Presented by SG2019006

IMMC 2019 - Earth’s Carrying Capacity For Human Life

Summary:
Overpopulation is a major issue faced in the present day. Attaining Earth’s current carrying capacity for human life is essential in ensuring that we know the maximum size that the human population can grow to without depleting the resources available on the planet. Also, by identifying the major factors that limit the Earth’s current capacity, we will be able to come up with a suitable solution to raise the carrying capacity of Earth and maximise the use of the resources available to us.

Our first task is to identify the major factors that limit Earth’s current carrying capacity for human life under current conditions. We considered the basic necessities available in the environment that can sustain human life on Earth indefinitely. These basic necessities include food, water, energy and land. We considered land to be the most important factor as it correlates with the other factors. Key infrastructure used to support human life such as residential buildings, agricultural farms, water treatment plants, power plants, hospitals, etc. are mainly built on land. This makes land a vital resource since it houses these key buildings that directly affect the carrying capacity of Earth for human life.

Our next task is to create a mathematical model to determine the current carrying capacity of Earth for human life under today’s condition and technology. Our model aims to determine the current carrying capacity of the Earth for human life in a ideal situation by considering multiple major factors such as land, food, water and energy that limit the carrying capacity of Earth. We formulated equations to connect factors together. For instance, we expressed the land required to support one person indefinitely as the sum of the living space required per person and land required for food, water and energy per person. Then by taking the total land available on Earth divided by land required to support one person indefinitely, we obtained the carrying capacity of Earth for human life based on land requirements.

Our final task is to propose solutions of what mankind can realistically do to raise the carrying capacity of Earth in perceived or anticipated future conditions. By using our model, we simulated the current data and analyse what factors are feasible to change.

We found out that the factors that could be change are the total energy, food, water consumption. Based on sensitivity analysis, we determined that food affects the carrying capacity of Earth the most. Land, water and energy is the most sensitive to changes in food, hence we determined that food is the main factor that should be change. We propose that mankind can change the composition of their diet, by reducing the animal-base food intake and increase the carbohydrate and vegetable, we can effectively decrease the water and energy used to produce food.

1 Introduction

1.1 Background

Humans have populated Earth for many centuries and have been using its resources since. However, are there sufficient resources on Earth for all humans to consume? Could there be a possibility that the human population is too large, disrupting the Earth's equilibrium, demanding beyond what the resources could support?

With this problem in mind, we attempted to model the Earth's current carrying capacity for human life such that there will be no stress placed on Earth's available resources. Herein, we defined the Earth's carrying capacity for human life as the maximum human population that Earth can sustain indefinitely, given the food, habitat, water, and other necessities available in the environment.

1.2 Problem Restatement

To achieve a reasonable value for Earth's carrying capacity under current conditions and technology, we need to first identify the resources critical to human survival. This will allow us to explore the factors affecting the demand and supply of these resources based on current technology available to extract these resources. By studying the plausible mathematical relationships surrounding these factors, we can then generate a model based on the per capita demand of these critical resources, thereby obtaining the current carrying capacity of Earth based on the available supply of these resources resulting from current technology. With the appropriate data generated from the model, we can then explore which critical resource(s) and its factors will have the greatest impact on Earth's carrying capacity. This will allow us to identify which resource and the associated factors to focus on in terms of both human and technological activities, in order to raise the Earth's carrying capacity to support the demand arising from Earth's future population size.

1.3 General Assumptions

In developing our model, we will be considering general assumptions that apply throughout the modelling process, and specific assumptions that are applicable to individual variables. Herein, we will discuss the general assumptions. Information on the specific assumptions is presented in Section 3 where appropriate, during the discussion of our modelling process.

General Assumption 1: Required data is accurate

- We will obtain our data from major databases provided by the United Nations (UN), World Bank, World Health Organisation (WHO) and the Organisation for Economic Co-operation and Development (OECD) and assume that the data provided is accurate and applicable worldwide.

General Assumption 2: Data on available resource supplies and demands reflects current technological capabilities

- We will assume that data on available resource supplies reflects the maximum amount of resources current technologies is capable of extracting.

- We will also assume that data on available resource demands reflects the necessary demand required to sustain human life and activities with no over- or under-consumption.

General Assumption 3: Equal resource and technological availabilty for each human

- We recognize that resource distribution is unequal in the real world, for example, people living in sub-Saharan Africa have a much more limited access to clean water as compared to people living in developed nations such as the States.

- To determine the carrying capacity the resources on Earth can support, we will however be assuming that every human has access to the technology that brings about access to these resources, hence achieving an equal distribution of resources.

General Assumption 4: Raw resources are in abundance and available supplies of these resources is limited by extraction capabilities of current technology

- We will be considering seawater, energy and land as fundamental raw resources required to derive any other resources necessary for survival e.g. food.

- Seawater as an unlimited resource
  - We consider clean water as a resource that is obtained from seawater. As seawater covers more than 70% of Earth's surface and that 97% of the Earth's water can be found in from seawater, we assume seawater to be an unlimited resource and available clean water resources ultimately depends on the technology available to harness clean water from seawater.

- Energy as an unlimited resource
  - While we recognise that non-renewable energy sources will ultimately be exhausted, the presence of renewable sources of energy will allow us to assume that sources of energy are in abundance and the available energy will just depend on the technology available to harness energy from both the non-renewable and renewable sources.

- All available arable and liveable land has the capacity to support any human activity and cultivate any type of food.
  - Due to physical and climate conditions, not all the arable and liveable land can support all types of human activities and cultivate all types of food. However, resulting from General Assumption 3, we shall assume that technology is available to overcome unfavourable conditions, allowing all arable and liveable land the capacity to support any human activity and cultivate any type of food.

