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Knowledge production and world population dynamics

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ABSTRACT

Three laws of knowledge production explaining the empirically observed hyperbolic growth of world population are formulated. Knowledge and demographic dynamics are developed on the basis of the least action principle to describe deviations from the hyperbolic growth. The efficiency of knowledge production defined as the share of technological knowledge in total knowledge production is introduced. It is proven that a monotonic population growth with reaching a plateau is possible only when efficiency is 1. At a lower efficiency, population reaches a maximum and then declines. The estimated efficiency is currently not more than 0.1. The calculations show that if efficiency remains constant, population will peak at 9 billion in the mid-21st century and then decline to 5 billion or lower over several centuries. To keep population at a level of not less than 90% of maximum, it is necessary to raise efficiency of up to 0.31.

1. Introduction

World population depends on the level of civilization development. For modeling the world demographic dynamics, we need to understand how the development level can be measured and how it influences the population. According to Malthus (1798), "Population is necessarily limited by the means of subsistence." In turn, the means of subsistence depend on development level. This level can be estimated by different criteria. Kuznets (1960) and then Kremer (1993) were of opinion that the crucial role belongs to the technological level of commodity production. Podlazov (2002) in his model has also used this idea but in a wider sense, meaning by this all life-support technologies, which include commodity production as a particular case. However, the quantification of the technological level has remained ill-defined. Korotayev et al. (2006), Korotayev (2007), and Malkov et al. (2007) attempted to resolve this uncertainty by proposing an interpretation of the technological level as labor productivity that is obtained by dividing the gross world product by population and measured in dollars per person per year. This definition rather characterizes rate of technological development than technological level as a static variable. The cited authors also pointed to the importance of women's literacy as a regulator of fertility. For this reason, the base model, which takes into account only population and level of technology, has been extended by including an equation for the share of literate population. The models of Podlazov (2002) and Korotayev et al. (2006) were intended to describe not only the hyperbolic growth, which was first detected by Foerster et al. (1960) from the analysis of demographic data, but also the deviation from this empirical rule during the current transition period.

Development level is synonymous with culture, which is understood as innovations in agriculture, social organization, tool manufacture, and other technologies. Ghirlanda et al. (2010) considered a demo-cultural dynamical system in which cultural components consist of two factors, promoting and inhibiting population growth, and the population component is taken as the logistic equation with carrying capacity depending linearly on the cultural components.

Taagepera (2014) proposed a model of demographic growth that includes three factors: exponential growth propensity of any biological species under steady favorable conditions, limits imposed by Earth's carrying capacity, and – specific to humans – impact of technological–organizational change on the two other factors. The model consists of three differential equations for population, technological level, and carrying capacity. Solution of this system was approximated by a "tamed quasi-hyperbolic function" that gives quasi-hyperbolic growth at early stages of the process and then population reaches a plateau.

In the phenomenological models of Kapitza (1992, 1996), Naidenov and Kozhevnikova (2003), and Miranda and Lima (2010, 2011), the development level of civilization is not used at all. These models were applied to describe the hyperbolic growth and current transition. Miranda and Lima (2010) have introduced the Allee effect in the logistic model with a constant carrying capacity to describe the dynamics of an isolated, unstructured, population. The Allee factor was used in the exponential form as well as in the form of Hill function that gives the power-law population growth dynamics as a particular case. Later, Miranda and Lima (2011) have shown that the power-law modeling may provide a reasonable description only at the early stages of the process when the system is in a replication, or depensation, phase. As the system evolves in time and reaches some critical size, its evolutionary growth becomes an S-shaped time dependence described by the logistic function. Verisimilitude of the results of this group of works can be explained

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by the fact that there is a significant correlation between population and development level (Kuznets, 1960; Kremer, 1993). Usually it is considered that the development level controls population (Malthus, 1798), and not vice versa. So, Kapitza's concept of the "demographic imperative," which implies that population controls economic development, raises objections. It is more appropriate to talk about the "knowledge imperative."

In the spirit of the knowledge (or informational) imperative, Dolgonosov and Naidenov (2006) and Dolgonosov (2009, 2010a, 2010b, 2012a, 2012b) have formulated an informational model, which describes dynamics of knowledge and population. Then the dynamic equations were generalized on the basis of the least action principle. In this model, development level is defined as the amount of accumulated knowledge. The approach developed in these studies qualifies a civilization as an informational system that produces knowledge for its survival. It is the creation of knowledge that distinguishes civilization from a common informational system. According to Chernavsky (2004), an informational system perceives the incoming information, stores it, and generates macroinformation, but does not necessarily create knowledge. The informational model's advantage is the small number of parameters (three) that facilitates interpretation of its results.

