A DISCUSSION ON HUMAN CARRYING CAPACITY AND ECONOMIC GROWTH

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ABSTRACT
This work discuses the concept of human carrying capacity within the context of economic growth theory. We discuss a standard economic growth model with increasing returns on capital due to technological progress, and also included a logistic population growth. We offer some estimations of long-term population growth for some countries and regions which, in some cases, happen to have logistic paths. We reconstruct a simple economic growth model with capital accumulation enhanced by technological progress, as in endogenous growth models. The model uses a production function with increasing returns to scale on capital enhanced by technological innovations. Under logistic population growth, the steady-state equilibrium was found to be unstable. We also show that, in the context of logistic population, technology and production, human carrying capacity is just the steady-state level of the labor input. Finally, we model human carrying capacity as a function of effective labor, population times the technology level, and concluded that, in advanced stages of technical development, the logistic population growth becomes simply exponential (Malthusian) growth.

KEYWORDS: Economic growth, population growth, carrying capacity.
MSC: 91B62, 91B82, 91D20

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RESUMEN
Este trabajo analiza el concepto de capacidad de carga humana dentro del contexto de la teoría del crecimiento económico. Discutimos un modelo de crecimiento económico estándar con rendimientos crecientes del capital debido al progreso tecnológico, y también incluimos un crecimiento poblacional logístico. Ofrecemos algunas estimaciones del crecimiento demográfico a largo plazo para algunos países y regiones que, en algunos casos, tienen trayectorias logísticas. Reconstruimos un modelo de crecimiento económico simple con acumulación de capital potenciada por el progreso tecnológico, como en los modelos de crecimiento endógeno. El modelo utiliza una función de producción con rendimientos crecientes a escala del capital mejorado por innovaciones tecnológicas. En condiciones de crecimiento poblacional logístico, se encontró que el equilibrio de estado estacionario era inestable. También mostramos que, en el contexto de la población, la tecnología y la producción logísticas, la capacidad de carga humana es simplemente el nivel de estado estacionario del insumo de mano de obra. Finalmente, modelamos la capacidad de carga humana como una función del trabajo efectivo, la población multiplicada por el nivel tecnológico, y concluimos que, en etapas avanzadas de desarrollo técnico, el crecimiento logístico de la población se convierte simplemente en un crecimiento exponencial (malthusiano).
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PALABRAS CLAVE: Crecimiento económico, crecimiento poblacional, capacidad de carga.

1. INTRODUCTION

This paper discuses the concept of carrying capacity of human populations within the context of neoclassical economic growth theory and logistic population growth. We use a standard Solow-Swan growth model with increasing returns to capital, to simulate endogenous growth caused by innovations and technological progress along with a logistic population growth scheme. Within this framework we discuss the stability of the model and the concept of human carrying capacity implied by the results. At the end, we conclude that the standard Malthusian population growth model may still an important tool to simulate human populations.

Formulated in the mid XIX century, the Solow-Swan growth model has being a work-worse in theoretical analysis and a cornerstone for policy formulation and national accounting. It offers a clear and simple understanding on the key variables that influence capital accumulation and therefore economic growth. On the other hand, the Malthusian population growth scheme has been the standard assumption on most economic growth models, but the current trends of population growth may suggest that there may be convergence (limit) at some point of time. This is the main reason to introduce logistic population growth into economic growth analysis, and an example of this is [10]. Furthermore, it is important to reflect on the concept of human carrying capacity as a different to other species that only depend on natural endowments.