2 Key Factors Affecting Earth's Carrying Capacity and Associated Variables

We decided that the main factors limiting the Earth's carrying capacity for human life are land, food, water, energy and essential human services. In this section, we shall discuss the necessity of these factors and the variables associated with their demand and supply.

2.1 Water

Water is directly essential for survival, as all humans need to hydrate themselves in order to maintain proper bodily functions. Apart from direct use, water is also required in energy and food production and to support other essential human services, which are the other critical factors that we consider essential for survival. In modelling the supply and demand for water, we will be considering the following variables.

Table 1 Variables associated to water supply and demand

$GHWC$	Global annual household water consumption (litres year^{-1})
GP_{water}	Global production of water (litres year^{-1})
K_w	Amount of energy required to produce 1 litre of water (J litres^{-1})
m	Volume of water required to produce 1 joule of energy (litres J^{-1})
T_W	Total clean water produced in a year (litres year^{-1})
W	Amount of water required per person per year (litres person^{-1} year^{-1})
W_e	Water needed to produce energy for a person for per year (litres person^{-1} year^{-1})
W_f	Water required to grow food for a person for a year (litres person^{-1} year^{-1})
W_l	Water required for living for a person for a year (litres person^{-1} year^{-1})

2.2 Food

An average human can only survive for three weeks without food. Hence food is a basic necessity that all human require for survival. In modelling the supply and demand for food, we will be considering the following variables.

Table 2 Variables associated to food supply and demand

F	Amount of food required per person per year to live a healthy life (Cal person^{-1} year^{-1})
$F_{age\ group}$	Recommended yearly calorie intake (based off the recommended daily intake and assuming they consume the same amount of calorie each day) for people in an age group (Cal year^{-1})
$F_{age\ group\ female}$	Recommended yearly calorie intake (based off the recommended daily intake and assuming they consume the same amount of calorie each day) for females in the chosen age group in (Cal year^{-1})
$F_{age\ group\ male}$	Recommended yearly calorie intake (based off the recommended daily intake and assuming they consume the same amount of calorie each day) for males in the chosen age group (Cal year^{-1})

$FC_{food\ type}$	Mass of a particular food consumed per person per year (kg person^{-1} year^{-1})
$P_{age\ group}$	Proportion of the total population that is in the particular age group
$Q_{food\ type}$	Volume of water required to produce 1kg of food type (litres kg^{-1})
$R_{food\ type}$	Mass of food type required in a 2000 Cal diet per day (kg day^{-1})
T_F	Total food produced in a year (Cal year^{-1})
$Y_{food\ type}$	Yield of the food type (kg year^{-1} km^{-2})

2.3 Energy

Energy is used daily in households for activities such as for lighting and heating. In addition, energy is required in water and food production and also to support essential human services, all of which are factors we consider critical to human survival. In modelling the supply and demand for food, we will be considering the following variables.

Table 3 Variables associated to energy supply and demand

E	Amount of energy required per person per year to live a healthy life (J person^{-1} year^{-1})
E_f	Energy required per person for food production per year (J person^{-1} year^{-1})
E_h	Energy required per person for human services per year (J person^{-1} year^{-1})
E_l	Energy required per person for household consumption per year (J person^{-1} year^{-1})
E_w	Energy required per person for water production per year (J person^{-1} year^{-1})
GE_{sector}	Annual global energy consumption for that sector (J year^{-1})
$GHEC$	Global annual household energy consumption (J year^{-1})
$K_{food\ type}$	Energy required to produce 1 kg of food type in (J year^{-1})
$P_{energy\ source}$	Proportion of energy produced by a certain energy source
T_E	Total energy produced in a year in (J year^{-1})
$X_{energy\ source}$	Land per (energy per year) using that energy source in (km^2 year J^{-1})

2.4 Land

We are taking into account land as a major factor as land is the foundation of any building be it farms, wastewater treatment plants, desalination plants, power plants, residential buildings, schools, hospitals, factories etc. As such, without land, the number of essential buildings will be limited, affecting the production of food, water and energy and the availability of essential human services, which in turn puts a cap on the total carrying capacity of Earth. In modelling the supply and demand of land, we will be considering the following variables.

Table 4 Variables associated to land supply and demand

L	Space required to support 1 human living a healthy life indefinitely (km^2 person^{-1})
L_e	Land required for energy production per person (km^2 person^{-1})

L_f	Land required for food production per person (km^2 person^{-1})
L_l	Living space required per person (km^2 person^{-1})
LU_w	Global land use for production of water (km^2)
L_w	Land required for water per person (km^2 person^{-1})
Q	Land required to hold institutions for essential human services (km^2)
T_L	Total arable and liveable land in km^2
X_e	Land area per unit energy produced per year in (km^2 J^{-1} year^{-1})
X_w	Land used to produce 1 litre of water per year in km^2 litres^{-1} year^{-1}

2.5 Essential Human Services

Human services that are considered as essential for human survival include healthcare and sanitation, education and manufacturing. These services are essential because:

- Healthcare is vital in preserving human life

- Education helps to broaden humanity’s knowledge of technology, which is essential in production of food, water and energy, as well as in the provision of other essential human services. Educating people ensures that they know how to operate develop new and operate existing technologies to sustain global extraction (and production) of resources.

- The manufacturing industry helps to produce goods to provide people with basic human needs for example clothing. Manufacturing helps in producing technological tools such as tractors for farms, tools for mechanics, machines in factories, solar panels, wind turbines, hydro dams for energy production etc, necessary on a daily basis.

