CYCLIC AND STATIONARY MODES OF THE DEVELOPMENT OF CIVILIZATION IN GLOBAL MODELS

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The World2 model of the global socioeconomic system (GSES) was modified using the Mathcad software environment. Based on the resulting World2-MC model, long-term scenarios of the evolution of GSES were considered, upon the premise that only fuel resources are unrenewable, and were compared with the main conventional global models and the respective algorithms of transition of modeled systems to stable equilibriums. With account for the ecological demography data about convergent oscillations of populations in the course of their transitions to steady states below the maximum population sizes that can be sustained with environmental resources, it has been shown that such convergence may occur if resources for growth have been accumulated before the growth started. This is what is exactly true for fossil fuel resources. The initial level of unrenewable resources is underestimated three- to fourfold in the World2 model. The developmental scenarios realized with the World2-MC model show that increasing the initial levels of resources may lead to oscillations of all components of a modeled system. The numbers of the oscillations range from two to four, and population size in each of the oscillation is limited by not fuel resources but by food deficit and environmental pollution. Each scenario leads to a stationary population size ranging from 1.3 to 1.5 billion. In scenarios accounting for shale oil resources, oscillations number may be as high as 15. Increasing the available power with thermonuclear power production will transform developmental trajectories into undamped harmonic oscillators. Only population control measures can be effective in preventing the repetitions of population size oscillations. The first oscillation is already inevitable. The time to prevent it has been lost. A stationary state is possible only following the first or the second oscillation. The optimal time of transition to a final stationary state depends on the position of the local stationary state of population size in time. This state is determined by the phase portrait in the "population size – relative population increment" plain (Allee curve). Population size in a local stationary state is assumed as the initial condition in the logistic model of population growth, and the tolerable threshold of population size is found to be 1.5 billion. The time to Lyapunov stationary state of GSES critically depends on a single parameter, which is the coefficient of population size increment at a local stationary point.

***Keywords**: civilization, global model, fuel resources, oscillatory development, stationary state.*

INTRODUCTION

The humankind is currently going through demographic, socioeconomic, and environmental crises prone with catastrophic consequences, which are unrecognized by ignoramuses and disregarded by optimists. The recent concept of "sustainable development", i.e. development that meets the needs of the present without compromising the ability of future generations to meet their own needs, is comforting; however, it cannot be helpful in searching for approaches to preventing or ameliorating the looming collapse.

Helpful in this regard may be the mathematical models of global development. Jay Wright Forrester who developed the first of such models declared his concept of global modelling at a special meeting of the US House of Representative as the following: "The human mind is not adapted to interpreting how social systems behave. In the long history of evolution it has not been necessary until very recent historical times for people to understand complex feedback systems. Social systems are far more complex and harder to understand than technological systems. Why then do we not use the same approach of making models of social systems and conducting laboratory experiments before adopting new laws and government programs? I suggest that we now do know enough to make useful models of social systems".

The shrewd investigator delineated the critically important components of the global system to include them in his World2 model, which makes the basis of a number of further global modelling attempts, including the one described in the present paper.

The paper is about long-term prospects for human civilization as it depends on the global socioeconomic system (GSES). It will be shown below that in the XXI century the humankind will face not a collapse but a profound crisis followed by recovery. In the third millennium, GSES will go through a number of developmental cycles, which will depends on power availability. Any transition to a stationary trajectory, which may be tolerable for the biosphere, is possible only after the first or some subsequent developmental cycle is completed. The logistic model of population size growth is shown to be the most relevant for such transition.

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1. Searching for ways to global equilibrium

1.1. Malthus's concept

In 1798, the English cleric and scholar Thomas Robert Malthus issues the book "An Essay of the Principle of Population" where he proposed the simplest model of population size (P) growth, which may represented with the equation:

$$\frac{dP}{dt} = \varepsilon P \quad (1)$$

where t is time, and $\varepsilon = \text{const} > 0$ is the rate of natural may be called population growth factor.

The solution of Eq. 1 is:

$$P(t) = P_0 e^{\varepsilon(t-t_0)}, \quad (2),$$

where P_0 is population size at t_0, and e is the base of natural logarithm.

In classic ecological demography, the plot of an exponential increase in population size (Eq. 2) is called biotic potential curve. The increase is consistent with that when time (not resources abundance!) increases arithmetically, population size increases geometrically if there are no factors that restrain population growth. Population size is constant when $\varepsilon = 0$ and decreases when $\varepsilon < 0$.

In wild animal populations, negative correlations between ε and P are typical suggesting the existence of factors that limit population growth to an optimal size corresponding to the carrying capacity of the environment. The only species that features a positive correlation between ε and P is Homo sapiens (human intelligent). Indeed, during the last 190 years the total human population increased from ca. 1 billion in 1827 to 7.3 in 2016, the values of ε increasing too: $\varepsilon(1880) = 0{,}0065$, $\varepsilon(1945) = 0{,}0133$, $\varepsilon(1968) = 0{,}0191$, $\varepsilon(1981) = 0{,}0179$, $\varepsilon(1993) = 0{,}014$, and $\varepsilon(2006) = 0{,}0128$. Thus, human population on the Earth was increasing in 1827 through 1968 even faster than it may follow from the Malthus model. By the words of M. Mesarovich and E. Pestel who developed one of global development models, the world is affected by cancer, which is the human race.

In the model by Eq. 2, no factors can limit population growth. It is assumed on an intuitive basis that food shortage will ruin GSES and, therefore, the apocalypses may be delayed by wars, epidemics, and famines. The antihuman and unsubstantiated spirit of such assertions were the reasons for proponents of communism to criticize the Malthusian concept severely and to treat it as an antiscientific and reactionary theory.

1.2. Malthuses with computers, or prophets?[1]

In 1971–1974, J.W. Forrester and O.L. Meadows developed the first global models of GSES development, World2 and World3. The models are based on systemic dynamics principles implemented in a method of studies of complex systems having nonlinear feedbacks, which had been developed at Massachusetts Institute of Technology [32, 39]. The English economist K. Freeman who was dissatisfied with the apocalyptic prophecies derived from World3 modeling nicknamed World3 author as "Malthus with a computer". The nickname may be judged as either a reproach or a compliment. The reproach is for predicting demographic, economic and environmental catastrophes by the end of the XXI century. The compliment is for the clarity of the model providing for understanding the validity of its predictions.

The model World2 is, basically, a system of 5th-order ordinary differential equations. The right parts of the equations are defined with graphic or tabulated data presenting nonlinear relationships between the components of GSES, such as population size P, *capital investment*[2] K, the share of the agricultural capital investment X, environmental pollution Z, and nonrenewable natural resources R [32]. Equations for the above variables are constructed based on the balance principle:

$$d\varphi_i/dt = V_i^+ - V_i^-, i = 1, 2, 3, 4; \quad (3)$$

where: V_i^+ and V_i^- are the rates of increases or decreases in the components of a system, and φ_i is one of the components.

In equations for the variable R, the balance principle is irrelevant. Nonrenewable resources can only decrease at a rate V_5^-, which depends on population size and living standards.

GSES development in 1900 through 2100 was modeled. The initial conditions were defined based on available global statistics data. The model segment related to 1900 through 1970 was represented analytically, and its parameters were determined by varying their values and tabulated relationships at accuracies defined by available historical data.

World2 computations suggested that, upon current developmental trends, the explosive development of GSES in the XX century will be followed by GSES collapse associated with the exhaustion of the unrenewable natural resources, including all sources of food, and with environmental pollution (Fig. 1).

Starting from the years 2020-2030, global human population growth is envisioned to discontinue and then, over the subsequent 75 years, population size must decrease by 2 billion. There will be left less than 1/3 of the initial amount of natural resources. By 2050, environmental pollution will be 7 to 8 fold higher than in 1970. Diminished natural and labor resources will lead by mid-XXI century to considerable decreases in industrial and agricultural outputs.

In search for means of preventing the catastrophe, J. Forrester suggested the concept of transition to global equilibrium based on zero GSES growth. Several modeling scenarios have shown that such a transition is

[1] Christopher Freeman. Malthus with a computer, Futures, Volume 5, Issue 1, 1973, Pages 5-13, ISSN 0016-3287, https://doi.org/10.1016/0016-3287(73)90053-0. (http://www.sciencedirect.com/science/article/pii/0016328773900530).

[2] This term is adopted in the book by J.W. Forrester "World dynamics".

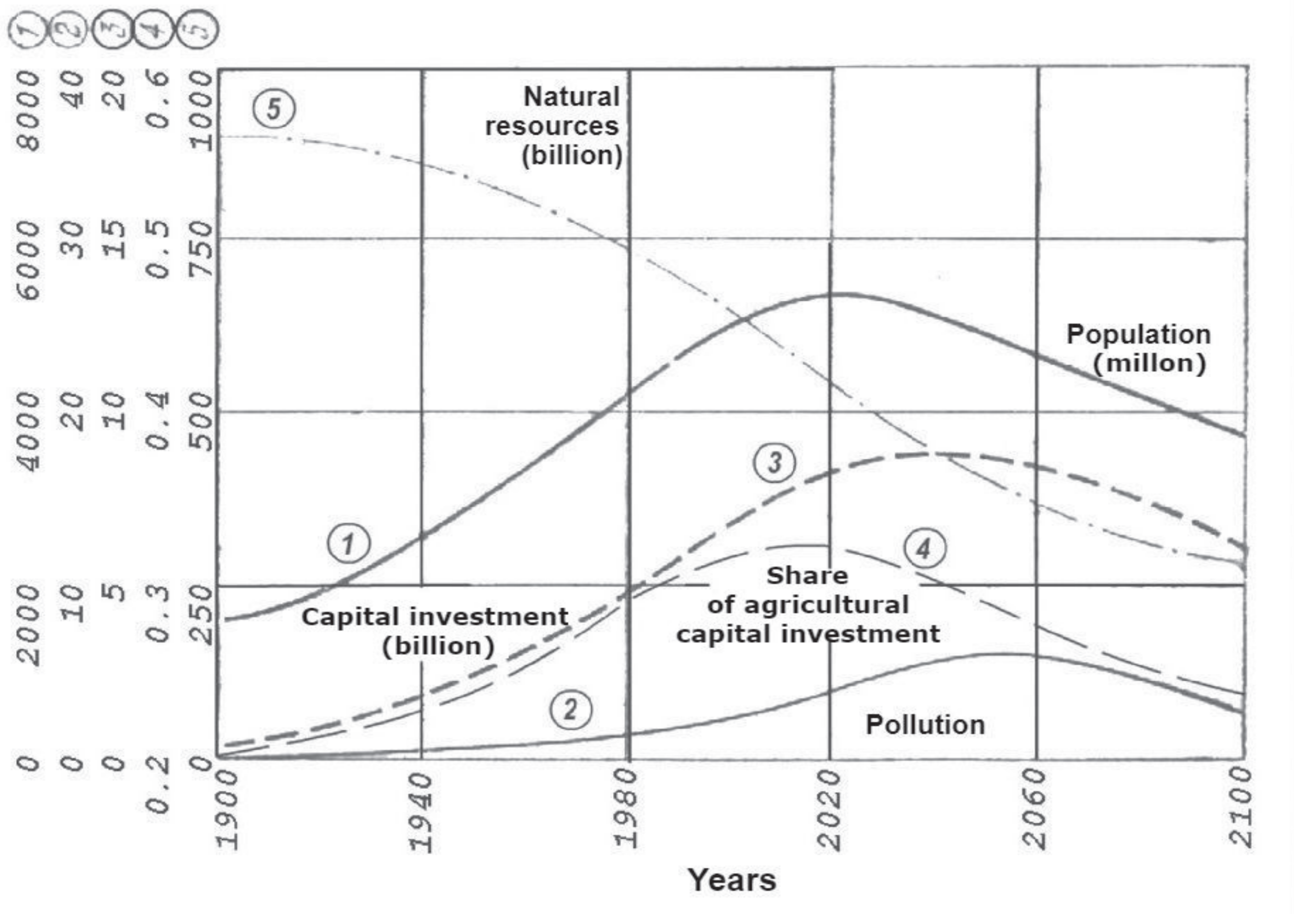

Fig. 1. The temporal variability of GSES components according to the basic scenario of World2 model [32]. The initial natural resources (100%) are assumed to amount to 900×10⁹ resource units (RU)

feasible within the years 1990–2100 upon the following constraints: the consumption of the nonrenewable natural resources must decrease four times relative to its rate as of 1970; pollutants generations must decrease two times; investments in economy must decrease two times; food production, by 20%; and birth rate, by 30%. Obviously, these constrains are unrealistic.

The apocalyptic prophecy aroused much tumult in public. Critical comments, such as that GSES structure is too simple and comprises no means to control its development, motivated the Club of Rome to continue sponsoring the development of global models. The next model World3 was developed by the team lead by D.L. Meadows [39].

The model World3 comprises 12 basic first-order ODE, 16 accessory ODE designed to capture the effects of smoothing and temporal delaying of some socioeconomic parameters, and a number of algebraic and tabulated inputs. The components of the model include four age groups of human population, capital investments assigned to industrial and servicing enterprises, the areas of potentially cultivable lands, urbanized areas, soil erosion areas, environmental pollution, and nonrenewable natural resources.

The sophistication of Wold3 structure produced no significant effects on modeling results. Computations suggested once again that, in the second half of the XXI century, there must occur demographic, economic and environmental catastrophes caused by rapid population growth, food shortage, environmental pollution, and nonrenewable resources exhaustion. The only means to prevent the collapse of GSES, that is to come to “a global equilibrium”, is, according to World3, the immediate (i.e. starting from early 1970ies) implementation of the following: birth rate must not exceed death rate; population size must be stabilized at a level as of 1945 (ca. 2.6 billion) and industrial production, as of 1980; per capita resource consumption must not exceed 1/8 of the level as of 1970; the lifetime of capital investment must be increased 1.5 times, and pollutant generation per production unit must not exceed ¼ of the level as of 1970. Obviously, this all is unfeasible.

1.3. Spatially compartmentalized global models

The above global models did not account for the regional differences within GSES. The subsequent elaboration of models made them increasingly complex because of transition from pointwise (spatially homogenous) to blockwise models that were structured in spatial terms (compartmentalized). The world was regarded as not a whole, but as a differentiated entity. Novel economic, demographic, and environmental components were devised, and the previous ones were disassembled. Diverse mathematical techniques of representation of mental images of the real world were devised. The new projects included "Strategy of Survival" (M. Mesarovich and E. Pestel [40]), Latin American Model (Herrera et al. [33-35, 42]), and the Japanese "New Vision for Development" (Y. Kaya [36]).

The trust in an increasingly closer correspondence between a model and the original resulted in the emergence of monster models, which in fact obscured the principles of GSES functioning and shortened the tractable temporal ranges of modeling, e.g., to 1975–2025 in "Strategy of Survival", 1975–2100 in the Latin American model, and 1970–2010 in the Japanese model.