Human overpopulation has been a topic that always raised heated debate since Robert Malthus wrote his famous *An essay on the Principle of Population* in 1798, during a time the world population was about to reach its first billion people. Since Malthus' time, the human population has increased seven-fold and it is still growing. During the XX century, loud concerns have warned about depletion of natural resources, pollution, global warming, environmental degradation, among other important issues that highlights the fragility of ecosystems and the limited natural resources available in our planet. The Malthusian perspective has been adopted in many areas, including economic growth, where standard models still use exponential population growth as part of the analysis. Malthus' assumption is that the population grows exponentially without positive checks such as wars, pandemics, etc. Another Malthusian assumption is that food production grows linearly, so there will be a point in time where the population will be restricted by famine, wars, pandemics, and other natural checks. In the natural world, the size of any population is determined by the resources found in the environment. And the term "carrying capacity" denotes the maximum population that any species can reach within the limit of the resources available without degrading that environment's productivity. Although this concept can be objectively applied to most animal species, human societies face different constraints that allow them to support a larger population. It might be argued, that humans are an evolutionary drift, an species that develop skills and accumulate human capital and technology as no other species has done in the evolutionary history of our planet. But despite our powerful technology, the amount of natural resources available on our planet are still limited. Furthermore, the resources available for human populations are unevenly distributed around the world (e.g. water, fertile soil, minerals, etc.). For some countries there may still be some room to accommodate more population, but this also implies that better technology is needed to house and feed more people, increasing the pressure on our planet resources.

The Malthusian ideas were recalled in the book *The Population Bomb* in 1968 by Paul Ehrlich [7], who predicted severe famine due to over population and resource exhaustion. Later, [9] emphasized in five theorems the negative impact of human overpopulation on the environment. However, during the last century, we have seen a rising crop yield and a general increase in calorie intake, due to improvements in food production in general. In some respects, humans have the advantage of free markers where the right incentives for food production can be channeled properly. Human societies engage in positive human capital accumulation thanks to improvements in technology and efficient allocation of resources. [8] is an apology to his 1968 book, saying that, while failed to make a good scientific forecast, it still provided a warning about environmental deterioration. [5] approached environmental impact by adding the component of technology used in production and including this component into the carrying capacity of the human population.

Some works such as [12], [3] and [6] provide some insights on the concept of carrying capacity of human populations. These works try to estimate the possible maximum population that the earth can sustain, some using logistic type growth models to estimate such capacity. They agree that food production is the key variable that determines the carrying capacity of the humans, though offering very different estimates. While [12] estimate a carrying capacity of 23 billion for the year 2000 with current food production, [3] projected a stabilization of the human population around the year 2025 in more than 10 billion. [6] tries to give some theoretical support for understanding carrying capacity of human populations as well as the need to prevent environmental degradation. [13] is a discussion on human carrying capacity and biocapacity, also arguing in favor of the logistic population growth path, and also alerts on environmental degradation. [19] is good survey for understanding human carrying capacity from different perspectives, which also discusses the logistic population growth path. They include additional elements to human carrying capacity such as social, economic and cultural aspects that make this abstract limit different from the mere biological one.

[15] predicted at the beginning of the century the end of population growth, using standard probability techniques. They estimated that the human population will reach its maximum at the end of the 21st century at around 10 billion people. [14] also discuses the difficulties encountered for estimating the human population due to several factors such as immigration, mortality, demographic transitions, among other variables, which justify the revision of UN population forecast of about 10.1 billion people for the year 2100. Finally, we must add that a good source for historical estimates of the human population can be found in [16].

On the side of economic growth theory, we must recall the 1990 work of [17], which is a breakthrough from the traditional Solow-Swan model. The major contribution of endogenous growth, is that ideas and knowledge can expand the productivity of inputs, justifying the use of increasing returns to scale production functions. Because the production of ideas are non-rival with other inputs, there will be an expansion effect on production that can be modeled in different ways.

When relating population growth with economic development, there are still many questions to be addressed . [4] is a book edited by the US National Science Council in 1986 which intends to give some light on the role of slow population growth in key issues. They agree that slower population growth may increase the availability of renewable resources and public goods, such as education and health care, as well as reducing environmental degradation and pollution. But there was no consensus on how this would affect per-capita income, consumption, capital accumulation and technological innovation in the long run.