In general, we perceive the provision of these essential human services as demands on the supply of water, energy and land. Hence we the variables associated with essential human service have been broken down into components subsumed under the variables outlined in Sections 2.1 to 2.4 where appropriate. An example is Q, which is the variable associated to the land required to hold institutions for essential human services.

3) A Model of Earth's Carrying Capacity Based On Resource Demand Per Person

3.1 Basis of the Model

Our model of Earth's carrying capacity works on the basis that one needs to fulfil all the requirements of food, water, energy and land to live a healthy life. As such, the maximum possible population that can sustain itself indefinitely would be the minimum of populations supported by each of the critical resources i.e.

$$C = \min\left(\frac{T_{land}-Q}{L}, \frac{T_{food}}{F}, \frac{T_{energy}}{E}, \frac{T_{water}}{W}\right),$$

where each of $\frac{T_{land}-Q}{L}, \frac{T_{food}}{F}, \frac{T_{energy}}{E}, \frac{T_{water}}{W}$ gives the maximum population that can be supported by the available land, food, energy and water respectively, to sustain a healthy life.

3.2 Modelling Annual Demand for Food per Person to Sustain Healthy Living (F)

Food is the primary source of energy that supports the survival of humans. As the energy requirement varies for individuals depending primarily on their age and gender, the world's food requirement will depend on the world's demographics. In modelling the annual demand for food per person to sustain a healthy life (F), we will hence consider the average annual ideal calorie intake per person, which is a weighted average derived based on the world's age and gender distribution.

To do so, we will first determine the average annual calorie demand of a person in a particular age group using the following weighted model:

$$F_{agegroup} = P_{age\ group\ female} * F_{age\ group\ female} + P_{age\ group\ male} * F_{age\ group\ male}$$

Next, the average annual ideal calorie required per person will be determined based on another weighted model:

$$F = \sum_{all\ age\ groups} P_{age\ group} * F_{age\ group}$$

where $P_{age\ group} = \frac{number\ of\ people\ in\ the\ age\ group}{world\ population}$.

Specific Assumption 1

Average values of calorie demand reported by WHO shall be used for a particular gender and age group. We shall assume that the daily activity profiles that may result in differing calorie requirements (e.g. the calorie requirement of an 18-year old student vs. an 18-year old labourer) have been taken in account by WHO for ease of calculation.

3.3 Modelling Annual Demand for Water per Person to Sustain Healthy Living (W)

As mentioned in Section 2.1, water is a vital resource that supports human life, the production of other resources critical to survival and the provision of essential human services. We will hence model the annual water demand per person as the sum of water required for energy production (W_e), food production (W_f) and land required for essential human services (W_l).

$$W = W_e + W_f + W_l$$

In order to determine W, we have to first determine the values of W_e, W_f and W_l.

Determining W_e

W_e is determined as the product of the water required to produced 1 joule of energy (m) and the energy production required per person in a year (E) (See Section 3.4).

$$W_e = E * m$$

where $m = \frac{global\ water\ use\ for\ generating\ energy}{global\ energy\ production}$.

Specific Assumption 2

Average values provided by UN for water required to produce energy shall be assumed to account for all energy sources for ease of calculations.

Determining W_f

In determining W_f, we first consider the annual mass of each food type consumed by an individual in an ideal diet ($FC_{food\ type}$). We then consider how much water is required to produce 1 kg of that food type ($Q_{food\ type}$). The product of these two quantities will yield the annual water demand for the cultivation of that food type for an individual. By summing up the annual water demands for the production of each food type, we will obtain the annual demand of water for the production of food necessary to sustain the healthy living of an individual.

$$W_f = \sum_{for\ each\ food\ type} FC_{food\ type} * Q_{food\ type}$$

Specific Assumption 3

In our calculations, we assumed that every human consumes the same diet, which can be broken down into plant-based foods, animal-based foods and carbohydrates. Different dietary requirements have been accounted for by considering the total consumption of a particular food type over the total world population.

Determining W_l

By considering the annual global household water consumption ($GHWC$) versus the world population (WP), we will be able to obtain the amount of water required for living by a person:

$$W_l = \frac{GHWC}{WP}$$

Specific Assumption 4

For ease of calculations, all household water consumption is assumed to be used for ingestion and/or other human activities essential for survival.

3.4 Modelling Annual Demand for Energy per Person to Sustain Healthy Living (E)

As mentioned in Section 2.3, energy is required to sustain food and water production and to support essential daily human activities and essential human services, all of which are necessary for survival.
The energy required for the production of different resources and provision of essential human services are different. Hence we will model E as the sum of energies required to provide the critical resources and essential human services to individual in a year

$$E = E_h + E_l + E_f + E_w$$

In order to determine E, we have to first determine the values of E_h, E_l, E_f and E_w.

Determining E_h
As mentioned in Section 2.5, the essential human services consists of three key components, namely education, healthcare and manufacturing. We will hence model the annual energy demand for essential human services per person (E_h) by considering the sum of annual energies used by each of these components versus the world population

$$E_h = \frac{GE_{healthcare} + GE_{education} + GE_{manufacturing}}{WP}$$

Determining E_f
The energy demand for annual food production required to sustain the healthy living of a person (E_f) is calculated in a similar fashion as the annual water demand for food production for the same purpose. This is done by considering the product of the annual mass of each food type consumed by a person in an ideal diet ($FC_{food\ type}$) and the energy required to produce 1 kg of that food type ($K_{food\ type}$). The sum of the energy demands will be the energy required to produce food necessary to sustain healthy living of an individual annually.

$$E_f = \sum_{for\ all\ food\ types} FC_{food\ type} * K_{food\ type}$$

As such, Specific Assumption 3 will also apply in this calculation.