"Strategy of Survival"

An exemplary monster model is "Strategy of Survival", where interactions between 10 regions (North America, West Europe, Japan, Australia and South Africa, East Europe, Latin America, Middle East and North Africa, Tropic Africa, Southeast Asia, and China) are treated. Each region is represented with a system of sub-models related to economy, demography, energetics etc. For each region, 19 categories of industrial, 2 of agricultural, and 5 of energetics-related capital investments are envisioned. Separately considered are asserts related to fishery and mining industries. The region are interconnected via migration, export, and import.

The preoccupation of the authors of the model with differentiation and particularization is apparent from the following examples. In demographic sub-models, mortality and age transitions of 85 age-stratified subgroups are considered. In production sub-models, net production rates of 26 foods, including eggs, honey, and giblets, are included. In a review of reports for the Club of Rome[3], it is noted that, whereas the Meadows's model includes about one thousand equations, there are more than two hundred thousand equation in the model devised by Mesarovich and Pestel.

Clearly, the model "Strategy of Survival" violates one of the key principles of systems analysis, i.e. not all, but only the most significant relationships within a system under study should be mapped onto its model. This is because the equations included in a model cannot describe the related phenomena exactly, and data obtained by socioeconomic and environmental monitoring are burdened with noise generated by measurements and sampling errors. Since the equations are essentially nonlinear, the noise is not dampened but instead is amplified by solving them thus making the solutions probabilistic rather than deterministic [4]. Therefore, on long time intervals, the models World2 and World3, which are pointwise, in terms of T.A. Aizatullin's classification[4], are preferable over compartmentalized models.

The main inference from the model is that GSES is under the threat of not a single global catastrophe in epy mid-XXI century, but of a series of regional catastrophes at different times and in different regions due to different reasons. The "novelty" of this conclusion in association with its labor intensiveness prompted to S.D. Dadayan the metaphor "computer without Malthus" for the team of its developers [10, p. 145]. The structure of the model may be characterized as so excessively complicated that it takes months to understand what it is about if not to believe it by default. This makes it is hard to tell genuine conclusions from the input assumptions of the model.

The Latin American model of global development.

This model relates to four regions: Africa, Latin America, Asia, and developed countries. It includes five sub-models related to population, economy and housing, urbanization, education, and nutrition. The regions interact via trade and gratuitous aid. The global crisis is assumed to have already occurred because of the fallaciousness of consumer society. The crisis is not associated with natural resource exhaustion and environmental pollution. It is assumed that R&D progress will allow cost effective developing of minefields even upon their constantly decreasing productivity, that nuclear synthesis will become an inexhaustible source of energy, and that the development of waste treatment technologies will solve the environmental protection problems.

The development of each region is modeled by solving an optimization problem. The shares of capital investment and labor resources are assumed as the guiding parameters. Two scenarios are modeled. According to the first one, the developed countries refuse to provide gratuitous aid. Then the components of the developed countries sub-model must reach stationary conditions in 20-30 years after the starting time, i.e. by 1980. The same must occur ten years later in Latin America and never in Asia and Africa, even upon an optimum governance. According to the second scenario, aid is provided to developing countries starting from 1980. Ten years after that, the aid reaches 2% of the annual product of the capital generation sector of economy of developed countries. According to this scenario, a

[3] http://www.ihst.ru/~biosphere/Mag_3/gvishiani.htm

[4] https://studopedia.ru/2_32769_tipi-matematicheskih-modeley.html

governance regimen that ensures stationary conditions of all regions is possible. In Asia and Africa, the stationary conditions are reached in about 60 years.

Thus, it has been shown, using a spatially compartmentalized global model, that economic aid provided by the developed countries to the developing regions of the world can prevent catastrophes and drive GSES to stationarity.

Global economic models

Some models are designed to tackle specific global problems. Often such models either lack some of the subsystems of the global system or include them as external or predefined variables. "Such approaches are prone with the loss of the main advantages of global modeling, i.e. the systems analysis of reciprocal influences of different factors and processes on each other. Such specialized models should be constructed by not excising of blocks from the general structure of a global models but by disaggregation of one or several blocks upon obligatory preservation, let it be even in a most aggregated mode, with the rest of the global model [11, p. 20].

A special place among economic models belongs to the project "The Future of the World Economy" run under the guidance of the Novel Laureate V. Leontief [37]. The project is based on the method of intersectorial modeling known as input-output production analysis. For each of 15 world regions, 45 sectors of economy are modeled, including 22 industry and construction sectors, 4 agriculture sectors, and sectors related to trade, services, transport, and communication. Environmental pollution is modeled with account for 8 types of pollutants and 5 waste treatment methods. The model, which comprises 2500 equations, envisions 8 scenarios of global economy development in the period of 1980–2000 and is aimed at designing the economic development of the world.

The system LINK developed by the Nobel Laureate L. Klein [12] is an agglomeration of independently designed models of countries and regions of the World, which are combined via the international trade sub-model to form a Global Model. The system includes the models of the economies of the USA (207 equations), Canada (183 equations), France (32 equations), United Kingdom (226 equations) etc. – more than 20 regional models. The system is designed to make economic prognoses for up to three years ahead.

Of special interest is the model "The Future of Civilization and the Strategy of Civilizational Partnership", which has been developed under the aegis of Pitirim Sorokin-Nikolai Kondratyev International Institute in Russia and Kazakhstan by a team of researchers [1]. The forecasting technique in this case is based on additive logistic and cyclic models. Their parameters are determined by applying the least square method to time series related to the period of 1950–2006. The model has yielded a prognosis of advances in technologies and labor force balances in 12 local civilization and countries therein. However, the model is, basically, a statistical one and thus may be regarded as fully workable only *a posteriori*, so as other similar models. The modeled prognoses for up to the year 2050 may be valid only as far as the economic situations of 1950–2007, which were used for learning, may be recapitulated.

Models of regional development

The first modeling-based reports presented to the Club of Rome, «especially "Limits to Growth" with its worldwide resonance, gave a strong impetus to global modeling efforts in 1970ies. However, the more models were being developed, the less public attention they were attracting, and thus interest to them was becoming increasingly limited to a narrow group of specialists. The Club of Rome gave heed to the reprimands related to its preoccupation with techniques and started searching for broader approaches to global problems»[5]. This resulted in a sort of inversion of the different phases of global studies: systems analysis was replaced with system approach, and mathematical models were replaced with verbal reasoning.

However, such inversions do not last for long. "Narrow" specialists went on to develop global and regional models.

The first spatially structured regional model was, perhaps, another recapitulation of World2 applied to a study of interactions of "rich" and "poor" regions of Switzerland [43].

The regional model of the system "USSR–Cities–Villages–Leningrad", which was developed at Leningrad (currently Saint-Petersburg) University, is a symbiosis of World2 and World3 models [26, 27]. Tabulated relationships between demographic, economic, and environmental processes accounted for in the models were obtained from State Statistical Records of the USSR. The model implemented the principle of priority of upper hierarchical levels over lower ones, i.e., a country can influence its regions being independent from their influences.

More detailed descriptions of the above and other important pointwise and spatially compartmentalized models may be found in the monograph "Global Models of Humankind Development" by G.V. Osipov and V.A. Lisichkin [14]. In a useful review [44] the methodology of studying of what its authors name anthropocene is discussed, and a list of publications that address socioeconomic systems modelling is presented.

1.4. Restoring the finite natural resources

A number of papers published in the USSR and the Russian Federation addressed the issue of searching for algorithms that can lead global models to stationary conditions

[5] http://www.ihst.ru/~biosphere/Mag_3/gvishiani.htm

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(global equilibrium). The authors did not construct novel models but rather modified the models World2 and World3. The studies were based on the idea of reallocation of world capital investment investment in favor of the industrial restoration of spent unrenewable natural resources and the generation of useful products from pollutants. This was assumed as implementable worldwide during the nearest 30–50 years of model time, i.e. the period predicted by the developers of World2 and World3 to precede the global catastrophe.

The first such modification of World2 was suggested by V.A. Yegorov et al. [11]. The authors introduced to the right parts of the equations that capture the nonrenewable resources and environmental pollution the additive control members (KU_R^0/C_R^0) and (KU_Z^0/C_Z^0), and to the right part of the equation that captures the agricultural capital investment they introduced the multiplier (1-U_X^0). The parameters U_R^0, U_Z^0, U_X^0 are the shares of *capital investment K* that are allocated to restoration of natural resources, mitigation of environmental pollution, and management of agriculture, respectively. C_R^0= 0,3 and C_Z^0= 0,4 are the amounts of capital investment units (CU) that are required to restore one unit of resources and eliminate one unit of pollution. The controls for U_R^0, U_Z^0 and U_X^0 are functions of time. After they have been defined, it is possible to reallocate capital investment K between traditional and novel industrial sectors. To define the control functions, the optimum control problem have to be solved by defining a criterion and finding a function that maximizes the criterion. This variational problem was solved for the period from 1975 to 2100, and the solution suggested that it is possible to prevent a global catastrophe in the XXI century. For that, the capital investment of enterprises intended for restoration of resources and prevention of pollution must increase annually to become in the XXI century comparable to the capital investment of all industries "…that is, human labor intended for prevention of the economic crisis must be quantitatively comparable with human labor in all other fields of human activities" [11, p. 140]. The questions however remains how long can the restoration of resources last after the year 2100. The resources are finite all over the geographic envelope and, according to World2 algorithm, are consumed for production and cannot all be restored completely.

A thorough modification of the global model World2 and World3 was performed by a research group led by V.M. Matrosov. In addition to the traditional World2 components, the modification included new variables, such as technological progress, political tension, and total plant biomass, which influence capital investment reallocation in favor of restoration of the nonrenewable resources and correction of agricultural capital investment as it interpreted by the V.N. Yegorov. No optimization procedures were used in the model. Nevertheless, upon the use of only the functional relations between model components, stable stationary conditions of GSES were reached. The algorithm of the model is advantageous in taking account for causal relationships between technological progress, political tension and ecological variables and is disadvantageous in adopting the hypothesis that it is possible, at least in the nearest decades, to restore the nonrenewable resources, except for rare metals.

One more World2 modification, perhaps the most interesting one, is designed by S.A. Makhov [17]. In this model, so as in Yegorov's one, a part of capital investment is allocated to restoration of resources and to prevention of pollution; however, no controls for agriculture are introduced. The controls U_R and U_Z are not functions of time. To define them, World2 is supplemented with two equations:

$$\frac{\mathrm{d}U_R}{\mathrm{d}t} = \frac{G_R(R_R) - U_R}{T_{UR}}, \quad (4)$$

and

$$\frac{\mathrm{d}U_z}{\mathrm{d}t} = \frac{G_z(Z_s) - U_z}{T_{UZ}}, \quad (5)$$

where: G_R and G_Z are investments in industries for restoration of nonrenewable resources and for removal of pollutants from the environment; R_R and Z_s are the shares of the remaining resources and of the specific pollution (these are World2 variables); and T_{UR} and T_{UZ} are the periods of the losses of the capital investment of the respective industrial sectors.

For G_R (R_R) and $G_Z(Z_s)$, functions have been found that guarantee stationary conditions of GSES, and their parameters have been determined. In particular, it has been established that G_R (R_R) must be hyperbolic, whereas $G_Z(Z_s)$ must be linear. The equations of the modified World2 model were integrated on the period between the years 1900 and 2200. It was found that transition to stationarity must occur before the year 2150. It has been also determined that "good" stationary solutions are possible upon G_Z= 0, i.e. the constancy of pollution level. Possibilities for such stationary regimens have been shown to exist only if the industries designed for restoration of resources and elimination of pollution re launched no later than in 2030. Regretfully, such bright prospects are based, once again, on the assumption that the capital investment of the newly developed industries in the XXI century is comparable with that of the traditional industries.

2. Developmental cycles are typical for the evolution of civilization

2.1. Cyclic phenomena in population ecology

From the standpoint of population ecology, the apocalypse predicted by Wold2 and World3 models does not seem fatal. The rational for this assertion is as follows. The two known types of population growth are characterized with J- and S-like growth curves [20]. With a J-like curve, a population first increases exponentially, and then, due to negative feedback from the environment, the growth discontinues. The population exhausts available resources. Proliferation ceases and mortality increases.

A decrease in population size is followed by relaxation oscillations (Fig. 2A$_1$, A$_2$). Many species featuring complex and lengthy life cycles exhibit S-like curves for changes in the sizes of their populations. A population first grows, and then its size undergoes damped oscillations near some equilibrium level (Fig. 2B$_2$, B$_3$). The level is the maximum corresponding to the carrying capacity of the environment.

Two causes of oscillations of animal populations are envisioned [20]. The first cause is that nutrients and other vital resources may have accumulated before the start of the S-growth of a population. For a time, organisms have sufficient resources for overshooting the maximum population size that the environment can support constantly. The second cause relates to a lag between population size increase under favorable conditions and the negative feedback from the environment, which develops when overpopulation is achieved. The lag, which is roughly equivalent to the maturation period of the organisms, makes it possible for the population to exceed the maximum size sustainable by the environment.

The same factors must be at work when it comes to the humankind. As a component of fauna, the human race cannot but obey the laws valid for the whole biosphere. Fossil fuels, ores and other resources, which are consumed by humans due to technological advances, have been accumulating over geological epochs and today sustain human population size above the level that the environment can bear on a constant basis.

According to E.P. Odum's opinion on this matter (see [20]), the Mankind has two options. The first one is to allow the unlimited growth of population until its density will exceed limits determined by the availability of food and other resources. After that, most humans will die or fall into misery until population density will decrease (or limits increase, if possible). This is the time when more population bursts may occur if no control measures will be taken (Fig. 3). The other options is to acknowledge that overpopulation is the problem. By taking responsibility for it, humans will be able take appropriate measures, such as global birth control, limited land use, environmental protection and restoration, and refusal from stimuli for economic growth.