The main objective of this paper is to contribute to the debate on the limits of human population in the context of economic production and growth. We expanded on the work of [10], which is a neoclassical Solow-Swan type economic growth model with logistic population, constant returns to scale production function and constant growth rate (exponential growth) of the technological parameter. They found that logistic population growth is compatible with a stable steady-state path for total labor and the stock of capital per unit of labor. However, [11] and [1] are two works that introduced logistic population to a Ramsey growth model, and found that the steady-state equilibrium is a saddle point. [2] introduces a energy model of capital accumulation in Solow-Swan growth model, adding logistic population. They build a neoclassical Solow-Swan type growth model using a delay differential equation for population growth, but their objective is modeling energy as an input and accumulation of capital. The interesting part in [2] is that they model human carrying capacity with a delayed differential equation and divide it in two parts: the pre-existing carrying capacity provided by nature and the carrying capacity created (or destroyed) in society. We use this last concept to model human carrying capacity.

This research is organized into four parts. The first is a short introduction on economic and population growth, with literature review. The second part includes estimates of population growth rates using exponential and logistic growth. The third contains an economic growth model with increasing returns and logistic population growth, and the last part contains the main results and final comments.

2. EXPONENTIAL VS LOGISTIC POPULATION GROWTH

There are two main models to simulate population growth, used often in biology and other natural sciences. The most simple type is exponential growth $P_t = P_0 e^{rt}$, also called Malthusian growth in demographics and economics. This exponential path can be observed in many animal populations, especially in insects and microorganisms (e.g. bacterial culture), and it is useful for explaining the rapid surges in population numbers. If we take a look at the human population wave in the last millennium, we may interpret this wave as exponential growth.
Another important model is the logistic growth, expressed in the form of a sigmoid curve, first proposed by Pierre François Verhulst in 1845, which is a better approach to describing populations that are restricted by an upper limit due, among other things, to resource exhaustion. This model says that the population reaches a upper limit called "carrying capacity" which is the maximum population the environment can support:

$$\frac{dP}{dt} = rP\left(1 - \frac{P}{C}\right) \tag{2.1}$$

This model expresses the change in population size P over time t that depends on two important parameters: the growth rate r and the carrying capacity C. This differential equation has a solution in the form:

$$P(t) = \frac{CP(0)}{P(0) + (C - P(0))e^{-rt}} \tag{2.2}$$

So, given an initial population $P(0)$, and the parameters r and C, we can predict the size of any population at time t. In recent times, logistic population path has become a more accepted assumption for modeling human populations. For example, the OECD forecasting for world population from the year 1950 to the year 2050 was constructed fitting a logistic model. In table 1 we show the estimation of logistic and exponential models using the OECD data, where the carrying parameter C is estimated along with the population growth rates. The first nonlinear regression analysis was performed for the OECD countries, and the second was done for the rest of the world population.
The carrying capacity estimated for the OECD countries population is about 1.585 billion while the estimate for the rest of the world is 10.4 billion. The population growth rate estimated is slightly higher for the rest of the world, about 2.8%, compared with the OECD countries 2.47%. Both models are statistically significant, but the logistic model has a better fit. This is somehow evidence that the OECD is already considering that world population will converge at some point, and the logistic model might be a more realistic assumption. Figures 1 and 2 shows the projected world population with fitted logistic and exponential curves.
But the logistic assumption still cannot be applied to all human populations, especially those in developing countries. For example, Mexico and Japan are two OECD countries but their respective populations follow distinct historical paths. Mexico is a upper-middle income country while Japan is a high income one, both with very different levels of economic development. We estimated both logistic and exponential models for these two countries to observe the differences. In table 2 we show the estimates for both exponential and logistic models for these countries. The Mexican data comes

Table 1: World population projection estimates 1950-2050

OECD Countries		
Parameter	Logistic	Exponential
C	1585.4813 ***	
	(5.816)	
r	0.0247 ***	0.008365 ***
	(0.00019)	(0.0001)
Rest of the world		
Parameter	Logistic	Exponential
C	10421.827	
	(69.68731)	
r	0.028138 ***	0.0164 ***
	(0.00015)	(0.00014)

Notes: Population in millions. Standard errors in parenthesis. The *** represent statistical significance at 1%. Nonlinear regression performed in R with the package "stats", which uses a Gauss-Newton algorithm for optimization. Bayesian and Akaike information criterion confirms a better fit for logistic growth.