Determining E_l
Similar to the calculations for determining the annual amount of water required by a person for living, the energy required by a person annually to sustain healthy living can be determined by considering the global household energy consumption versus the world population

$$E_l = \frac{GHEC}{WP}$$

As such, Specific Assumption 4 will also apply in this calculation

Determining E_w
To determine the annual energy demand to produce the annual water demand of a person, we found the product of the total global water production (GP_{water}) and the energy required to produce 1 litre of water (K_w) to first determine the global energy demand for water production.

This is then compared with the world population to determine the energy demand required to produced the water demand of a person annually.

$$E_w = \frac{GP_{water} * K_w}{WP}$$

3.5 Relationship between Annual Water Demand and Annual Energy Demand per Person to Sustain Healthy Living (E)

Considering the water-energy nexus, we can see that the production of energy and water are interrelated. Hence E is a function of W and vice versa. Hence the values of E and W needs to be determined simultaneously using the following system of equations.

$$E = \frac{E_h + E_f + E_l + K_w(W_l + W_h + W_f)}{1 - mK_w}$$

$$W = \frac{W_l + W_h + W_f + m(E_h + E_f + E_l)}{1 - mK_w}$$

3.6 Modelling Annual Demand for Land per Person to Sustain Healthy Living (E)

Land is associated to the production of food, water, energy, land for living and land for provision of essential human services. Hence the total land required per person can be found through the sum of the land required for the different production of food (L_f), water (L_w) and energy (L_e) as well as the land required essential services (L_h), given by:

$$L = L_h + L_e + L_f + L_w$$

To determine L, we will first need to quantify L_l, L_e, L_f and L_w

<u>Determining (L_f)</u>

To consider the land required for food, one first has to consider the amount and type of food required to live a healthy diet. This proportion is represented by $R_{food\ type}$ which refers to the mass of food type required in a 2000 Cal diet per day. This proportion is then scaled to the ideal average energy intake per person per year (F). By dividing the scaled value by the likely yield of that food type, which is the mass of food per unit area of said food type grown in a year, we obtain the land required for the cultivation of the annual food demand of an individual for that food type. The total required for all cultivation of all food required by a person in a year will then be as follows:

$$L_f = \sum_{for\ each\ food\ type} \frac{R_{food\ type} * \frac{F}{2000\ cal\ person^{-1} day^{-1}}}{Y_{food\ type}}$$

<u>Determining (L_w)</u>

The land required for water per person is calculated by multiplying water required per person (W) with land used to produce 1 litre of water per year (X_w).

To find X_w, we take the global water produced divided by the global land used to produce water that would give us the water produced per unit of land dedicated to water production with current technology.

$$L_w = W * X_w$$

where $X_w = \frac{GP}{LU_w}$.

Determining (L_e)

The land required to produce energy for a person is derived from the energy consumed by said person and the amount of energy per unit land dedicated to supplying energy. With a higher efficiency of energy production in terms of land use, we get a lower land required to produce energy for a person:

$$L_e = E * X_e$$

To determine X_e, we considered the different types of energy sources, coal, natural gas, nuclear, solar, wind and hydro energy. Next, we found the proportions of each type of energy source to the total energy produced, to find how much of each energy source weighs in comparison to the other sources, given by $P_{energy\ source}$. Then we take a weighted average of the amount of the efficiency (in terms of land use) of the different energy sources.

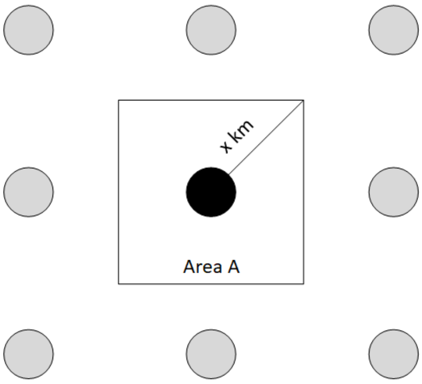
$$X_e = \sum_{for\ each\ energy\ source} P_{energy\ source} * X_{energy\ source}$$

where $P_{energy\ source} = \frac{Energy\ by\ that\ source}{Total\ energy\ produced}$.

Determining L_h

As for the land required for institutions providing essential services, we assume the ideal situation to be that the public institutions are distributed evenly throughout the world and that one cannot be more than x_i distance away from any type of institution i. For ease of calculations, we assumed the essential institutions to be schools, hospitals and manufacturing firms, in relation to the essential services discussed in Section 2.5

We estimated what the shortest distance it should be from a person to the closest institution and deriving the area density of each kind of institution. Logically, there should be the presence of many firms as they are the basis of the country’s economy, hence the area density for firms should be the largest and thus the shortest distance between a person to the nearest firm should be the least. Next, we decided that there should be more schools than hospitals per unit area of land as a far greater amount of people require education every day, compared to the number of people entering hospitals a day.



If we take the shortest possible distance to the closest public institution of type i to be x_i. We can prove that there needs to be 1 of such public institutions every $2*x_i^2$ km^2. From there, we are able to find out the total number of institution i, and then, using the average land area of said type of institution, calculate the total land area institutions of type i would take up.