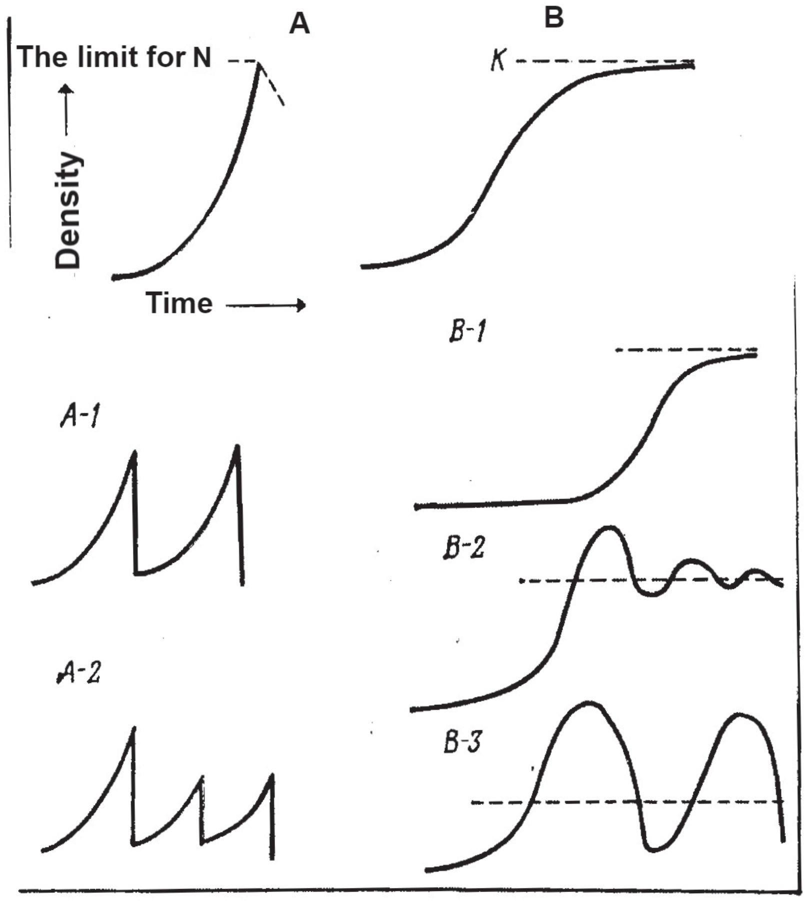

Fig. 2. Examples of population growth curves [20]. A – Exponential growth: the J-curve and variations thereof. B – Logistic growth: the S-curve and variations thereof

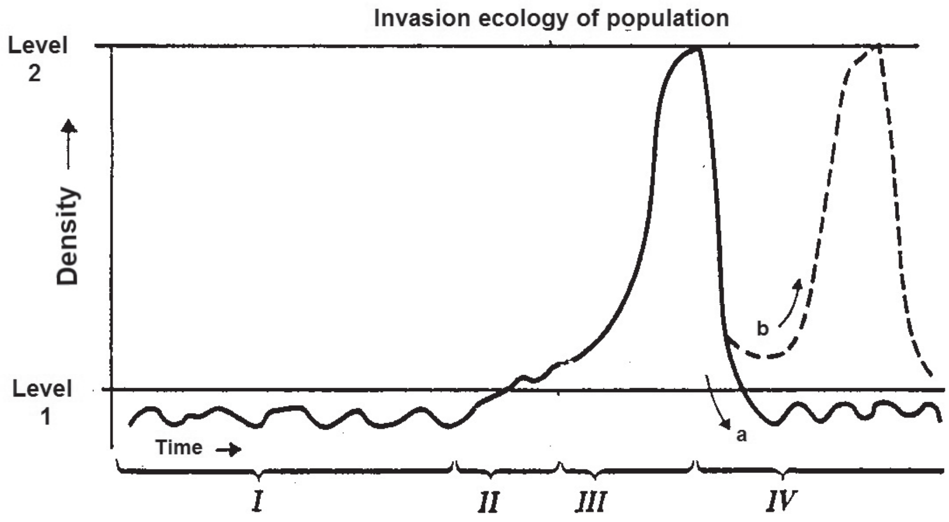

Fig. 3. Changes in population size of the Australian psyllid *Cardiaspina albitextura*, which feeds on the eucalyptus *Eucalyptus blakelyi* [20]. Normally, population density is limited by the combination of factors, such as weather, predators, parasites, which may be either dependent on or independent from the density, and thus is stabilized at a relative low level. Occasionally, the population evades the natural regulation and exhibits overshoots to higher density levels

2.2. Estimating the critical size of global human population

The estimate is based on the biospheric concept of the development of GSES. The concept put forward by V.G. Gorshkov and K. Ya. Kontratyev [8, 13] is derived from the theory of natural biological regulation. The authors believe that the biosphere is able to remain stable, i.e., to compensate for any disturbances caused by human activities as far as the consumption of the biotic output by humans is within ca. 1%. The rest 99% of the output is required to stabilize the environment. The authors estimate that the 1% threshold was exceeded early in the XX century. In the recent decades, humans directly use 6-8% of the biotic output. Moreover, 30% to 32% of the annual output of the "intact" biota is consumed by humans indirectly, i.e. by replacing natural biocenosises with agrobiocenosises in combination with urbanization, desertification and so forth [13].

The critical size of global human population may be calculated based on the estimates of the primary output of the biosphere and of the nutritional norm of human population with account for the Lindeman-Odum "10% law".

Several estimates of the primary output of the biosphere have been made. According to E. Odum [20], the productivity of the terrestrial biomes is $57.4 \cdot 10^{16}$ kcal/year, and of the marine biomes, $43.6 \cdot 10^{16}$ kcal/year. Assuming that the energy value of terrestrial plants is 4.5 kcal per 1 g of dry matter, the annual output of the terrestrial biomes may be estimated as amounting to $127 \cdot 10^9$ tons of dry matter, and of the marine biomes, to $97 \cdot 10^9$ tons. Tentative estimates of annual net terrestrial and marine outputs are $63 \cdot 10^9$ and $48 \cdot 10^9$ tons of dry matter, respectively.

According to Whittaker and Likens (see [5]), the net annual primary output of the biosphere is $164 \cdot 10^9$ tons of dry organic matter. R.H. Whittaker's estimate is $170 \cdot 10^9$ tons, including $115 \cdot 10^9$ and $55 \cdot 10^9$ tons attributed to the terrestrial and marine ecosystems respectively (see [23]). F. Ramade [23] thinks that these estimates are inflated. He prefers the ones suggested by P. Duvigneaud: $83 \cdot 10^9$ for the entire biosphere, $53 \cdot 10^9$ for terrestrial biomes and $30 \cdot 10^9$ for oceans, which is close to Odum's estimates.

Let us now apply the Lindeman-Odum law to the trophic chain "primary producers – herbivores – humans". The law posits that the output of a trophic chain link is 10% of its input. The rest 90% is dissipated by ecological metabolism. The primary annual output amounting to $53 \cdot 10^9$ tons of dry matter is equivalent to $2.385 \cdot 10^{17}$ kcal/year. With account for the above assumption, the 1% tolerable disturbance threshold of the biosphere is $2.385 \cdot 10^{15}$ kcal/year.

An equivalent of the annual nutritional minimum for a human is 230 kg of wheat. This corresponds to 770000 kcal/year (2110 kcal/day). Nutritional norms depend on human age and occupation, that is (kcal/day): 700-900 for infants, 1000-1300 for children aged 1 to 3 years, 1500–1900 for children aged 3 to 8 years, 2000–2400 for children aged 8 to 10 years, 2500–3500 for adolescents, 3000 for sedentary workers, 3500 for machine operators, and 4000–5000 for people employed in hard physical work. With account for typical proportions of the above population groups, 3800 kcal/day (1387000 kcal/year) may be assumed as an average.

The critical population size sustainable by the biosphere is defined as the ratio of 1% of its primary output and the average human nutritional norm. This will make 1.73 billion people.

2.3. The global energy resource potential

The energy resource potential, by analogy with the land resource potential, is a component of the natural resource potential. It may be regarded as the totality of energy resources available at given level of technologies and socioeconomic relationships. The potential includes both renewable and nonrenewable resources and increases in the course of the development of GSES.

During the Paleolithic, humans obtained energy from the renewable resources of the intact biosphere by hunting, foraging and plants burning of. The size of human population in those times was 200–300 thousand. Fire was used for cooking and rewarming (about 40% of total energy consumption); however, this energy could not compensate for expenses required to maintain temperature homeostasis [18].

In the Neolithic and Bronze Ages, the energy turnover of human GSES significantly increased. By this time, the traditional rural GSES developed based on agriculture and cattle breeding. About 10 thousand years ago, human population reached 5 million people.

Later on, in slave-owning and feudal societies, wind and water energy resources were harnessed. By the time of formation of the Rome Empire, human population reached 150 million, and by 1650, 500 million people [23].

In the Industrial Era, when steam and gas engines, turbines, and electric generators and motors were invented, energy supplies for human GSES originated mainly from fossil hydrocarbons. The rate of their extraction increased. In line with increasing energy availability, human population increased exponentially to reach 7.3 billion people by January 1, 2016.

In the Postindustrial Era, controlled thermonuclear power is expected to supplement nuclear power and thus to solve forever the problem of energy supplies. The question arises what law will determine changes in human population size under such conditions.

The development of productive forces is limited by natural resources according to the law of decreasing resource availability. Indeed, for a certain type of

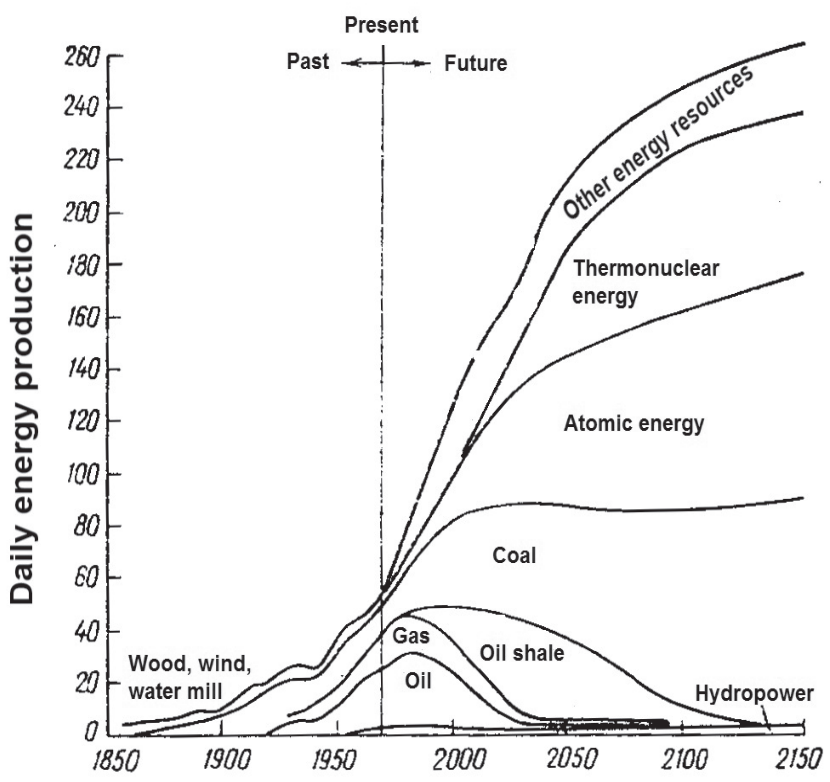

Fig. 4. Exponential growth of energy production as a sum of logistic curves related to different sources [2]. The scale on the left shows dimensionless orders of magnitude

socioeconomic system equipped with a given repertoire of technologies natural resources become increasingly costly in terms of energy spent to obtain them from dwindling available stores [23]. Productive forces develop gradually until resources become exhausted. This is followed by a crisis, which becomes resolved due to revolutionary changes in productive forces brought about by scientific and industrial revolutions. The verbal models of limited economic growth are usually illustrated with an S-like logistic curve, which shows how the initial exponential growth gradually transforms into an asymptotic approach to a limit featured by a given socioeconomic system.

E.A. Arab-Ogly suggested a series of logistic models of power availability, which were used to construct a verbal model of exponentially growing power availability [2, p. 211]. This approach has three shortcomings.

The first shortcoming is that the logistic models of changes in energy resource potentials related to renewable and renewable resources are treated on equal terms (Fig. 4).

In his polemics with the authors of World2 and World3, E.A. Arab-Ogly declared the following: "One needs no special mathematical imagination to see that the exponential growth of aggregated parameters can last much longer than the separate components of the resulting aggregate can grow. An exponent is formed in such a case by a series of logistic curves. This may be confirmed, e.g., by that the exponential growth of energy production lasting far beyond foreseeable future is formed by a sequential involvement of the mechanical energy of humans and animals, wind energy, water energy, thermal energy obtained by wood, coal, oil and gas combustion, nuclear energy, and thermonuclear energy. This is true even more with regard to such economic parameters as gross national product, per capita national product, working efficiency etc." [2, p. 210-211].

However, the chemical energy of life is derived by photosynthesis from the sunlight energy, then is transmitted via food chains up to humans and is assimilated and dissipated by ecological metabolism. The chemical energy of food is what sustains human activities at all of the stages of the development of the humankind. This energy is limited by the productivity of the biosphere. World2 and Wold3 models take account for this important aspect of life. They treat separately the energy of food and the nonrenewable resources consumed by industry.

The second shortcoming is underestimation of shale oil stores and overestimation of coal stores. The logistic curve attributed to coal should be attributable to shale oil and vice versa.

The third shortcoming of the model of the exponential growth of power availability is that the use of thermonuclear power refutes, albeit in an indirect way, the law of decrease in the potential of natural resources. For the sake of justice, it should be mentioned however that in Fig. 4 its author timidly bends the energetic exponent towards a logistic curve. Another Sun cannot be ignited on the planet Earth.

One more remark relates to the idea of restoration of nonrenewable natural resources as it is realized in World2 and World3. The authors of the idea ignore the fact that the resources include the material and the energetic components. To recover secondary raw materials, energy is consumed. The nonrenewable fuel resources include hydrocarbons, which store the chemical energy generated by photosynthesis and assimilated by consumer organisms over the past geological epochs, whereas the nuclear fuel is a sort of ash of long burnt-out stars where light atoms collisions formed the atoms of uranium, while the hydrogen fuel, the oldest of fuels, is a sort of ash of the Big Bang (according to G.A. Gamov).

According to one of formulations of the Second Law of Thermodynamics, energy transformation processes can be spontaneous only upon energy transformation from its concentrated to dissipated forms. Fossil fuels feature low entropy and "high-quality" energy, which is suitable for being transformed into useful work. Fuel combustion is a spontaneous process associated with dissipation of energy and reduction of its "quality". According to the fundamental asymmetry of Nature, the quality of energy cannot be transformed from low to high. Therefore, fossil fuel stores cannot be restored. An objective of civilization is to find means for more efficient management of high-quality energy that is to decrease entropy production.

2.4. The initial reserves of resources in the models World2 and World2-MC

World2 algorithm may be used to confirm E. Odum's hypothesis that civilization may develop in cycles. The algorithm has been published [32], and its implementation using programming DYNAMO language facilitated its implementation in MathCad environment [29]. The latter implementation will be called World2-MC hereinafter. It was compared with the original World2 (Fig. 1) by solving the same problems within the 1900–2100 interval. The solutions were identical.

In World2, nonrenewable fuel and non-fuel mineral resources are not distinguished, and their initial reserves R_0 are defined in relative terms. The unit of resources (resource unit, RU) is assumed to amount to the annual resource consumption in the basal year 1970. It is assumed that at the basal annual consumption the resources are sufficient for 250 years. It remains unclear, however, what method was used to make an integral assessment of numerous non-fuel resources, such as common and rare metals, agrochemical and chemical raw materials, construction materials etc.