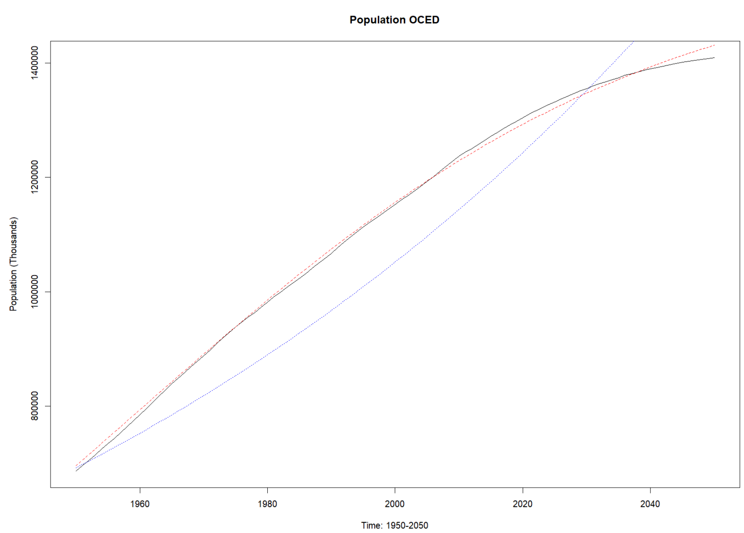

Figure 1: OECD countries total population 1950-2050

Notes: Data from OECD. Dashed red line is logistic fit and the dotted blue line is the exponential fit.

mainly from the Mexican National Institute of Geography and Information (INEGI) and the Mexican National Population Council (CONAPO), and the data for Japan comes from the Statistics Bureau of Japan.

In the case of Japan, we obtained a carrying capacity factor of 199.6 million, which is relatively high considering that the population is currently declining and reaching a maximum of 128 million in 2016.

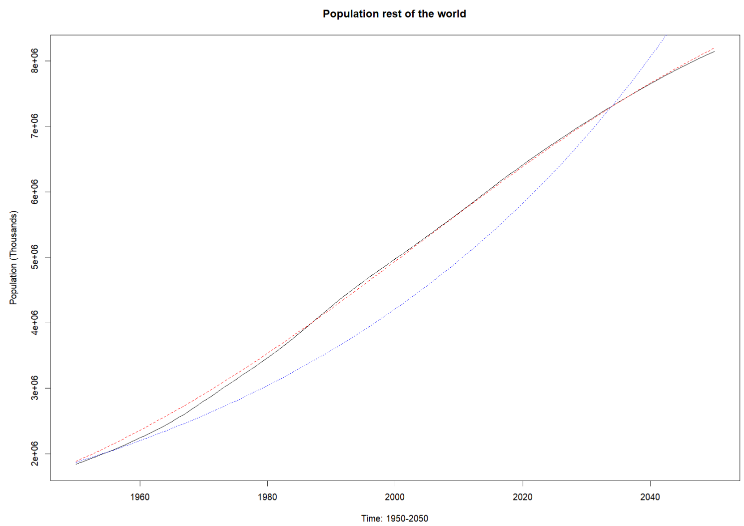

Figure 2: World population (except OECD countries) 1950-2050

Notes: Data from OECD. Dashed red line is logistic fit and the dotted blue line is the exponential fit.

As for the population growth rate, it was 1.65% for the logistic model and 1.04% for the exponential model. All estimates are statistically significant, but the logistic model fits much better than the exponential growth.

Table 2: Mexico and Japan population growth models and estimates 1872-2020

Japan				
Parameter	Logistic		Exponential	
C	199.58492	***		
	(8.02768)			
r	0.016543	***	0.0104163	***
	(0.00041)		(0.00007)	
Mexico				
Parameter	Logistic		Exponential	
C	-4798.0190			
	(12625.95)			
r	0.01807	***	0.01822	***
	(0.00038)		(0.00006)	

Notes: Standard errors in parenthesis. The *** represent statistical significance at 1%. Nonlinear regression performed in R with the package "stats", which uses a Gauss-Newton algorithm for optimization.