Specific Assumption 5

Since essential institutions are shared by people, it is assumed that the number of institutions does not increase with increasing population

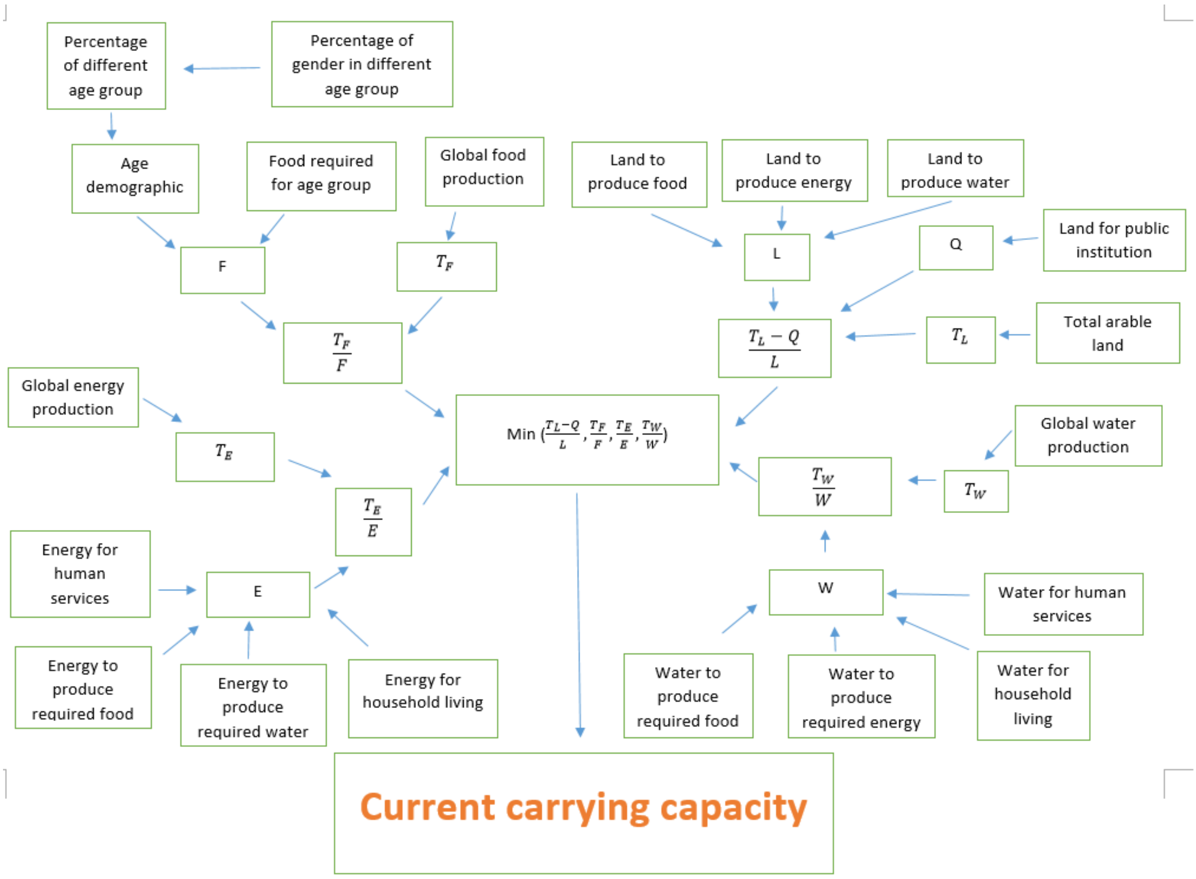
3.7 Optimal allocation of land

Assuming optimal allocation of land

$$C = \frac{T_{land} - Q}{L}$$

3.8 Determining Current Carrying Capacity

We used Python to model the features discussed in Sections 3.1 to 3.7 using the following logic



Initially in our first testing phase, we determined the total food produced in a year, total clean water produced in a year, total energy produced in a year and total arable and liveable land. These values were:

$T_f = 8.03 * 10^{15}$ Cal
$T_w = 3.97 * 10^{15}$ litres
$T_e = 9.21 * 10^{20}$ J
$T_l = 63620746$ km^2

The inputs for the raw data used in the calculation were as follows

Table 5 Worldwide Age-Gender Distribution

Age Group	**Elderly**	**Adult**	**Children**
Proportion of Age Group to World	0.09	0.65	0.26
Proportion of sex in Age Group (male : female)	0.805	0.985	1.07

Table 6 Calorie-Intake Values

Age Group & Sex	**Elderly male**	**Elderly female**	**Adult male**	**Adult female**	**Child male**	**Child female**
Daily calorie intake	2100	1800	2500	2000	2000	1800

Table 7 Values for Water-Associated Variables

Input	**GHWP**	**GP_{water}**	**k**	**m**
Value	$1.24*10^5$	$3.97*10^{15}$	3.17	$7.48*10^{-6}$

Table 8 Proportion of Food Types in an Ideal Diet

Food type	**Animal-based**	**Plant-based**	**Carbohydrates**
$R_{\text{food type}}$	0.103	0.725	0.2925

Table 9 Values for Energy-Associated Variables

Human Service Sector	**Schools**	**Healthcare**	**Manufacturing**
GE_{sector}	$1.08*10^{13}$	$1.28*10^{12}$	$3.46*10^{15}$

Table 10 Energy Demand for Production of Different Food Types

Food type	**Animal-based**	**Plant-Based**	**Carbohydrates**
$K_{\text{food type}}$	$1.03*10^{8}$	$4*10^{6}$	$1.22*10^{7}$

Table 11 Energy Sources and Proportion of Total Production

Energy Source	**Coal**	**Natural Gas**	**Nuclear**	**Solar**	**Wind**	**Hydro**
$P_{\text{energy source}}$	0.54	0.24	0.04	0.01	0.01	0.07
$X_{\text{energy source}}$	$1.57*10^{-15}$	$1.59*10^{-15}$	$1.63*10^{-15}$	$5.58*10^{-15}$	$9.06*10^{-15}$	$4.04*10^{-14}$

Table 12 Values for Land-Associated Variables

Input	LU_w	**Q**
Value	8710	$1.98*10^{5}$

From here, by inserting these values into our equations and codes, the output of F, W, E and L were given to us.