The uncertainty of the integral estimate of non-fuel resources and the primary importance of combustible fossils as energy sources are arguments in favor of a revision of the basal condition $R_0 = 9 \cdot 10^{11}$ RU adopted in World2.

In the basal World2-MC scenarios, R_0 is defined with account for world resources of oil, gas and coal all lumped under the term "traditional fuel and energy resources". Their reserves are well assessed and their estimates, which are periodically revised, are expressed with CI units, i.e. Joules. Besides that, the possibility to increase fuel resources with promising sources, such as shale, bituminous sand, and nuclear and thermonuclear energy, is stipulated. To preserve links between World2 and World2-MC, let us still regard the year 1970 as basal, and resource consumption in this year as resource unit (RU). The numerical estimates of RU are derived from plots shown in Figs. 5 and 6. The plots were also used World2-MC validation.

In devising the scenarios of the development of GSES, the algorithm of calculating the period of full exhaustion of fuel resources is of primary importance. The algorithm is as the following. The resources "oil", "oil + gas = mobile hydrocarbons", "mobile hydrocarbons + coal = traditional fuel resources", "traditional fuel resources + shale oil = hydrocarbon fuel", and "traditional fuel resources + nuclear and thermonuclear energy = future fuel resources" are taken into account consecutively. The terms R_m and R_n, V_m and V_n, and τ_m and τ_n designate reserves, consumption rates, and exhaustion periods of the m-th and n-th resource respectively; $R\delta n$ is the amount of the n-th resource, which is consumed during the time of exhaustion of the m-th resource; $R\Delta n$ is the residue of the n-th resource left after the exhaustion of the m-th resource; V_Σ is the rate of consumption of the n-th resource after the exhaustion of the m-th resource; and τ_s is the period of exhaustion of the n-th resource after the exhaustion of the m-th resource. With this notation:

$$\begin{aligned} &\tau_m = R_m / V_m \\ &R_{\delta n} = V_n \times \tau_m \\ &R_{\Delta n} = R_n - R_{\delta n} \\ &V_\Sigma = V_{m} + V_n \\ &\tau_s = R_{\Delta n} / V_\Sigma \\ &\tau_n = \tau_m + \tau_s \end{aligned} \quad (6)$$

Now let us designate the initial conditions for the nonrenewable resources in the models World2 and World2-MC as $R_0 = 9 \cdot 10^{11}$ RU and R_0^* and as $\tau_m = 250$ years and τ_n^* (the periods of exhaustion of the resources in the respective models), respectively. R_0^* is found by solving the proportion

$$R_0 / R_0^* = \tau_m / \tau_n^* . \quad (7)$$

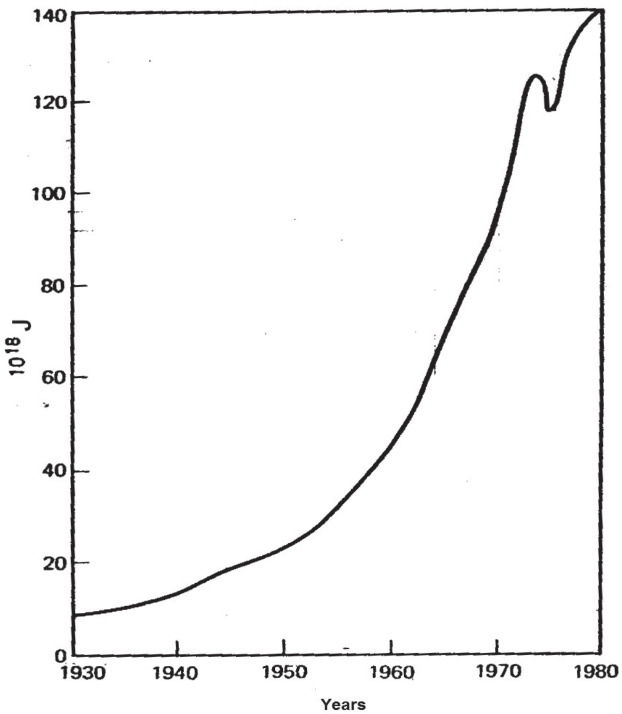

Fig. 5. Global oil production (according to UN and US Bureau of Mines) [31]. The calculated fuel efficiency is $9 \cdot 10^9$ J/barrel

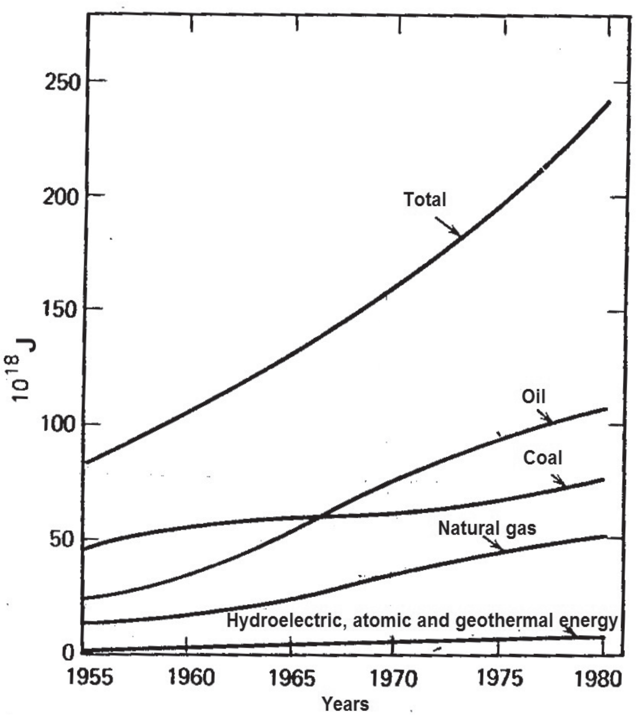

Fig. 6. Global consumption of different energy sources (according to UN) [31]

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An estimate of recoverable oil and gas resources, which is one of the most reliable a close by its time to the basal year 1970, was published in the proceedings of World Energy Conference held in 1980 (see [31]). Assuming that the caloric value of oil is 44 MJ/kg, of gas is 40.8 MJ/m^3, and of coal is 29.4 MJ/kg, oil reserves $R_{1980}^{(oil)}$ are equivalent to $1.5 \cdot 10^{22}$ J; gas reserves $R_{1980}^{(gas)}$ to $1.1 \cdot 10^{22}$ J, and coal reserves $R_{1980}^{(coal)}$ to $21 \cdot 10^{22}$ J.

The estimates corresponding to the year 1900 may be obtained by the integration of the plot of oil recovery (Fig. 5) over the interval from 1930 to 1980 years, and of that of gas and coal recovery (Fig. 6) over the interval from 1955 to 1980 years. This will make $\Delta R^{(oil)} = 0.25 \cdot 10^{22}$ J, $\Delta R^{(gas)} = 0.07 \cdot 10^{22}$ J, and $\Delta R^{(coal)} = 0.23 \cdot 10^{22}$ J. Thus, the world reserves of mobile hydrocarbons are estimated as $R_{1900}^{(oil)} \approx 1.75 \cdot 10^{22}$ J and $R_{1900}^{(gas)} \approx 1.2 \cdot 10^{22}$ J.

Upon the rates of consumption of oil and gas in 1970 estimated as $0.95 \cdot 10^{20}$ J/year and $0.35 \cdot 10^{20}$ J/year respectively, their reserves will be sufficient for consumption during 184 and 343 years respectively. Upon the assumption that gas will be consumed at the same rate when it will replace oil after the exhaustion of oil reserves, the Eqs. (6) and (7) suggest that mobile hydrocarbons will be exhausted in 227 years and that $R_0^* = 11.1 \cdot 10^{11}$ RU. This estimate is close to $9 \cdot 10^{11}$ RU assumed in World2.

It was estimated at the World Energy Conference that recoverable coal reserves amount to 13800 billion tons. This figure is likely inflated. By P. Averitt's estimate, recoverable coal reserves may be as high as 7135 billion tons, which is equivalent to $21 \cdot 10^{22}$ J (see [31, p. 59]). The recoverable reserves are assumed to be those present in rows that are not less than 30 cm thick and not more than 2 km deep, with account for that it is impossible to recover all coal and that 50% recovery is rated as good [31]. Upon coal consumption rate $0.6 \cdot 10^{20}$ J in 1970, coal reserves will be sufficient for 3500 years. Upon the assumptions that coal will replace oil and gas after their reserves will be exhausted, and that the total rate of consumption of the traditional fuels will not change, all fuels will be exhausted, according to Eqs. (6) and (7), in 1034 years, and R_0^* is equivalent to $37.2 \cdot 10^{11}$ RU. Thus, this initial assumption of World2 is 4.16-fold understated.

The reserves of oil, gas and coal in 2014 amounted, according to BP Statistical Review of World Energy 2015, to 239.8 billion tons, 187.1 trillion m^3, and 891.5 billion tons respectively. These values are equivalent to $L_{2014}^{(oil)} = 1.06 \cdot 10^{22}$ J, $L_{2014}^{(gas)} = 0.76 \cdot 10^{22}$ J, and $L_{2014}^{(coal)} = 26.2 \cdot 10^{22}$ J.

With the rates of resource consumption assumes to be the same as in 1970, it may be estimated that $= 0.65 \cdot 10^{22}$ J, $R_{2014}^{(gas)} = 0.6 \cdot 10^{22}$ J, $R_{2014}^{(coal)} = 25.41 \cdot 10^{22}$ J (the initial reserves being $R_{1900}^{(oil)} = 1.75 \cdot 10^{22}$ J, $R_{1900}^{(gas)} = 1.2 \cdot 10^{22}$ J, and $R_{1900}^{(coal)} = 26 \cdot 10^{22}$ J).

Thus, the biases $\Delta = L\text{-}R$ are estimated as $\Delta^{(oil)} = 0.41 \cdot 10^{22}$ J and $\Delta^{(gas)} = 0.16 \cdot 10^{22}$ J. Positive biases may be caused by new hydrocarbon deposits discovered after 1980, such the Shtokman Field. In any case, such bia–ses only increase the estimates of R_0^*. Coal bias was not calculated because of tenfold discrepancies between the estimates of coal reserves. The reasons of the discrepancies may include different ideas about coal production efficiency and uncertainties concerning the fuel efficiency of coal, which is different in brown coal (15 MJ/kg), black coal (22 MJ/kg), and anthracite (29 MJ/kg).

Notably, fossil fuels are not limited to mobile hydrocarbons (Table 1)

Table. 1

Potential fossil fuel reserves [31]

Combustible fossils	**Total reserves (10^{22} J)**	**Recoverable reserves (10^{22} J)**
Coal	42	21
Oil and gas	2.1	2.6
Dead oil	2.5	0–?
Unstripped oil (bitumen sand)	5.0	0.5–2.5
Nontraditional natural gas	10+	0.07–?
Combustible shale (above 40 L/ton)	200	1.0–?
Combustible shale (below 40 L/ton)	10000	?
Global oil and gas consumption in 1983	*0.018*	
Global energy consumption in 1983	*0.03*	

2.5. Model scenarios of the development of GSES upon expanding the energy resource potential with traditional fuel resources

For World2-MC scenarios realization, the same initial conditions as for World2 are stipulated except for the nonrenewable resources: $P_0 = 1.65 \cdot 10^9$ people; $K_0 = 0{,}4 \cdot 10^9$ CU (it is assumed that, in 1900 compared with 1970, four times less per capita capital investment was available); $X_0 = 0.2$; R_0^* depends of the scenario chosen; and $Z_0 = 0.2 \cdot 10^9$ PU (it assumed that, in 1990 compared with 1970, per capita pollution was eight time lower). The subscript * at R_0 will be omitted hereinafter.

Let us first consider four scenarios featuring fixed values of the global energy resource potential. The first scenario will be associated with the current estimates of mobile hydrocarbon reserves, which at the current rate of their consumption will be exhausted in 250 years, i.e. by 2150. Their reserves are assumed as 100%. The starting condition is $R_0 = 900 \cdot 10^9$ RU.

The second scenario models the prospect of expanding of energy resource potential due to oil and gas resources found on the shelves and the continental slopes of the World Ocean. Mobile hydrocarbon reserves are assumed to increase to 150% thus making them sufficient for 375 years, that is till the year 2275, and the initial condition is $R_0 = 1350 \cdot 10^9$ RU.

The third scenario models the situation of using coal to substitute for the exhausted mobile hydrocarbon recourses; however, coal production is limited by the efficiency of available technologies. Fuel reserves are assumed to increase to 300% in this case, making them sufficient for 700 years, i.e. till the year 2600; and the initial condition is $R_0 = 2700 \cdot 10^9$ RU.

In the fourth scenario, requirements to the threshold efficiency of coal production are reduced to make coal stores sufficient for 1000 years, i.e. till the year 2900; and the initial condition is $R_0 = 3600 \cdot 10^9$ RU.

With regard to the above scenarios, additional comments are required.

1. According to World2, «Natural resources are a system level. The only rate of flow is the outgoing usage rate. As defined here, natural resources include only those nonreplacable materials in the earth. They do not include wood and any products that can be grown and replenished, for the latter are classed as part of the agricultural sector» [32].

However, the fuel resources of GSES are the sum R of renewable and nonrenewable resources. Therefore, the equation for the resources should be:

$$\frac{dR}{dt} = V^+ - V^-,$$

where: V^+ is the primary productivity of terrestrial systems (the rate of assimilation of solar energy by terrestrial plants); and V^- is the rate of consumption of the nonrenewable fuel resources

The annual productivity of the terrestrial ecosystems is estimated as $53 \cdot 10^9$ tons of dry matter, which is equivalent to 10^{19} J/year. The rate of consumption of the traditional nonrenewable fuel resources in the reference year 1970 was $1.9 \cdot 10^{20}$ J/year. This is one order of magnitude higher that the productivity of the terrestrial ecosystems. This difference in scales makes it possible to simplify the above resource equation:

$$\frac{dR}{dt} \approx -V^-.$$

In this way, the productivity of the terrestrial ecosystem is adopted by default (implicitly) in World2-MC. This approach is useful for explaining the stationary flux of population when resources and population size are constant, and GSES exists at the expense of consumption of the renewable resources, the population size being less than 1.5 billion people.

2. People obtain foods from agricultural lands, which are withdrawn from the native biosphere and feature the productivity estimated to amount to $9.1 \cdot 10^9$ tons/year [24]. This estimate is 5.8 times less than the productivity of the terrestrial ecosystems. Therefore, the equivalence of agricultural production and the renewable resources of the terrestrial ecosystems, which is assumed in World2, is false. In World2-MC, the agricultural production is but an apparent part of renewable resources accounted for by default.