This informational model was later modified by Akaev and Sadovnichy (2010, 2011) and Akaev et al. (2012) by taking into account three time lags associated with the reproduction of population, diffusion of basis technologies within population, and biospheric response to anthropogenic load. The modified model is more complex by the number of parameters than the basic informational model: 8 parameters in the modified model against 3 parameters in the basic one. Because of the uncertainty in parameter values, the reliability of prediction falls.

Aral (2013, 2014) proposed a population model which may reflect the climate change effects on world population stability in aggregate. The author was based on the informational model in the version of Akaev and Sadovnichy and extended the latter by introducing an additional term which takes into account global temperature change. In this model, the number of parameters has risen to 10. So, calculations within this model have qualitative rather than a predictive character, but nevertheless allow tracing the effect of global temperature growth on population.

Despite the formal extension of the informational model, its basic version needs to be substantiated in more detail and presented more consistently that will give better understanding of the model. In addition, this will provide a solid foundation for further extensions of the model.

In the above-stated studies, there was no sufficient understanding of what knowledge is and how it differs from information; what features of the least action principle are for a system that produces knowledge (civilization), in contrast to mechanical systems; what in this case the action functional and Lagrangian are. There was no understanding of the knowledge production mechanisms needed to establish a relationship between the amounts of knowledge and information that is important for the derivation of dynamic equations. There was no clarity as to how Earth's carrying capacity is expressed in terms of economic indicators, taking into account the costs of restoring the environment. The questions of the structure of the informational space, relationships between the general and technological information, general and technological knowledge were never addressed. Finally, it was not clear what the meaning of the key parameter α is, which controls the course of demographic process. It was thought that this parameter reflects an effectiveness of civilization, but it was not clear what the effectiveness is meant. So, the interpretation of results has remained quite limited. The aim of this article is to study these issues as well as the issues concerning clarification of the relationship between neuronal and external memory, estimation of the memory capacity, calculation of demographic scenarios and their comparison with the retrospective demographic data, assessment of the prospects of population change, and the possibility of population decline. Analysis of these problems will allow us to reach a higher level of understanding of the influence of knowledge amount and its production efficiency on world population dynamics.

2. Empirical regularities

2.1. The Doomsday model

Foerster et al. (1960) have shown that world population grew hyperbolically during the last 2000 years. In log–log scales, the population curve looks like a straight line as depicted in Fig. 1. The hyperbolic law may be extended to an earlier period that covers 1.6 million years ago, but the accuracy of the paleodemographic data decreases as the distance of the past. This empirical demographic law called the "Doomsday model" has a general form:

$$N = \frac{C}{t_1 - t}, \qquad (1)$$

where N is the world population, t is the time, t_1 is the singularity moment, and C is a coefficient. As found by Foerster et al. (1960), $t_1 = 13$ November $2026 \approx 2027$ and $C \approx 2 \cdot 10^{11}$ person × year (the determination coefficient is $R^2 = 0.973$). According to Eq. (1), population obeys the second-order kinetics:

$$\dot{N} = N^2 / C. \qquad (2)$$

Meanwhile, we know from population ecology that a biological population grows usually in the first-order kinetics, which gives an exponential growth:

$$\dot{N} = aN \quad \Rightarrow \quad N = N_0 e^{at}, \qquad (3)$$

where a is a positive growth coefficient and N_0 is the initial population size. By analogy, this type of kinetics is widely used in demography in contradiction with Eq. (2). But then the question arises: why does human population obey the *second-order* kinetics instead of the *first-order* one?

2.2. Hyperbolic growth and knowledge paradigm

Means of subsistence that determine population size are produced using knowledge-based technologies. Knowledge induces technological development, including new life-support technologies in dwelling, food, medicine, education, etc. (Markov and Korotayev, 2009). This

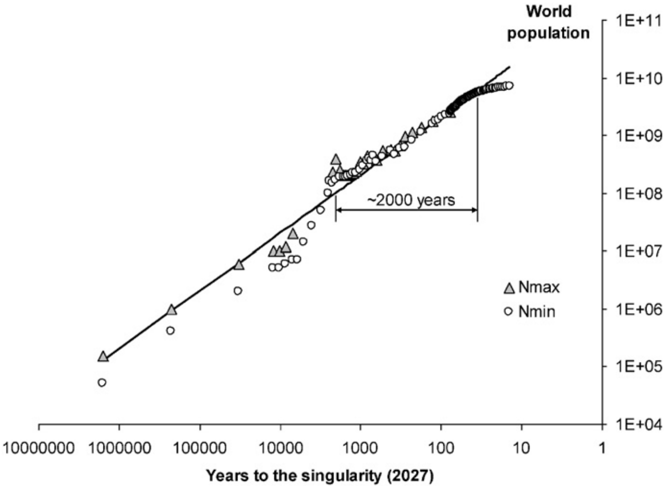

Fig. 1. The long-term world population growth. From 1.6 million years ago to the singularity in 2027. Data sources: Biraben, 1980; Jones et al., 1994; US Bureau of the Census, 2014.