$F = 777520.3787897098$ cal person^{-1} year^{-1}
$W = 671269.45160074$ litres person^{-1} year^{-1}
$E = 9338447493.197926$ J person^{-1} year^{-1}
$L = 0.002674085907927087$ km^{2} person^{-1} year^{-1}

These values ultimately gave us the population with respect to each variable F, W, E and L. From here, based on our model, we will take the smallest value of $\frac{T_z}{z}$, with z being one of the variables F, W, E or L as our maximum current capacity.

This maximum current capacity was dictated by the variable W, which is a maximum of **5918439146 people**.

3.9 Validating our Model

Paul R. Ehrlich, Bing Professor of Population Studies and President of Center for Conservation Biology, Stanford University. Fellow, National Academy of Sciences and Royal Society; Crafoord Prize Laureate, claims that the ideal population on Earth should be around 1.5 to 2.0 billion people based on people’s lifestyles.

The difference in our results could be due to different considerations and factors when researching and coming up with models to determine the maximum carrying capacity of Earth. However, both our results and the referred source agree that the Earth is current over-populated.

There could be a possibility of referring to food by Paul R. Ehrlich when talking about human lifestyles, in the sense that people are consuming more than what they should be. Perhaps our maximum current capacity could have changed and was determined by food instead of water.

Our T_f calculated could have mistakes as we initially used the total mass of food and converted into calories instead of using the average calories per person per day to find total calories. This initial process allowed for the existence of more uncertainty in our data, as we had to rely on more sources in order to calculate T_f.

Thus after realising this point, we changed our method to using the average calories per person per day to find the total calories for a person in a year.

4 Modelling for the Future

4.1 Projected Conditions in 2050 Versus Current State

With our adjusted values, we conducted a prediction of the resource requires based on projected data provide by UN in 2050 and obtained the following values.

Table 13 Energy Associated Values

Variable	T_E	**P**	$E = T_E / P$
2019	9.21×10^{19}	7.53×10^{9}	1.22×10^{10}
2050	1.3982×10^{20}	9.8×10^{9}	1.43×10^{10}

Table 14 Food Associated Values

Variable	T_f	**P**	$F = T_f / P$
2019	8.03×10^{15}	7.53×10^{9}	1.07×10^{6}
2050	1.09×10^{16}	9.8×10^{9}	1.11×10^{6}

Table 15 Water Associated Values

Variable	T_W	**P**	$W = T_W / P$
2019	3.97×10^{15}	7.53×10^{9}	5.27×10^{5}
2050	6.15×10^{15}	9.8×10^{9}	6.28×10^{5}

According to the United Nations Department of Economic and Social Affairs, it is projected that the world's population will increase to 9.8 billion by 2050. Global energy demand will reach 1.3982×10^{20} J and the energy demanded per person will increase to 1.43×10^{10} J per person. As for water, the water demanded per person would also increase by 19.2%, this would put an increased strain on the water infrastructure and thus reduce the carrying capacity of earth.

To deal with these increased demands, we need to look at how we can decrease the energy and water required per person. As for food, we can advise people to reduce their intake of food (if they are consuming over the ideal) as it provides benefits to both their health and the sustainability of the earth to reduce their intake.

4.2 Sensitivity Analysis to Determined Plausible Conditions to Tackle for Increased Carrying Capacity

Based on our model, it can be seen that a factor such as energy per person is linked to other variables such as water and food. Hence we will develop a way to find out that when a variable is changed for a certain factor, how drastic will the factor be affected. Simply, we are trying to find how sensitive each factor is to the variables that it comprises of. To standardise this process, we will be increasing selected variables by 50% one at a time.

We would want to change the variables which affect the factors most as they will have a greater impact on the carrying capacity on Earth. For E, we determined that it is most sensitive to changes in mass of food type consumed. When everyone consumes only carbohydrates, which in turn affects the mass of plant based food, animal based food and carbohydrates consumed in a day and year, there will be a percentage change in E of -42.1% (3 significant figures).

This could be due to the fact that many people consume animal-based foods daily, and there is very inefficient production of animal-based food (given to be $1.03*10^8$ J kg^{-1} for meat) compared to the production of carbohydrates and plant-based foods ($1.21*10^7$J kg^{-1} and $4*10^6$ J kg^{-1} respectively). Hence, when people only consume carbohydrates, far less energy is required for the production of only carbohydrates, hence leading to a drastic decrease in E. However, you might be questioning, since plant-based foods require less energy to produce per kg of it than for carbohydrates, shouldn't a diet strictly on plant-based foods lead to a greater decrease in E?

That is not the case because when we consider the calories per kilograms of both plant-based foods and carbohydrates, it is obvious that carbohydrates provide more calories per kilogram as they are the main source of the body's energy, hence for the same 2000 calories we require a day, we require less mass of carbohydrates than plant-based foods to supply the same amount of calories. Hence, the mass of carbohydrate to supply everyone's calorie intake in a year is lower than that of plant-based foods. Hence the production of carbohydrates will also require less energy, ultimately reducing the value of E the most, also implying that L_e will decrease.

Similarly for W, when everyone only consumes carbohydrates, the percentage change of W is -32.1%. Our calculations and scientific evidence have suggested that animal-based foods require the most to produce as we have to take into account the water used to produce feed for the animals and water for the animals to drink, compared to the production of plant-based foods and carbohydrates. This means if we only rely on carbohydrates for food, less water is required for the production of carbohydrates, hence reducing the value W, implying that L_w will decrease.

Realistically, it is not possible for everyone to only consume carbohydrates, but based on the results we've found, what we can do is to reduce our animal-based foods consumption and increase our consumption of carbohydrates and plant-based foods, and this will allow us to raise the carrying capacity of Earth, in the perceived future.