For the Mexican population, the estimate of carrying capacity C is not statistically significant and only the growth rate r is. Therefore, the exponential growth model suits better the evolution of Mexican

historic population over the last centuries, rather than the logistic model. In our regression analysis, the initial population of Mexico was about 6 million people at a time Japan had approximately 26 million. Mexico's population growth rate was estimated at 1.8%, slightly larger than Japan while Japan grew only at a rate of 1.6% for the entire period. With this initial conditions, both countries reached the same population in the year 2019, then it took over 220 years for Mexico to catch up with Japan's population. From the year 2020 Japan's population is still declining, while it is expected that the Mexican population will continue to rise and, in 2050, it might be close to 150 million. Figure 3 shows the population of both, Japan and Mexico, and it is easy to see that Mexican population follows an exponential path while the Japanese population follows a logistic one.
As in the case of Mexico, most developing countries' populations still follow an exponential path or the Malthusian model. The reasons are several, and some may be found in the social and economic structures of each country. For example, many poor countries have a large and primitive agriculture sector, where production is labor-intensive and the incentives for large households are relevant, contrary to developed countries where the cost of raising children is relatively higher as a proportion of a household income.

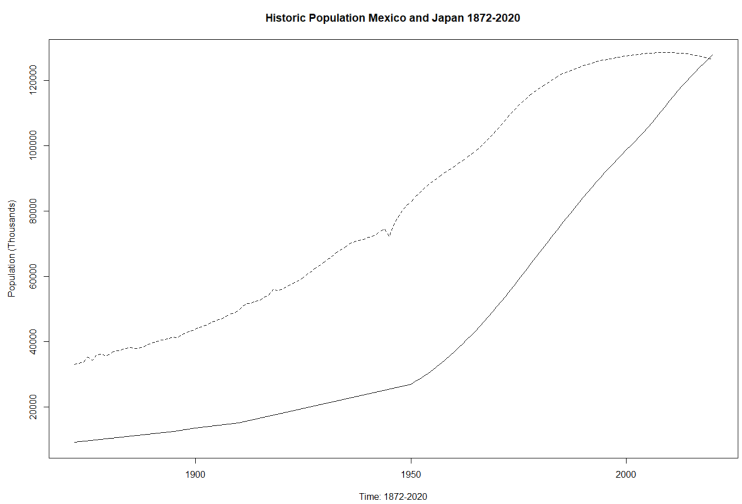

Figure 3: Mexico and Japan Population 1872-2020

Notes: Data from Statistics Bureau of Japan and Mexican National Institute of Statistics, Geography and Informatics of Mexico. Dashed line is the Population of Japan.

3. ECONOMIC GROWTH WITH LOGISTIC POPULATION

The question is how to model human populations in the context of economic growth. In a bigger picture and for developed societies, it looks that logistic model is more realistic, while for developing societies still the Malthusian model fits better. But we must admit that the over all trend is for a world population that is growing at a slower pace. If we accept that, in the long run, all human populations will behave in a logistic pattern, then we must discuss the concept of carrying capacity as well. And in doing so, we must agree that humans do not depend entirely on the natural endowments as others animal and plant species do.

We must say that, humans are a remarkable species: ingenious, inventive, creative, and they involve themselves in the process of economic production and technological advancement. For example, [18] suggested that the classic Mayan collapse was due to nutritional stress, disease, agriculture intensification, monocropping, and degradation of the agrarian landscape, among other issues. This is a clear argument for C being a environmental variable for this specific human population, as its carrying capacity was determined mostly by natural endowments, where biophysical constraints were at play. These natural constraints, such as climate, fertile soil, animal and plant stocks susceptible for domestication, etc., may have influenced the collapse of other civilizations in Mesoamerica as well, such as the Olmecs, Teotihuacans, Toltecs, among others. Even though we cannot rule out nutritional stress at the dawn of many other civilizations around the world, we some times overlook the fact that humans began to depend less on the natural endowments since at least 11 thousand years ago, when humans began to domesticate plants and animals. Production, as we know it, began during this time when humans began to abandon hunting and gathering to become farmers and herders. This economic revolution changed our nature and therefore expanded our carrying capacity; freeing ourselves, at least partially, of the limits imposed by nature.