Modelling based on the above premises (Fig. 7 and 8; Table 2) suggest that an expansion of the energy resource potential in GSES is associated with oscillations of all components of the potential. The number of oscillations increases as the amount of available resources increases. Upon increasing the resources to 150% vs. the norm adopted in World2 ($9\text{-}10^{11}$ RU), two oscillations of population size emerge. With 300%, there are three oscillations, and with 400%, there are four. The amplitudes of the oscillations are 2 to 5 billion people. The time of the peak of the first oscillation will not shift significantly with increasing the potential (from 2018 to 2033), and that of the second and third oscillation will shift within the limits of 33 and 45 years respectively.

Notably, the numbers of the oscillations of environmental pollution and of the share of the agricultural capital investment are always one unity less than the number of oscillations of human population.

Nonrenewable natural resources do not limit population growth, which is limited by agricultural production and environmental pollution. These two factors act perpetually over all time intervals when population decreases. The maximums and minimums of pollution and agricultural capital investment a delayed by one or two decades relative to those of population.

The capital investment of economy gradually decrease in all scenarios and correlate with decreased reserves of nonrenewable resources. Small oscillations of capital investment are phase-shifted and thus lag behind the oscillations of population. This likely reflects deficits of labor resources during the descending phases of GSES cycles.

In each of the scenarios, the final oscillation of population size is followed by its stabilization, which occurs in 437 years in the scenario with a 150% expansion of the energy resource potential, in 609 years with a 300% expansion, and in 1000 years with a 400% expansion. Stabilized is a level between 1.3 and 1.5 billion people, probably the maximum number of humans sustainable by the natural and socioeconomic environments.

Along with population size, other components of GSES also reach stationary conditions (Table 3).

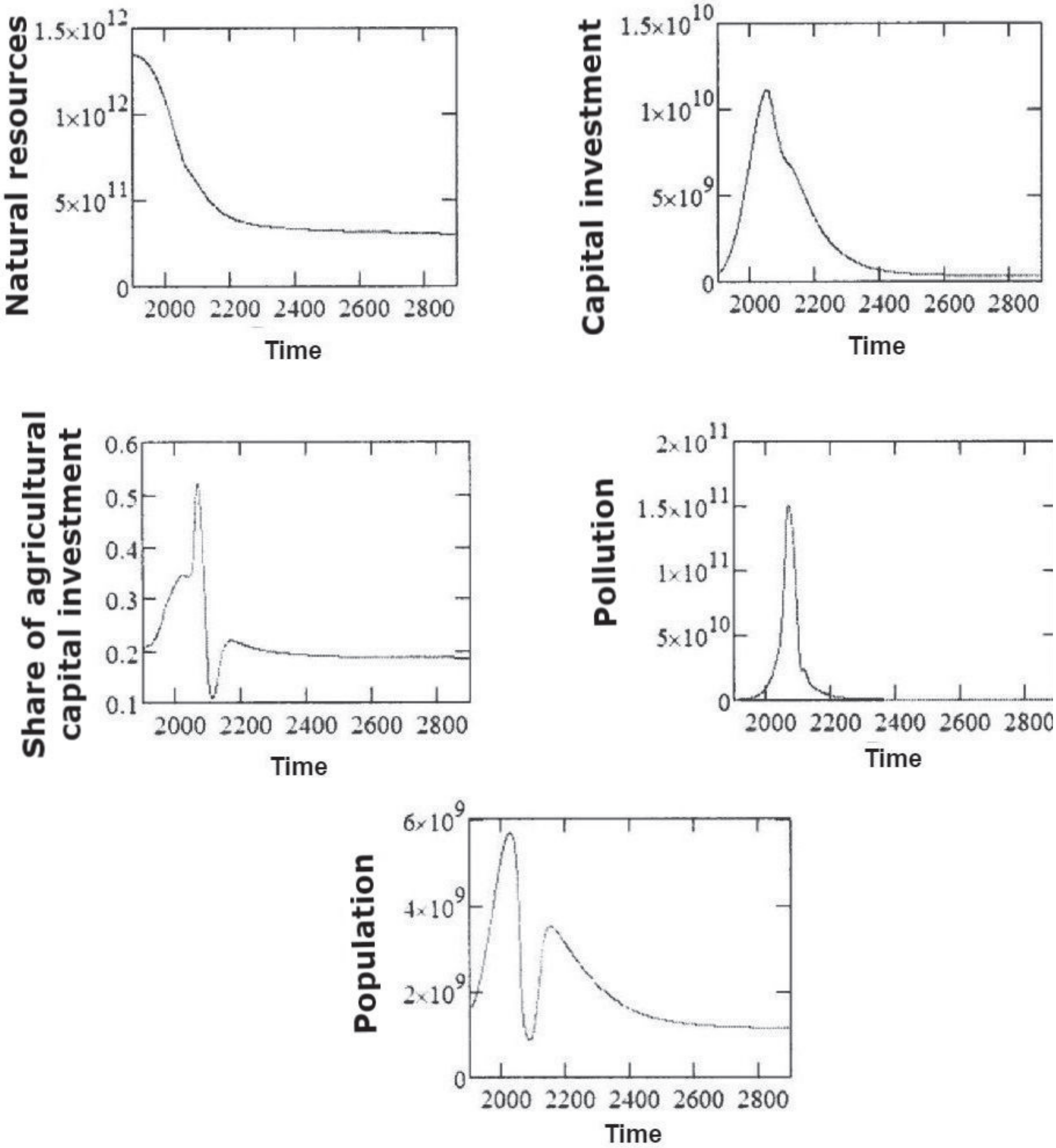

Fig. 7. Time-dependent changes in GSES components modeled with World2-MC at $R = 1350 \cdot 10^9$ RU (the 150% scenario). See text for explanations

The possibility of a cyclic development of GSES followed by a stationary phase has been independently demonstrated in [44] based on very different premises. The authors used the classic Volterra-Lotka model of prey-predator relationships supplemented with interspecies competition between preys. The idea to treat the environment as a prey and the human population as a predator and to use the Volterra model of biological systems comprising producers, consumers and substrates (resources) proved to be fruitful (a similar model was discussed in the monograph by Yu.M. Svirezhev and D.O. Logofet [25, p. 130-169]). The authors of [44] treated the property-related structure of human society, which consists of "rich men" and "common people", by analogy with the species structure of a biological community. Birth and death rates in different strata of a human population were assumed to depend on the allocation of production, which is generated by common people and distributed by rich men. The authors have shown that excessive exploitation of resources and inequality of incomes are the

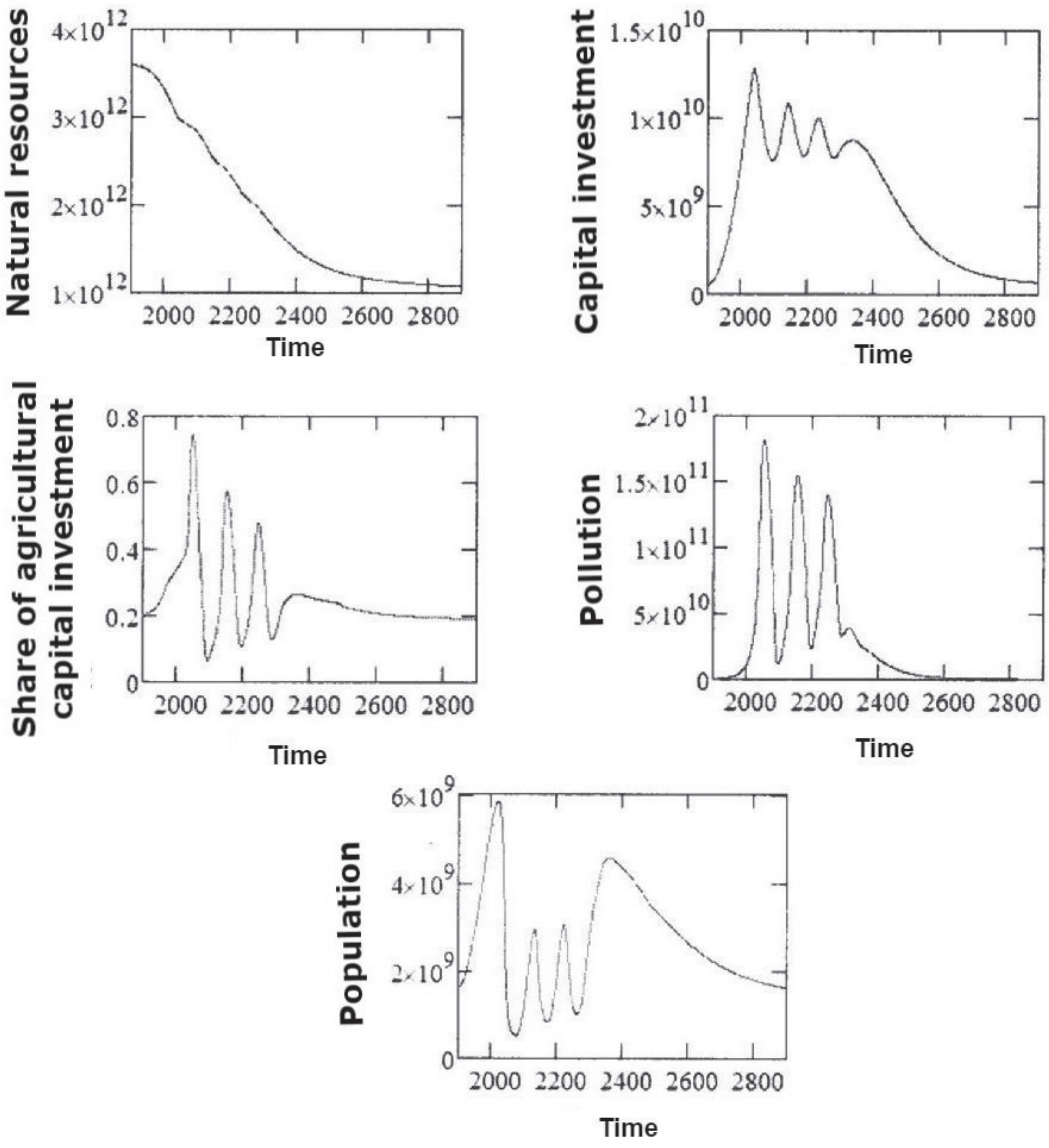

Fig. 8. Time-dependent changes in GSES components modeled with World2-MC at *R* = 3600 · 10⁹ RU (the 400% scenario). See text for explanations

Table 2

The maximums and minimums of global populations and the years of their achievement according to World-2MC scenarios of global development

R, % of the reference value	Year	Population size P · 10^9	
		Min	Max
100	1900 2022 2450	1.65 1.25	5.29
150	1900 2033 2084 2163 2600	1.65 0.87 1.26	5.62 3.54
300	1900 2021 2075 2132 2179 2271 2880	1.65 0.54 0.97 1.3	5.81 3.05 4.43
400	1900 2018 2075 2130 2170 2226 2265 2363 2900	1.65 0.51 0.83 1.01 1.5	5.83 2.95 3.08 4.53

Table. 3

The years of achievement and the levels of stabilization of GSES, according to different World2-MC scenarios [29]

Scenario	Year	Population, billion people	Nonrenewable natural resources	Capital investment	The share of agricultural capital investment	Environmental pollution
150%	2600	1.26	$3.10 \cdot 10^{11}$	$3.23 \cdot 10^{8}$	0.18	$2.77 \cdot 10^{8}$
300%	2880	1.30	$7.58 \cdot 10^{11}$	$4.82 \cdot 10^{8}$	0.18	$3.33 \cdot 10^{8}$
400%	2900*	1.50	$10.8 \cdot 10^{11}$	$6.96 \cdot 10^{8}$	0.19	$4.82 \cdot 10^{8}$

* The system is not stabilized completely on a 1000 years interval

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two independent factors of a series of catastrophic events, and openly declared the necessity to level off incomes and to reduce resource spending.

2.6. Model scenarios of GSES development upon expanding the resource and energy potential due to prospective fuel resources

Shale oil

Currently, shale oil field development is considered as cost-effective if one ton of shale contains not less than 90 liters of oil[6]. World reserves of such shale amount to 650 trillion tons, which makes 26 trillion tons of oil. This is 13 times more than mobile oil reserves. Upon shortage of energy, the cost-effectiveness threshold may be reduced to 40 l/ton [31]. According to 1980 World Energy Conference, the reserves of combustible shale that contain more than 40 l of oil in one ton is equivalent to $200 \cdot 10^{22}$, which is 8.5 times more that may be yielded from world reserves of oil, gas and coal.

The extremely rich combustible shale fields in Estonia may yield 320 l of oil products from 1 ton of raw shale. The development of the fields started in 1915. The annual yield of shale oil was 315 thousand tons. For years, oil and gas were successfully extracted from shale in the USSR and China[7]. Following the World War II, Leningrad was supplied with gas extracted from Estonian shale. Let us assume that shale oil has been being produced starting from the year 1900.

The assumed reserves of fossil hydrocarbons (traditional oil, gas, coal, and shale oil) are equivalent to $223.9 \cdot 10^{22}$ J (Table 1). Let us assume that the calorie value of shale oil is $44 \cdot 10^6$ J/kg, and its production before the exhaustion of the traditional fuels is equal to that in 2013, i.e. $1.1 \cdot 10^9$ barrels/year, which is equivalent to $6.6 \cdot 10^{18}$ J/year. Upon the assumption that shale oil will substitute for the traditional fuels after their reserves will have been exhausted and that shale oil will be produced at a rate equivalent to $1.97 \cdot 10^{20}$ J/year, the time of exhaustion of all carbohydrates determined using the algorithm defined by Eqs. (6, 7) will be 10117 years. The proportion (7) suggests that $R_0 = 36.4 \cdot 10^{12}$ RU. Upon the assumption that cost-effective oil production from shale having oil content above 40 L/ton makes 28% of world reserves, the estimate of R_0 will be $8 \cdot 10^{12}$ RU. This is 8.9 times more that the reserves of resources adopted in the World2 model. The time of exhaustion of resources according to the present scenario is 2220 years, i.e., they will be exhausted by the year 4120.

Fig.9 illustrates the realization of GSES development scenario upon the initial reserves of carbohydrate fuels amounting to $8 \cdot 10^{12}$ RU (a 800% scenario). The number of oscillation of population size increase to 15, and of the other components of GSES, to 14. With increasing time, carbohydrate reserves decrease in a piecewise-linear manner and reach a stationary regimen. Capital investment reaches maximum during the second oscillation and then goes through damped oscillations around the main trend, which correlates with the fuels trend.

Environmental pollution will reach maximums during the first oscillations because of rapid growth of capital investment and then will reduce the maximums of population size during the second and third oscillations. To prevent hunger, GSES will have to increase the share of agricultural capital investment up to 0.9 to the total capital investment. The subsequent time trajectories of agricultural capital investment share and of environmental pollution will be analogous to the behavior of “dry friction oscillators”. In the theory of oscillations, such dissipative structures are known as oscillators with perpetual “Coulomb” friction. The role of friction in the present case is played by perpetually decreasing fuel resources and closely associated capital investment, which attract GSES components to equilibrium states.