Apart from changing one's composition of diet, we could potentially reduce the average calories per person per year, F, by encouraging those overeating to reduce their energy intake. This would reduce the average F and thus reduce the average W and E by large amounts.

5 Further Sensitivity Analysis and Conclusion

In the future, some variables we used in our model such as population size, food, water and energy consumption are set to increase. However, with the aid of technology, mankind can come up with new innovations or methods to produce food, water and energy. This innovation and methods can ensure that food, water and energy are produced in a more efficient manner, with minimal land and resource use and hence Earth will be able to accommodate a larger population. Therefore mankind can harness and come up with new technology via upgrading of skills and knowledge so as to speed up technological advancements which can help to raise the carrying capacity of the Earth.

The most important of such technologies would be the water and energy required to produce meat. With a 50% increase in the water required per mass of meat, $\%\Delta W = 15\%$. This means that much water is currently used for animal-based food production and that development of technology which would make the production of animal-based food more water efficient would have a great impact on the water consumed per person per year. Hence, to decrease the water required per person, we should channel our technological development to the water efficiency of animal-based foods production.

With a 50% increase in the energy required per mass of animal-based foods, percentage change of E is 22%, which is higher compared to 50% increase in the energy required per plant-based foods or carbohydrates. This implies that a lot of energy is used for animal-based food production, hence a change in energy required to produce animal-based foods (per kg) will affect E the most. Thus, a development of technology would cause more efficient production of animal-based foods in terms of energy use, which in turn impact the energy consumed per person per year greatly. Thus, in order to decrease the energy required per person, we should also channel our technological development to the energy efficiency of animal-based food production.

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Appendix B – Sample Python Coding

IMMC 2019 Model

For age groups

- 0 --> Elderly
- 1 --> Adult
- 2 --> Children

For genders

- 0 --> Male
- 1 --> Female

For Food

- 0 --> meat
- 1 --> Vegetables
- 2 --> Carbohydrates

For energy

- 0 --> Coal
- 1 --> Natural Gas
- 2 --> Nuclear
- 3 --> Solar
- 4 --> Wind
- 5 --> Hydro

```
#Food Parameters
food_proportion_mass = [0.103, 0.725, 0.2925]                 #Proportion of food by (ma
annual_production_kg =[317850000000,1044380000000,755000000000]#Global production of foo
global_annual_food_consumption = 1.95e+12                     #Mass of food consumed per
global_agricultural_land = 15000000

land_for_meat = 0.80*global_agricultural_land
land_used = [152674970.4, 555.98, 1716279.06977]              #global land use to produc

production_energy_per_kg = [1.0296e+8, 4e+6, 12186000]
annual_consumption_kg = [annual_production_kg[i]*2/3 for i in range(3)] #Account for foo

global_annual_calorie_intake = 1066895                        #Global calorie in-take pe

#Demographic Parameters
age_demographic = [0.09, 0.65, 0.26]                          #Proportion of elderly : a
age_group_gender_ratio = [0.805,0.985,1.07]                   #Male:Female for each age_

F_age_gender = [[2100, 1800],[2500,2000],[2000,1800]]         #F_age_gender[i][j] is F f
world_pop  =  7530000000

#Water Parameters
water_for_food = [5000,200,500]                             #liters of water per kg of t
household_water_consumption = 340.687*365                     #annual per capita househo
land_use_water = 8710                                         #Global land use for water
global_water_production = 3.9728674e+15                       #Global water production i
global_water_consumption = 4.001e+15
global_water_use_agricultural = 2.7605735e+15
global_water_use_energy = 7.65639502e+14*0.9                  #90% of industrial water u


#Energy Parameters
global_energy_production = 9.21e+19                           #joules
energy_water_efficiency = k =  3.17                           #The amount of energy per
household_energy_consumption = 2.7e+9                          #Amount of energy per cap
```

https://colab.research.google.com/drive/1gHAdEyEyE4VL83zNEo88hizB39OH4_FJ#printMode=true 1/5

```
energy_for_schools = 1.08e+13                                  #J per year
energy_for_manufacturing = 3.46e+15                            #J per year
energy_for_healthcare = 1.28e+12                               #J per year

energy_proportion = [0.54,0.24,0.04,0.01,0.01,0.07]            #Proportion of energy sour
energy_land_efficiency = [1.56665E-15,1.59231E-15,1.63081E-15,5.58143E-15,9.06373E-15,4.


#Land Parameters
total_livable_land = 63818925                                #Total livable land in km^2 (


water_energy_efficiency = m = global_water_use_energy/global_energy_production #Amount o
```

Calculating F, Xf and thus Lf

$$F = \sum_{0}^{2}(age_{demographic}[i] * F_{agegroup}[i])$$

- where age_demographic is the proportion of elderly:adult:children

$$F_{agegroup} = F_{agegroupmale} * P_{male} + F_{agegroupfemale} * P_{female}$$

- where P(male) is the percentage of male within the age group

```
F_age = [F_age_gender[i][0]*365*(age_group_gender_ratio[i] / (1+age_group_gender_ratio[i
#F_age[i] is F for age group i
F = sum([F_age[i]*age_demographic[i] for i in range(3)])
print("F:", F, "cal per person per year")
```

```
F: 777520.3787897098 cal per person per year
```

```
#Calculating the mass of food eaten by a person per year
mass_of_food_per_year_ideal =  [food_proportion_mass[i]/2000*F for i in range(3)]
mass_of_food_per_year_current = [global_annual_food_consumption/world_pop for i in range(
print("Mass of food per person per year (Ideal)", mass_of_food_per_year_ideal)
print("ideal food per day", [mass_of_food_per_year_ideal[i] / 365 for i in range(3)])
```

```
Mass of food per person per year (Ideal) [40.04229950767005, 281.8511373112698, 11
ideal food per day [0.10970493015800015, 0.7721948967432049, 0.3115406997205344]
```

```
food_yields = [annual_production_kg[0]/land_for_meat,2e+6,858000] #kg per km^2

lf = sum([mass_of_food_per_year_ideal[i]/food_yields[i] for i in range(3)])
print("Lf", lf, "km^2 per person")
```

```
Lf 0.001785200787946403 km^2 per person
```