Another example is the invention of synthetic fertilizers by Fritz Haber and Carl Bosch in 1910. They synthesized ammonia from hydrogen and atmospheric nitrogen to produce commercial quantities of fertilizers, that helped to increase food production ever since, and therefore increasing human carrying capacity. Currently, more than half of the population in the world is fed with crops produced by the Haber-Bosch process. Although we cannot deny that the natural resources on the planet are limited, it is clear that the biophysical carrying capacity does not fully apply to humans.

It would be inaccurate to say that, despite our limited resources, we can afford ever larger populations just by applying our technology accumulated by thousands of years of innovation. Though we are a unique species, we cannot say that the human population can grow infinitely because our technology can allow us to enjoy such an advantage permanently. This idea of exponential population growth seems to be too unrealistic in the long run because the resources available in our planet are evidently finite. But to forecast a world population limit, given our planet resources, is quite a difficult task. History shows that technological innovations increase with the size of human populations, and we still expect major improvements in food production and health, with further increases in nutrition and life expectancy.

In our view, the concept of carrying capacity is closely linked to the concept of economic growth, capital accumulation and technological progress. Although there may be a natural population limit restricted by natural resources, there must be a higher threshold for human due to production and technological innovation. In this section, we construct a simple growth model with logistic population, with increasing returns on the input capital, as in an endogenous growth model. After showing the main results, we define the concept of carrying capacity in terms of a technological parameter and discuss the possible implications. Firstly, we must start with a production function with increasing returns in capital, in the form:

$$Q = K^{\alpha} K^{\lambda} (AP)^{1-\alpha} \tag{3.1}$$

This production function has two terms K with the exponent α being the share of physical capital in production and the term K^{λ} being the positive influence of human capital on physical capital, in the form of ideas and innovations. This is a simple way to model endogenous growth, rather than modeling ideas and innovations by a separate function as in [17]. Here, capital input has a broad interpretation, and is measured in terms of physical and human capital. If $\lambda = 0$, then there is no positive influence and spillovers of ideas and innovation on capital. Because $\alpha + \lambda > 1$, this production function has increasing returns on the factor capital, and we can rename these two parameters as $\tau = \alpha + \lambda$. Therefore, the economic growth model may be formulated as:

$$Q = K^{\tau} (AP)^{1-\alpha} \tag{3.2}$$

$$\dot{K} = sQ - \delta K \tag{3.3}$$

$$\dot{P} = P(r - bP) \tag{3.4}$$

This production function has increasing returns, with a technological constant $A > 0$, capital K and labor P as inputs. The factor P is used along with A, and interpreted as effective labor for production, and K is the capital stock in a broader sense, which may also includes intangible human capital. The second equation in this model describes capital accumulation over time, with a saving rate $0 < s < 1$, minus depreciation of capital with a rate $0 < \delta < 1$. The third equation describes the population growth scheme, which is logistic rather than the typical exponential growth. Here the population growth rate is $0 < r$ and the parameter $b = \frac{r}{C}$ contains the carrying capacity C in the denominator. Combining the above three equations we have a system of differential equations of the form:

$$\dot{\kappa} = s\kappa^{\tau} - (\delta + g + r - bP)\kappa \tag{3.5}$$

$$\dot{P} = P(r - bP) \tag{3.6}$$

Where $\kappa = K/AP$ is the effective capital labor ratio and $g = \dot{A}/A$ is a constant growth rate of the technological level, which enhances labor. Setting these equations equal to zero, we find the steady-state levels of capital-labor ratio and population:

$$\kappa^{*} = \left(\frac{\delta + g}{s} \right)^{\frac{1}{\tau - 1}} \tag{3.7}$$

$$P^{*} = \frac{r}{b} \tag{3.8}$$

These results are similar to [10], that uses a Solow-Swan type model with logistic population, and says that the steady-state capital-labor ratio κ^{*} level depend on the depreciation rate of capital, the savings rate and the rate of technological progress on any given time. If, for any cause, there are changes in the rates of savings, depreciation or technology, then, there will be a different level of κ^{*}.

