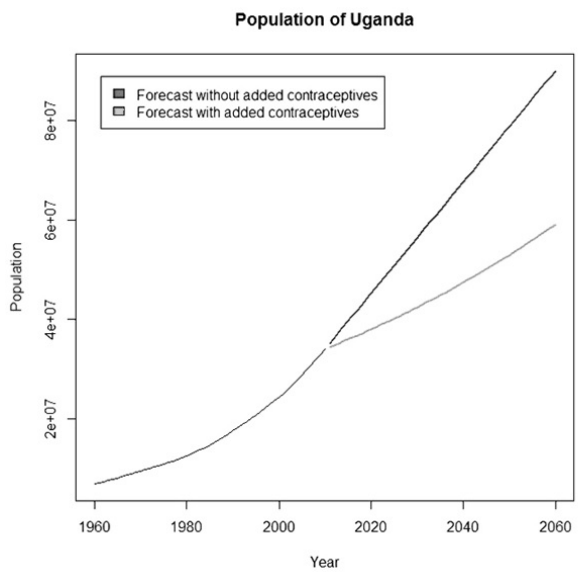


Figure 11: Uganda population forecast – with no change in current trends vs. after addressing unmet need for contraception

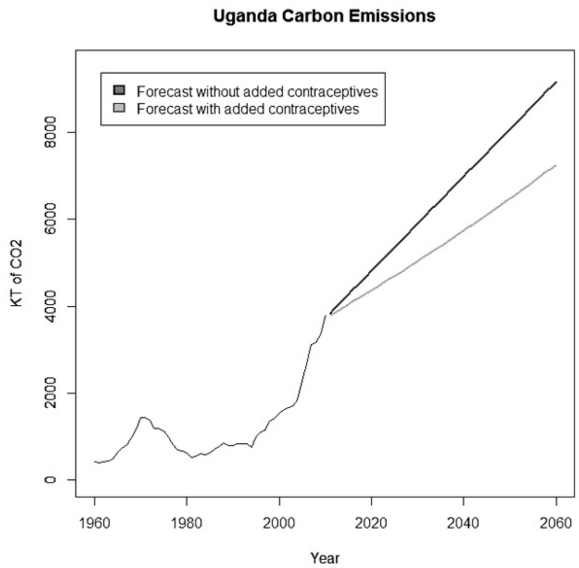


Figure 12: Uganda carbon emissions forecast – with no change in current trends vs. after addressing unmet need for contraception

4.2 Advancing the Status of Women

Initially, my plan for this section had been to perform a similar analysis to the one in section 4.1 to examine the effects of increased education for girls. However, what I found in my analysis was that the impact of education on fertility varied widely from country to country. As before, I performed linear regressions on countries where education of girls had increased steadily since 1960. I found that the model slope was as high as -0.56 in Algeria, to as low as -0.35 in Ecuador. In countries like Ethiopia and Senegal, where education levels have not increased as much [18], there was almost no relationship at all between education and fertility.

There are several possible explanations for this variability. An obvious one is that the modelling framework I've been using isn't well-equipped to handle these sorts of dynamics, since the impacts of education on a girl's eventual fertility will not become fully apparent for several years, and the impact of increased education may be lessened if it is not accompanied by a corresponding increase in economic opportunity. Another problem is that education in all countries is not equal: in a number of places, school may actually serve to reinforce gender inequalities, rather than reduce them [22]. This is, however, the exception rather than the rule. In most cases, educated women have fewer children and have them later in life. Furthermore, infants of educated mothers have a lower mortality rate [22], which contributes strongly to reduced fertility.

Increasing economic opportunities for women is another way to reduce birth rates [20]. If a woman can work to support herself, she is more likely to postpone marriage and childbearing. In addition, increased economic opportunity for women is typically linked to national economic development, which tends to coincide with increased urbanization. This is yet another factor which causes fertility rates to drop – children are economically useful on a farm as they can provide free labour, but in the city it makes less financial sense to have many children [20].

Finally, a key requirement for advancing the status of women is the availability of reliable family planning methods, as discussed in section 4.1. Aside from the immediate impact of preventing pregnancy, the availability of contraception allows women to decide for themselves if and when they want children. Being able to control her fertility allows a woman to focus on education or career opportunities rather than childrearing.

5 Conclusions

We have seen that, whether or not the Earth has yet exceeded its carrying capacity, rapid and sustained population growth puts a clear strain on the environment by accelerating demands for resources. I would argue that reducing fertility constitutes a key component of our living sustainably as a species. Smaller population size will not solve all of our environmental problems, but it can make it easier by slowing demand for resources.

Despite our reluctance to contemplate overpopulation as a problem, I argue that it can be drastically improved without draconian measures. By simply empowering women with education, economic opportunities and the ability to control their own fertility through family planning methods, we can greatly reduce population growth rates. We have already observed that in most developed countries, including Canada, the natural birth rate is below what is necessary to keep population levels stable.

There are further opportunities for future work based on what was done in this project. A key component would be the use of more sophisticated models, both for the forecasting and regression components of the analysis. Furthermore, if more data could be obtained about various socioeconomic and environmental indicators, the forecasts could be made more accurate. This project deals with several changes that could take place to reduce birth rates, but doesn't explore any concrete ways to implement these changes – this could be a good task for social scientists.

As with all statistical modelling techniques, these forecasts have the limitation that they can only predict broad trends and not specific events which may have large impacts on resource use. For example, there may be a groundbreaking technological solution that will be invented for the carbon emissions problem, or massive famine and warfare could dramatically decrease population size. Ultimately, there are many unknowns which cannot be captured by a simple statistical model.

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