Maximum population size will reach 5.6 billion people during the first oscillation and decrease to 2 billion during the second one. The latter figure us slightly above the maximum carrying capacity of the biosphere. The subsequent time trajectory of global population size corresponds to a “system of compelling forces”. This term is used in the theory of oscillations to designate systems where a force that is applied to a component compels it from an equilibrium. The role of compelling forces is played in the present case by decreases in environmental pollution and agricultural capital investment share upon a rather high total capital investment.

Global population size during the final oscillation reaches the second high maximum (4 billion people), and the period of the oscillation is the longest (up to 500 years). These anomalies are caused by that environmental pollution and agricultural production reach stationary conditions by that time and do not limit population growth. At the same time, because of the temporal lag of birth rate, population gradually comes a to stationary flux at a level about 1.6 billion people, which is consistent with the tolerable threshold of disturbance of the biosphere.

Thermonuclear energetics

Recent advances in controlled thermonuclear synthesis make reason to consider a scenario of GSES development based on the assumption that energy potential expansion will be brought about by using the thermonuclear energy.

The first cost effective (in terms of the Lawson’s criterion, i.e. the ratio of applied and yielded energy) thermonuclear synthesis has been carried out at Institute of Plasma Physics of the Academy of Science of China using a Tokamak-type reactor EATS.[8] By 2014, the effectiveness

[6] http://vseonefti.ru/neft/slancevaya-neft.html

[7] https://ru.wikipedia.org/wiki/Сланцевая_нефть

[8] https://ru.wikipedia.org/wiki/Управляемый_термоядерный_синтез

This open access translation of the original Russian paper published earlier shall be cited as Sergeev YuN, Kulesh VP.
Cyclic and stationary modes of the development of civilization in global models
Biosfera. 2017;9:13-47. DOI: 10.24855/biosfera.v9i1.322

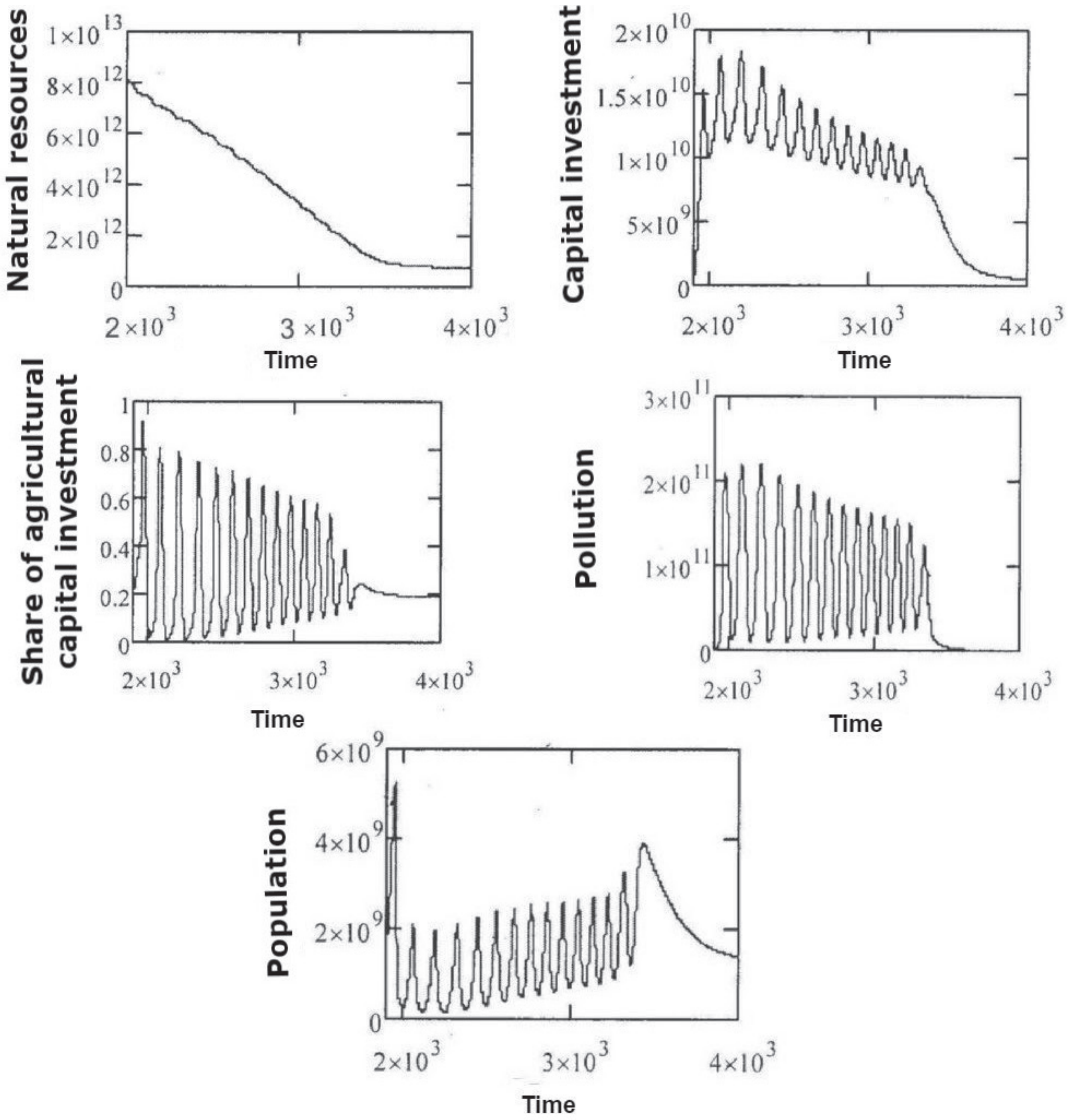

Fig. 9. Time-dependent changes in GSES components modeled with World2-MC at $R = 8 \cdot 10^{12}$ RU (the 800% scenario). See text for explanations

of synthesis reached 1/1.25, and it is planned to increase is up to 1/1.5 in near future.

It is claimed that at Max Planck Plasma Physics Institute (Germany), the experimental thermonuclear reactor "Stellator" stably produced more energy that it was applied.

The construction of the international thermonuclear reactor "ITER" is planned to be completed by 2025. The first industrial thermonuclear reactor is expected to be available in mid-XXI century.

The above makes reasons to assume that the use of thermonuclear energy in global economy will start in 2075 and that the time trajectory of its increase will be close to logistic.

Let us present the logistic model of energy availability R to GSES with the following equation:

$$\frac{dR}{dt} = (\alpha - \gamma R)R, \qquad (8)$$

where: t is time and $a > 0$ and $\gamma > 0$ are the parameters of the linear dependence of r (factor of increase in available energy) on R, i.e.

$r = \alpha - \gamma R$.

Eq. 8 may be solved [25]:

$$R(t) = \frac{\alpha R_0 e^{\alpha t}}{\alpha + \gamma R_0 (e^{\alpha t} - 1)}, \qquad (9)$$

where: R_0 is available energy at $t = 0$.

Available energy has an upper limit:

$$\lim_{t \to \infty} R(t) = \alpha/\gamma. \qquad (10)$$

For the numerical modeling of the scenario of expanding the resource potential due to thermonuclear energy, the model World2-MC is modified with regard to the equation related to the nonrenewable fuels. The equation adopted in World2 [32] is used for the period from 1900 to 2075, and the logistic model (Eq. 8) is used for the subsequent time. The conjunction of the right parts of the equations and of the solutions thereof is performed continuously. For this, the solution by Eq. 9 is not used, and Eq. 8 is transformed as the following:

$$\frac{dR}{dt} = r_0 \frac{(R_{max} - R)}{(R_{max} - R_0)} R, \qquad (11)$$

The resulting system of fifth-order equations is solved in World2-MC using a Runge-Kutta method.

In Eq.11: $R_0 = 1.9 \cdot 10^{11}$ is the reserves of fuel resources in the year 2075, which are assumed as the initial condition in the logistic model; r_0 is the factor of increase in thermonuclear energy at t_0=2075; $R_{max} = 21 \cdot 10^{11}$ RU is the upper limit of energy available to GSES, which is approached asymptotically by Eq.11 solution.

The derivation of the right part of Eq.11 is the same as in Section 3.3 of the present paper.

Fig. 10 illustrates the realization of the thermonuclear power scenario. Before 2075, when population size is locally stable (see Fig. 12), GSES develops by the $R_0 = 27 \cdot 10^{11}$ RU scenario. In 2075, upon the corresponding reserves of traditional fuels, the operation of industrial thermonuclear reactors begins to produce a logistic (Eq. 11) increase of energy available to GSES up to $R_{max} = 21 \cdot 10^{11}$ RU. This level will be sustained indefinitely long. As seen in Fig. 10, all other GSES components after 2075 will experience harmonic oscillations featuring constant amplitudes relative to their stable (according to Lyapunov) stationary trends. This means that widely used thermonuclear power will be associated with an endless series of profound economic, environmental and demographic crises.

3. Alternatives to the cyclic mode of GSES development

3.1. The concept of ecological dominance of humankind in the biosphere

In taxonomic terms, the species *Homo sapiens* is referred to the kingdom of animals, and hence the ecological concept of dominance [20, p. 185] is applicable to humans as well. According to the concept, only some of numerous species included in a biocenosis determine its state because of the sizes of their populations, trophic levels, involvement in ecological metabolism or other reasons.

Humans as biosocial entities are not limited by the natural environment where they are certainly dominant. Humans have developed their own environment, which comprises, besides the natural environment, the economic, social, technological, and cultural environments. An industrial (socioeconomic) metabolism has emerged. It is poorly controlled by the society and increases with increasing production. Socioeconomic anabolism, which consumes renewable and nonrenewable natural resources, and catabolism, which results in environmental pollution, have increased to extents able to undermine the natural reserved of the planet Earth. Humankind dominates not only biota but also the whole biosphere. The force of the dominance V.I. Vernadski equates to the geological forces that formed the present-time appearance of the Earth [7]. Therefore, attempts to achieve global equilibrium by limiting the industrial metabolism are futile without correcting the power of the principal generator of the metabolism, i.e. the size of human population.

By the words of K. Ya. Kondratyev: “If humankind were able to return to limits determined by the capacity of the biosphere to bear industry, all environmental problems would have disappeared automatically, so as the anthropogenic distortions of the environment. It is, however, necessary for that to take measures aimed at a stabilization and then at the reduction of human population” [13, p. 37].

Being aware that it unfeasible in the near future to implement “the global strategy of reducing the size of human population”, K. Ya. Kondtratyev seeks solutions in the restoration of the natural communities of the biosphere: “It is necessary to reduce the areas compromised by humans from current 61% to 38%, that is by 23% or 3.2 million km^2” [13, p. 38]. These estimates are based on the assumption that the primary biological productivity of the restored areas is the same as the global mean. However, the reduction of areas distorted by the civilization will disturb the socioeconomic metabolism. Anabolic assimilation will decrease, and the decrease with result in a decrease in human population size. This problem will be considered below in more detail.

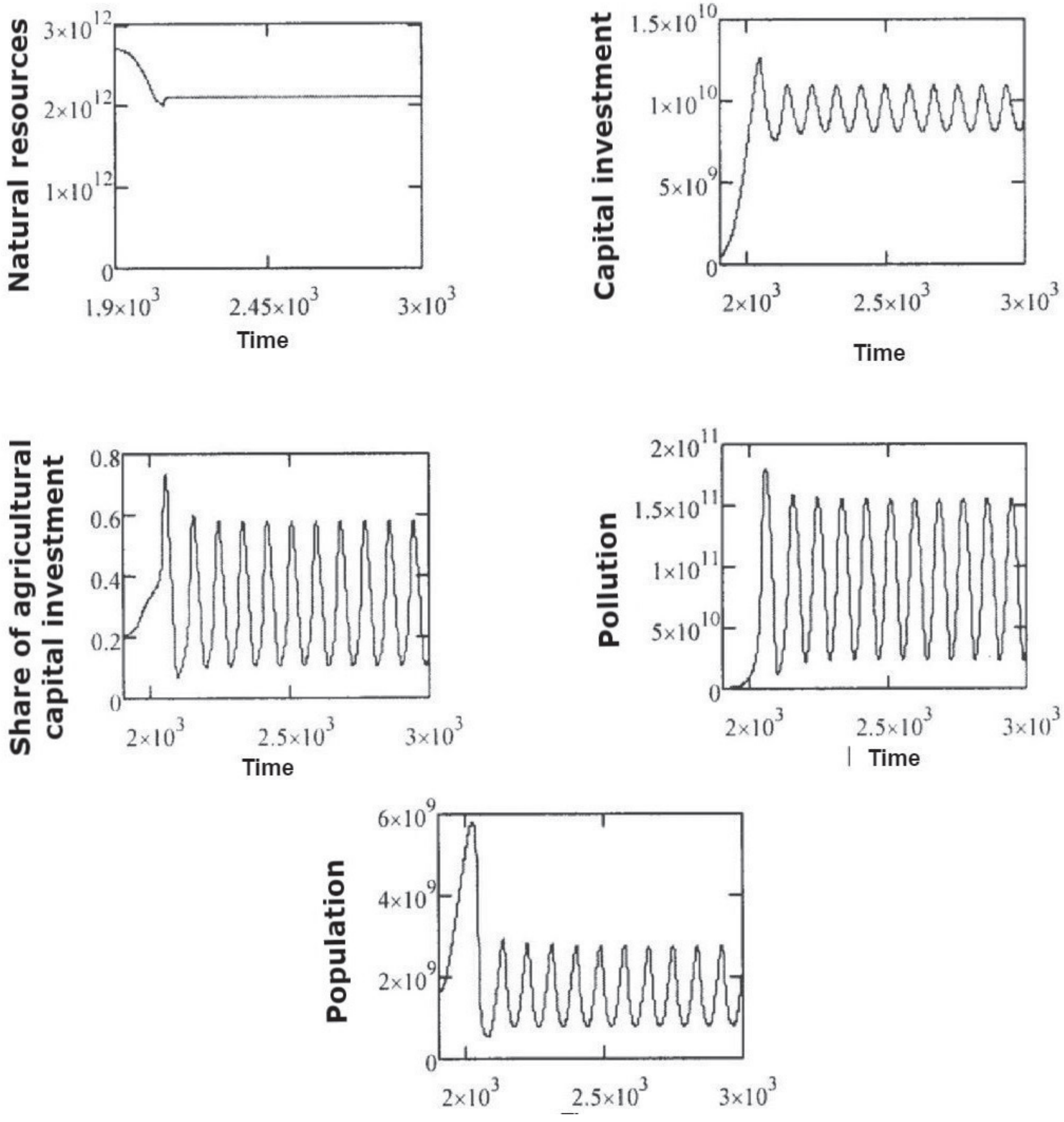

Fig. 10. Time-dependent changes in GSES components modeled with World2-MC at $R = 27 \cdot 10^{11}$ RU (the 300% scenario) until the year 2075 followed by the logistic increase of R up to $21 \cdot 10^{12}$ RU due to the use of thermonuclear energy. See text for explanations

Land reserves of GSES

The terrestrial area of the Earth is 146 · 10^6 km^2, of which 70.6 · 10^6 km^2 is suitable for life. Arable land and pasture make 15 · 10^6 and 25 · 10^6 km^2 that is 21% and 35%, respectively, of inhabitable territories.[9] The area of natural grassland and steppes is 9 · 10^6 km^2 [24]. This area should be abstracted from all pastures to estimate the area of anthropogenic interferences, which thus amounts to 16 · 10^6 km^2. On a whole, the area withdrawn from the biosphere for agriculture makes 31 · 10^6 km^2, i.e. 44% of inhabitable terrestrial areas.