We can also test the stability of the system using the Jacobian matrix:

$$J_{(\kappa^*,P^*)} = \begin{bmatrix} (\delta+g)(\tau-1) & b\kappa^* \\ \\ 0 & -r \end{bmatrix}$$

The determinant of the Jacobian is negative $|J| < 0$, therefore the equilibrium is clearly a saddle point, which is essentially unstable. This results is opposite to [10], who found a stable equilibrium in their growth model with a constant returns production function. Let us recall that in the traditional Solow-Swan model with Malthusian growth, the steady-state capital-labor ratio κ^* level depends on a positive rate of population growth r, but with logistic population as in [10], κ^* now depends on the growth rate of the technological constant g.
Another important result, perhaps overseen by [10], is that the steady-state of labor P^* is just the carrying capacity $P^* = \frac{r}{b} = C$. Needless so say, this result has important implications within the growth model. The steady-state level of population is $P^* = C$ allows us to interpret human carrying capacity as an economic variable, rather than an environmental one. This is to say, the carrying capacity of human population is the steady-state level of labor input, set alongside the steady-state level of the capital labor ratio. In this context, the logistic optimal growth of human population is simply:

$$\dot{P} = P(r - \frac{r}{P^*}P)$$

Unintentionally, we are analyzing the carrying capacity of human populations, which is defined as an abstract inter-temporal limit where population converge. For scientists in ecology, involved in experiments with bacteria, insects, birds, fish, and other animals, the limit C is defined as the maximum population that can be sustained by the natural world without degrading the environment, so the carrying capacity is a fixed number determined by nature (or the resources determined by a researcher in a lab). But when applying this concept to humans, C is the maximum population that can be sustained in a conjunction with a steady-state level of capital-labor ratio.
As previously shown, in the context of endogenous growth models as well as in neoclassical growth models with logistic population (as in [10] and [11]), the carrying capacity is just the steady-state level of the population, simultaneously determined with the steady-state level of capital-labor ratio. The initial assumption was that population limit was constrained by a biophysical carrying capacity determined by nature, but this assumption cannot be used in the context of economic growth.
So, the question remains on how to define carrying capacity for human populations. So, let us define C in other terms. As we mentioned before, humans are a complete different species, driven by technological innovation and economic progress. A simple form to define economic carrying capacity would be to express it in terms of population expanded by a technological factor:

$$P^* = C = \beta AP$$

This is a simple and linear description of human carrying capacity, which we defined as the population in a given time expanded by the technological level $A > 0$, and an adjustment parameter $\beta > 0$ which may account for institutional and societal conditions. Here the technology constant A is just an scalar that expand total population P; a large population with superior technology (effective labor) produces a large human carrying capacity. This is a straight forward way to interpret human carrying capacity: a population expanded by technology and social norms. Using this definition, we have a logistic growth in the form:

$$\dot{P} = P\left(r - \frac{r}{\beta A}\right)$$

Where the term in the parenthesis is a kind of effective growth rate, with a carrying capacity enhanced by technological progress. But taking the limit to this term when the technology level expands towards infinity, we have:

$$\lim_{A \to \infty}\left(r - \frac{r}{\beta A}\right) = r$$

This result takes us back to the exponential or Malthusian growth $\frac{\dot{P}}{P} = r$, which is used in the standard growth models.