Calculating Wf, Wl, Wh and Xw

```
## Wf
#Amount of water for food per person
wf = sum([mass_of_food_per_year_ideal[i]*water_for_food[i] for i in range(3)])

print("wf", wf, "l per person per year")

## Wl
```

```
wl = household_water_consumption
print("wl", wl, "l per person per year")

## Wh
#wh = 855158.5 #liters liters person per year
wh = 1.232e+15/world_pop
print("Wh", wh, "l per person per year")
#wh = 7.68e+14/world_pop

## Xw
xw = land_use_water/global_water_production #land area per l of water
print("Xw", xw, "km^2 year per l")
```

```
wf 313437.9826996018 l per person per year
wl 124350.755 l per person per year
Wh 163612.21779548473 l per person per year
Xw 2.192371182587166e-12 km^2 year per l
```

Calculating Eh, Ef, El and Xe

$$E_f = \sum mass_i * energy_i$$

- for each food type i
- energy i is the energy required to produce 1kg of the food

$$E = E_f + E_w + E_h + E_l$$
$$X_e = \sum P_i * Efficiency_i$$

- Efficiency is the

```
## Ef: Energy for Food production per person per year
ef = sum([mass_of_food_per_year_ideal[i] * production_energy_per_kg[i] for i in range(3)
print("ef", ef, "J per person per year")

## Eh: Energy for human resources per person per year
total_energy = energy_for_schools + energy_for_manufacturing + energy_for_healthcare

eh = total_energy/world_pop #J per year per person
print("eh", eh, "J per per person per year")

## El: Energy for household use per person per year
el = household_energy_consumption

## Xe: Land per unit of energy for 1 year
xe = sum([energy_proportion[i] * energy_land_efficiency[i] for i in range(6)])
print("xe", xe, "km^2 year per J")
```

```
ef 6635858469.434755 J per person per year
eh 461099.6015936255 J per per person per year
xe 4.271014400000001e-15 km^2 year per J
```

Calculating W, E, Lw and Le

```
W = (wl+wh+wf+m*(eh+ef+el))/(1-m*k)
E = (eh+ef+el+k*(wl+wh+wf))/(1-m*k)

print("W", W, "litres per person per year")
print("E", E, "J per person per year")

le = xe*E
```

```
lw = xw*W

print("Le", le, "km^2 per person")
print("Lw", lw, "km^2 per person")
```

```
w 671269.45160074 litres per person per year
E 9338447493.197926 J per person per year
Le 3.988464371709225e-05 km^2 per person
Lw 1.4716718014405528e-06 km^2 per person
```

Calculating q

```
#land for hospitals
max_dist_per_hospital = 15 #km
area_density = 2*(max_dist_per_hospital**2) #1 hostpial in this area
ideal_hospitals = total_livable_land / area_density
ave_area_per_hospital = 0.00583 #km^2
L_hospital = ave_area_per_hospital*ideal_hospitals

print("land for hospitals", L_hospital)

#land for schools
max_dist_per_school = 5
area_density_schools = 2*max_dist_per_school*max_dist_per_school
ideal_schools = 3.5*total_livable_land/area_density_schools
ave_area_per_school = 0.0119
L_school = ave_area_per_school * ideal_schools

print("land for schools", L_school)

#Land for plants
max_dist_per_plant = 4
area_density_plant = 2*max_dist_per_plant*max_dist_per_plant
ideal_plants = total_livable_land/area_density_plant
ave_area_per_plant = 0.0723
L_plant = ave_area_per_plant*ideal_plants

print("land for plants", L_plant)


q = L_plant + L_school + L_hospital #land reserved for public institutions
print("total land for institutions", q)
```

```
land for hospitals 826.8096283333334
land for schools 53161.16452500001
land for plants 144190.883671875
total land for institutions 198178.85782520834
```

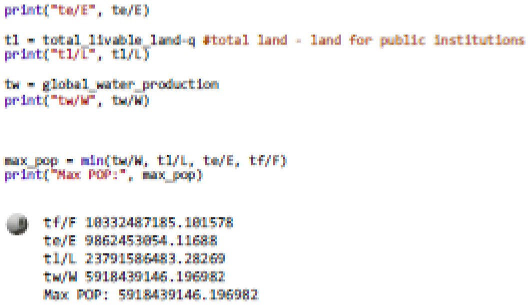
```
ll = 0.1*total_livable_land/world_pop
L = lf + le + lw +ll #+lh , lh is not included because land for h is constant and doesnt
print("L", L)
```

```
L 0.002674085907927087
```

Calculating Total Values

```
tf = global_annual_calorie_intake*world_pop
print( "tf/F",tf/F)

te = global_energy_production
```



```python
print("te/E", te/E)

tl = total_livable_land-q #total land - land for public institutions
print("tl/L", tl/L)

tw = global_water_production
print("tw/W", tw/W)



max_pop = min(tw/W, tl/L, te/E, tf/F)
print("Max POP:", max_pop)
```

```
tf/F 10332487185.101578
te/E 9862453054.11688
tl/L 23791586483.28269
tw/W 5918439146.196982
Max POP: 5918439146.196982
```