The urbanized areas was 4.7 · 10^6 km^2 in 1980 and increased to 19 · 10^6 km^2, i.e. to 27% of inhabitable areas, in 2007[10].

Thus, the total area of land disturbed by GSES is 50 · 10^6 km^2, i.e. 71% of inhabitable areas. To restore the natural communities of the biosphere, the area disturbed by humans as of 2007 should be reduced from 71% to 38% (according to K.Ya. Kondratyev) that is by 33% or 23.2 · 10^6 km^2.

Restoration of the productivity of the biosphere

This is possible at the expense of areas currently used for agriculture and (or) urbanized areas. The options for that will be considered below.

1. Restoration of the productivity of the biosphere at the expense of agricultural lands

First, let us estimate the number of people sustainable with foods obtained from the current agricultural areas. At human population size equal to 6.5 billion people and at agricultural area equal to 31 · 10^6 km^2 as of 2007, the per capita agricultural area is 0.48 hectares. "Calculations suggest that to sustain each one human on the Earth with foods, 0.4 to 0.5 hectares of land is required, provided that productivity is the maximum of what is possible" [3, p. 24]. Thus, the current agricultural areas can sustain 6.5 billion people.

Upon the withdrawal of 23.2 · 10^6 km^2 from the current agricultural area, 7.7 ·10^6 km^2 will remain, and the per capita area will be 0.12 hectares, which is four times less than the above estimate. Thus, the restoration of the productivity of the biosphere due to the reduction of the agricultural area will result in a four-fold decrease in human population that is down to 1.63 billion people. Notably, this is compatible with the 1% threshold of the consumption of the primary production of the biosphere that provides for its stability (see Section 2.2.) and with the initial values of *P* in the models World2 and World2-MC for the year 1900.

2. Restoration of the productivity of the biosphere at the expense of urbanized areas

Urbanized territories area makes 38% of all areas disturbed by GSES and thus must be withdrawn completely if treated as the only reserve for the restoration of the productivity of the biosphere. In this case, 6.6 billion humans will have to return to the primitive way of life in forests and caves.

3. Restoration of the productivity of the biosphere at the expense of a partial reduction of agricultural lands.

In a scenario implying that 19 · 10^6 km^2 of the urbanized area is not withdrawn, and the current area of agricultural lands (31 · 10^6 km^2) is reduced to 19 · 10^6 km^2, an area of 2 · 10^6 km^2 becomes restored. In per capita terms, this makes 0.18 hectares, which is 2.5 times below what is needed to sustain a human with food and thus is associated with a decrease in human population from 6.6 to 2.5 billion people.

The general conclusion is that restoring the productivity of the biosphere at the expense of reducing the areas currently disturbed by GSES is impossible without the concurrent decrease in the ecological dominant of the biosphere, i.e. the size of the global human population.

3.2. Local stationary points in the trajectories of the cyclic development of population size

An exit from the series of civilizational crises, which are predicted by the model World2-MC, should be sought based on the dominant role of humankind in the development of the biosphere. The equation of the demographic component of the model World2 may be written as the following:

$$\frac{dP}{dt} = B - D, \qquad (12)$$

where: B and D are birth and death rates (humans/year) and *P* is population.

B и *D* are defined as the following:

$$B = P \cdot C_B \cdot B_C \cdot B_F \cdot B_P \cdot B_Z, \qquad (13)$$

$$D = P \cdot C_D \cdot D_C \cdot D_F \cdot D_P \cdot D_Z, \qquad (14)$$

where: C_B = 0.04 (1/year) and C_D = 0.028 (1/year) are birth and death rates in the reference year 1970; $B_C = B_C(C)$ and $D_C = D_C(C)$, $B_F = B_F(F)$ and $D_F = D_F(F)$, $B_P = B_P(P_P)$ and $D_P = D_P(P_P)$ and $B_Z = B_Z(Z)$ and $D_Z = D_Z(Z)$ are the functions which are defined graphically (or in a tabulated format) to capture the dependencies of birth and death rates on living standards *C*, nutrition *F*, population density *Pp*, and environmental pollution *Z*. In the reference year 1970, these functions are equal to unity and do not influence the rates of birth and death. When living conditions become worse or better, the functions become, respectively, smaller of greater than unity. The arguments of these functions depend on the conditions of the components of the model.

With account for the above, Eqs. 13 and 14 may be generalized:

$$B = b(R, R, X, Z)P, \qquad (15)$$

$$D = d(R, K, X, Z)P, \qquad (16)$$

[9] http://www.activestudy.info/zemelnye-resursy/

[10] https://ru-ecology.info/term/12651/

where: b and d are birth and death coefficients; however:

$$B - D = E, \tag{17}$$

where: E is the rate of population size increase.

It is obvious that:

$$E = \varepsilon(R, K, X, Z)P, \tag{18}$$

where: ε is the coefficient of population size increase.

With account for Eqs. 17 and 18, Eq. 12 may be parameterized as the following:

$$\frac{dP}{dt} = \varepsilon(R,K,X,Z)P, \tag{19}$$

or

$$\frac{1}{P}\frac{dP}{dt} = \varepsilon(R,K,X,Z). \tag{20}$$

Recall that in the system of World2-MC equations, all variables are functions of time. The left part of Eq. 20, i.e. $1/P(dp/dt)$, which is identically equal to $\varepsilon(R, K, X, Z)$, allows constructing a phase trajectory using the parametric form $[\varepsilon(t), P(t)]$, where time is the parameter. The same trajectory may be constructed as a set of points in a $\{1/P(t)[dP(t)/dt], P(t)\}$ plane. Fig. 11 shows the plane trajectory for the 300% scenario upon the initial reserves of fuel resources $R_0 = 27 \cdot 10^{11}$RU.

In population ecology, the spiral phase trajectory in Fig. 11 is called the Olley curve. It is typical of populations featuring expressed altruistic behavior of their members, such as collective protection from predating, joint care for progeny etc. [25]. Olley curve appears to be featured by humankind too.

Spline approximation of an Olley-type trajectory makes it possible to solve Eq. 19 numerically. This solution is approximated by the behavior of $P(t)$ in World2-MC.

A stationary trajectory of a global model is the limit to which it approaches. A specific case of stationary trajectory is an implicit equilibrium where all rates defined by differential equations of a model turn to zero. Considering an equilibrium as global is possible only if there exists a point in the phase space of all components where all of the right parts of equations in a model turn to zero upon $t \to \infty$.

Let us denote local stationary points with the superscript$^{(c)}$. The local stationary points $P^{(c)}$ of Eq. 19 are defined by $dP/dt = 0$. In an Olley-type trajectory, several local stationary points are possible. There are six such points in the $R_0 = 27 \cdot 10^{11}$ scenario (300%). The stability or instability of these points is defined by the sign of the derivative $\frac{d}{dP}[\varepsilon(P)P]$ at the stationary point $P^{(c)}$ [25].

The derivative may be expressed as the following:

$$\varepsilon(P)P] = P\frac{d\varepsilon(P)}{dP} + \varepsilon(P)\frac{dP}{dP} = P\frac{d\varepsilon(P)}{dP} + \varepsilon(P). \tag{21}$$

With account for Eq. (20), it may be written:

$$\frac{d}{dP}[\varepsilon(P)P] = P\frac{d\varepsilon(P)}{dP} + \frac{1}{P}\frac{dP}{dt}. \tag{22}$$

However, dP/dt is 0 by definition at a stationary point. Therefore, Eq. 22 may be replaced with the following:

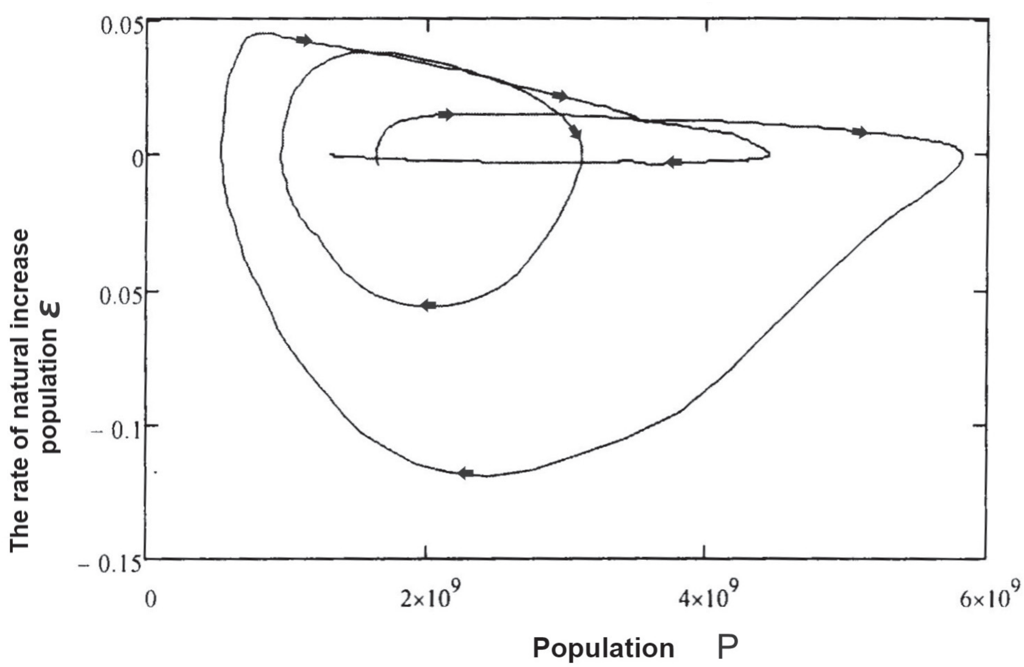

Fig. 11. Olley-type plots for World2-MC population size at $R_0 = 27 \cdot 10^{11}$ RU (the 300% scenario)

$$\frac{\mathrm{d}}{\mathrm{d}P}[\varepsilon(P)P] = P\frac{\mathrm{d}\varepsilon(P)}{\mathrm{d}P}. \qquad (23)$$

A local stationary point is stable if $d\varepsilon(P)/dP < 0$ at this point and is unstable if $d\varepsilon(P)/dP \geq 0$. The sigh of a derivative is defined by the tangent of $\varepsilon(P)$. It is seen in Fig. 12 that the $R_0 = 27 \cdot 10^{11}$ RU scenario features two stable $P^{(cs)}$ and three unstable $P^{(cu)}$ stationary points and a trend, which shows Lyapunov's stability and approaches the limit density P^*. In the present case, P^* is 1.3 billion people.

With any nonzero values of P, a population will tend to local stationary states. A population will tend to a stationary state $P_1^{(cs)}$ at $P \in (P_0, P_1^{(cu)})$; to $P_1^{(cs)}$ at $P \in (P_1^{(cu)}, P_2^{(cu)})$; and to P^*at $P \in (P_3^{(cu)}, \infty)$ (Fig. 12). Clearly, the local stationary state $P_1^{(cs)}$ is the optimal P_0 in a scenario implying an accelerated transition from cyclic to stationary GSES trajectory.

3.3. Accelerated transition from cyclic to stationary time trajectory of GSES

On Jan. 1, 2016, the population of the People's Republic of China reached 1.378 billion people, the annual increment being 7.28 млн[11], despite economic measures (one family, one child) taken to reduce birth rate. This is far above stationary values suggested by World2-MC. By the same date, the population of India reached 1.252 billion people[12]. In 1994, a UN Conference on Population and Development was held in Cairo[13]. The conference has shown that corporative, national and confessional egoism dominates over universal interests. Global population has increased by 1.622 billion since those times and achieved 7.296 billion on Jan. 1, 2016[14]. Global economic crises and numerous local wars in a unipolar World distract enormous resources from solving global problems. This being true, only overt social optimists may believe that everything will be all right be default. The right time for reforming the world system has been already missed. The first oscillation of global population is most likely inevitable.

The second and the third oscillations of the global population may be prevented if after the demographic crisis of the XXI century the global population will be controlled according to the logistic model:

$$\frac{dP}{dt} = (\alpha - \gamma P)P. \qquad (24)$$

where: $\varepsilon = \alpha - \gamma P$ is the coefficient of increase in population P; and $a > 0$ *and* $\gamma > 0$ are the parameters of the linear dependence of the coefficient ε on P.

Population cannot increase infinitely. Its size has an upper limit:

[11] countrymeters.info/ru/China

[12] countrymeters.info/ru/India

[13] https://www.unfpa.org/sites/default/files/event-pdf/icpd_rus.pdf

[14] https://ru.wikipedia.org/wiki/население_Земли

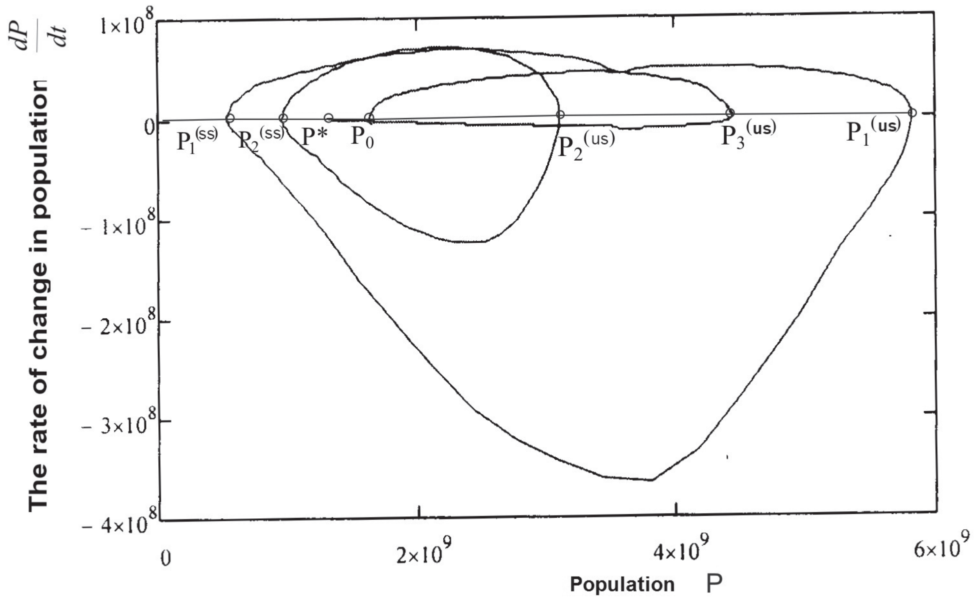

Fig. 12. Phase diagram of the model $dP/dt = \varepsilon(R, K, X, Z)P$ *upon the starting traditional fuel reserve* $R_0 = 27 \cdot 10^{11}$. P_0 – trivial stable state; $P_1^{(us)}$, $P_2^{(us)}$ – locally stable stationary states; $P_1^{(ss)}$, $P_2^{(ss)}$, $P_3^{(ss)}$ – *locally unstable stationary states;* P^* – limiting population density

$$\lim_{t \to \infty} P(t) = \alpha/\gamma = P_{max}\ , \tag{25}$$

where: P_{max} is the limit approached by P asymptotically. Eq. 24 may be rewritten as:

$$\frac{dP}{dt} = \frac{1}{\gamma}\left(\frac{\alpha}{\gamma} - P\right)P\ , \tag{26}$$

or, with account for Eq. 25, as:

$$\frac{dP}{dt} = \frac{1}{\gamma}(P_{max} - P)P\ . \tag{27}$$

where g is an independent parameter.