Let us use another concept of human carrying capacity that separates the natural endowments with the expansion made by societal progress, like in [2], which constructs a carrying capacity considering an environmental part and a societal part:

$$P^* = C = N + \overline{A}P$$

Where N is the pre-existing carrying capacity given by nature, and $\overline{A}$ is average carrying capacity created by society. We assume that $A > 0$ when there is creation through innovation, and $A < 0$ when there is destruction (e.g. wars, pandemics, famines, genocide, etc.). Although in the long run, we must assume that creation outweighs destruction, and technological progress always increases carrying capacity, so that $\overline{A} > 0$ is getting larger over time (accumulation). This is a realistic assumption as human population has been increasing in the last centuries[1]. Taking the limit again to this effective population growth rate, we go back to the Malthusian assumption:

$$\lim_{\overline{A} \to \infty}\left(r - \frac{rP}{N + \overline{A}P}\right) = r$$

¿Does this mean that all human populations grow exponentially? Well, perhaps not, but the Malthusian model might be an acceptable theoretical assumption for human population in the context of endogenous economic growth. Exponential population growth may be a good substitute of logistic growth when human carrying capacity depends on technological progress. When considering the impact of an increasing returns production function, as in endogenous growth models, we may consider to use exponential population rather than logistic as a practical convenience, as human carrying capacity may be always expanding by technological progress despite positive Malthusian checks.

[1] If $\overline{A} = 0$, then human carrying capacity is only determined by nature, which is not very realistic.

4. CONCLUSIONS

In this work, we reconstructed an economic growth model with a increasing returns production function to simulate the impact of ideas and innovation on capital accumulation, as in endogenous growth models. Additionally, we included a logistic path for the labor input, instead of exponential population growth. The assumption of increasing returns on capital may be a more realistic approach considering that, during the last centuries, human societies have been growing thanks to technological progress and innovations. Although the model is simple, it grasp the essence non-rival ideas and knowledge on capital, and also account for efficient use of labor with a technology level. Our results shows that the steady-state equilibrium is a saddle point, which is essentially unstable.

We discussed the term of human carrying capacity as the limit of human population that can be sustained with natural resources but also expanded by production and technology. Natural endowments may be fixed, but we must highlight the importance of production, technological progress, and capital accumulation in human societies. For this reason, we defined human carrying capacity as the result of technological progress, in terms of effective labor (technology level times population). Using this definition in a growth model with an increasing returns production function, the logistic population growth just becomes the traditional exponential growth.

Our results shows that the final steady-state equilibrium is unstable, which contrast with [10] that also uses a logistic population growth path. The main difference is that [10] uses a Solow-Swan model with constant returns production function while we are using a production function with increasing returns on capital. In [10], the steady-state equilibrium is stable and the inter-temporal path of the capital-labor ratio does not depend on the population growth. Similar to [10], the steady-state level of labor is also akin to the human carrying capacity.

Our work has a similar result as in [11], which uses logistic population but within a Ramsey type growth model, with a steady-state equilibrium becoming a saddle point. Although logistic population growth may be a more realistic way to model populations, it may not grasp the essence on how human populations grow, with carrying capacity ever expanding by technological progress. Following this reasoning, exponential growth may still be an acceptable assumption when theorizing about human population growth in the presence of technological advancement and production.

We do no imply that human populations may grow to infinity, but that the limit of human populations are not clearly defined, as it is not restricted by solely natural endowments. Therefore, in the presence of expanding technology and production, the theoretical assumption of exponential population growth might be reasonable until the carrying capacity is reached. We must also comment that, in recent times, the topic of overpopulation has been overshadowed by other issues such as global warming and sustainability, environmental protection, quality of life, or other relevant discussions. But still, despite the importance of natural endowments and resources, the concept of human carrying capacity cannot be exclusively defined by biophysical constraints.

There still much needed research on institutional and cultural variables that affect population growth, such as religious views, demographic policy, political instability and conflicts, among many other factors. But it might good to think that, as long as there is technological advancement and innovations, there is hope that our species will thrive for many centuries more, as long as we are wise enough to avoid the Malthusian positive checks.

RECEIVED: OCTOBER, 2023
REVISED: MARCH, 2024.

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