The parameter γ may be expressed with other constants, P_0 and ε_0, which are population size and the coefficient of its increase, respectively, at time t_0. Clearly, $\varepsilon_0 = \varepsilon_0(P_0)$. Let us assume that:

$$\frac{1}{\gamma} = \frac{\varepsilon_0}{P_{max} - P_0}\ . \tag{28}$$

Putting Eq. 28 in Eq. 27 will yield the following:

$$\frac{\mathrm{d}P}{\mathrm{d}t} = \varepsilon_0 \frac{(P_{max} - P)}{(P_{max} - P_0)} P\ . \tag{29}$$

Eq. 29 is equivalent to Eq.24. Obviously, the linear dependence of the coefficient of population increase on population size is defined as

$$\varepsilon = \varepsilon_0 \frac{(P_{max} - P)}{(P_{max} - P_0)}\ . \tag{30}$$

An accelerated transition from cyclic to stationary GSES development may be exemplified with the $R_0 = 27 \cdot 10^{11}$ RU (300%) scenario, which is the most likely one. According to it, the first local stationary state must be achieved in 2075 at P_1(cs) = 0.54 billion people (Fig. 12). This size may be assumed as the initial condition $P_0 = 0.54$ of the logistic model. Let us assume that is 0.02 in 2075 and that Pmax is P^* = 1.5 billion people, i.e. corresponds to the stationary, according to Lyapunov, trend of population size.

Fig. 13 illustrates an accelerated transition of GSES to a displaying a stationary Lyapunov's trend in time. It is seen that, at $\varepsilon = 0.02$, population becomes stationary approximately in 160 years, that is by 2240. The transition may be delayed or accelerated by varying the parameter ε_0.

To explain the temporal variability of GSES components in the present scenario, historical examples and the flux diagrams that show feedbacks in the model World2 [32] will be used below.

After the end of the first demographic crisis, global population size will fall to 0.54 billion people. This is similar to what had been achieved in mid-XVII century [23]. In those times, water wheels and windmills were used as engines. Population reached 1.5 billion in late XIX century when steam was mainly used in engines and wood was used as the main fuel. Humankind existed in those times due to the renewable resources. Now let as have a look into the future. The logistic growth of population will result in 1.5 billion people, and this population size will be constant during subsequent centuries. Population will be in a stationary flux sustained mainly due to the renewable natural resources. The nonrenewable natural resources will be virtually unneeded after 2075 and will be in a stationary flux at a levels of $19 \cdot 10^{11}$ RU.

According to World2 flow charts, the economic capital investment (the capital investment of industry, services, and agriculture) depend on population size (the number of investors) and living standards, which depend in their turn on the current reserves of fuel resources. The capital investment ($1.3 \cdot 10^{10}$ capital units, CU) built up during the ascending phase of GSES development in 1900–2022 due to the investors that have sufficiently high living standards (5.82 billion people) feature a considerable lifetime of about 40 years and the corresponding temporal lag of their development. In the descending phase of population size changes in the years 2022 to 2075, this lag maintains the basic asserts at a level of about $7.5 \cdot 10^9$ CU. In the phase of the logistic growth of the global population (the number of investors by inference), the capital investments increase up to 10^{10} CU and enter, following the size of the population, a stationary phase.

The share of the agricultural capital investment among the entire economic capital investment is determined primarily by the nutritional conditions of population and by the lifetime of the agricultural capital investment. During the phase of population increase, the share of the agricultural capital investment increases up to 0.75 of the entire economic capital investment. A small temporal lag of agricultural capital investment (15 years) does not present their degradation during the phase of population decrease. By 2075, their share must decrease down to 0.06. During the phase of the logistic grown of population, the share of the agricultural capital investment must increase up to 0.9 and reach its stationary level.

Environmental pollution depends on the rates of pollutants generation and destruction. Generation rate is a function of population size and *per capita* capital investment. Destruction rate depends of the level of pollution and the rate of environmental self-cleansing. During the phase of increases in population and capital investment, pollution increases up to $1.7 \cdot 10^{11}$ pollution units (PU). During the phase of decreases in these components of GSES, pollution decreases due to a decrease in the generation and an increase in the destruction of pollutants. During the logistic phase of capital investment increase, pollution increases up to $2.5 \cdot 10^{11}$ PU and reaches its stationary level.

It may seem that stationarity returns GSES back to the XIX century. To see that this is not so, it suffices to compare the initial conditions of GSES components with their levels upon reaching stationarity. Clearly, basic asserts increase so as the material component of living standards does. The nutritional component becomes increased too. Indeed, the agricultural capital investment, which is defined as the total capital investment multiplied by the share of the agricultural capital investment, was $0.08 \cdot 10^9$ CU in the year 1900 and must be $0.9 \cdot 10^9$ CU in 2500.

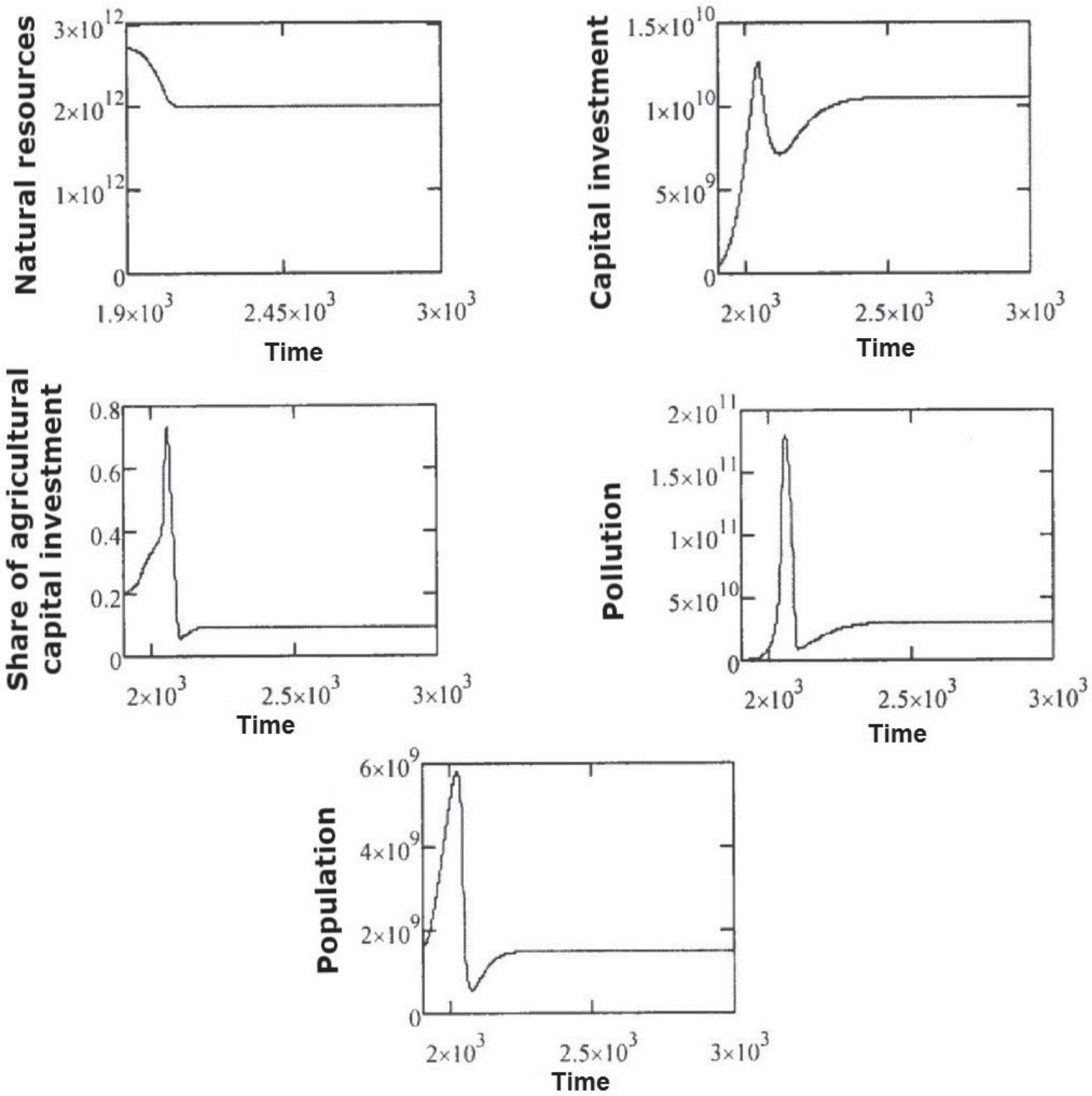

Fig. 13. Time-dependent changes in GSES components modeled with World2-MC at $R = 27 \cdot 10^{11}$ RU (the 300% scenario) until the year 2075 followed by the logistic increase in P at ε= 0.02 и $P^* = 1{,}5$ billion people. See text for explanations

4. GSES development cycles are associated with the developmental phases of the global hyper-ethnos: a hypothesis

A smooth transition of global population to stationarity is possible, by all appearances, only upon the formation of a global hyper-ethnic system based on a common mentality of population, that is on mental features and outlooks shared by all people. This assertion will be considered in more detail below.

The formation of a global hyper-ethnos is taking place already because of globalization. The postindustrial era that have come to existence at the turn of the XX and XXI centuries is characterized by the explosive development of transnational corporations and common market, which transforms global economy into an international enterprise. The natural landscapes, which accommodate ethnoses, become increasingly degraded. Information technologies are developing to an unprecedented scale. The world-wide web, telecommunication networks, and satellite TV are forming a unified informational medium. The mass culture is ousting the classic and folk cultures. Education is adopting international standards based on intergovernmental treaties, and languages are increasingly being adopted to the English language, which has become a means of international communication. International logistics is rapidly developing. Humankind is being stratified to form, in particular, a hunger belt along the equator through Africa, Middle East, South-East Asia, and Latin America where up to 30% of people are starving [14]. These inequalities in socioeconomic development drive planned and spontaneous labor migration, which results in ethnic mixing. All these factors promote the development of a unified mentality and the formation of a global hyper-ethnic system, which may be able to control birth rate upon the transition of the global population to the logistic mode of growth.

In [30], the development of North-American, Western European, Chinese, Islamic, and Eurasian super-ethnoses was considered. It was concluded that the most likely core for the formation of a global hyper-ethnos is the North-American super-ethnos because it is the youngest and the most dynamic and "passionate" (in the Gumilev's[15] sense of the word) of all super-ethnoses.

The below discussion will be based on the assumption that a global hyper-ethnos is developing already in the course of globalization based on the core comprised of the North-American and West-European super-ethnoses, which are highly "passionate" and similar to each other in the basics of their mentalities. This is the most likely scenario as of today. Among the three World2-MC scenarios of GSES development, the scenario to consider implies 300% greater reserves of nonrenewable resources than it is assumed in the Wold2 model. With account for the fact that resources are increasingly consumed and the cost of their production is increasing with time, this scenario seems to be the likeliest. A three-fold increase in reserves is equivalent to $R_0 = 2700 \cdot 10^9$ (starting from the year 1900, the reserves are sufficient for 750 years, the rate of the consumption of the resources being the same as in 1970). The initial conditions for all other model components are assumed in this scenario to be same as in the basic World2 variant: $P_0 = 1.65 \cdot 109$ people (global population), $K_0 = 0.4 \cdot 10^9$ CU (global capital investments; it is assumed that per capita capital investment in 1990 was four times less than in 1970); $X_0 = 0.2$ (the share of the agricultural capital investment); and $Z_0 = 0.2 \cdot 10^9$ PU (environmental pollution; it assumed that per capita pollution in 1990 was eight time lower than in 1970). The results of modeling of GSES development under these conditions is illustrated in Fig. 14.

The abscissa in Fig. 14 shows the timescale, which ranges from 1900 to 2800, and the phases of ethnogeny. The ordinate scale is the same for all components. Figure captions indicate the names and graphic identifies of the components and the divisors for dividing the values of components derived from the respective plots in order to obtain the actual values.

Modeling results suggest that the oscillations of GSES components qualitatively correspond to the phases of ethnogeny discovered by L.N. Gumilev in his studies of human history. This makes it possible to consider jointly the ethnic and the socio-ecological aspects of the development of civilization.

The ascending phase of hyper-ethnos

This phase comprises to stages: the latent and the manifest ascent. The latent ascent may be assumed to start in the early XVIII century, the time of increasing migration of "passionaries" from Europe to North America and the onsets of the industrial era (pre-monopolistic capital investmentism) and the demographic explosion (in 1650, global population amounted to but 550 million people [23]). This stage, according to L.N. Gumilev's estimate, lasted for 150–200 years. Thus, the manifest stage of the ascending phase began in the early XX century.

During the manifest stage of the ascending phase, the passionarity of an ethnic system drastically increases. The bearers of passinonarity consolidate within the field of their action the masses of ordinary personalities. This time is distinguished by highly expressed manifestations of all types of activities within a hyper-ethnos: demographic explosion, economic growth, environmental problems, inner conflicts, rapid proliferation of ethnic subsystems, and the emergence of highly disciplined ethnic collectives.

An exponential growth of a population is associated with a similar increase in the number of "passionaries". Because of their high fertility, their number may increase even faster than the number of ordinary people does.

Another evidence of an increased passionary intension is the breakdown of the colonial system after World War II. Former colonies became independent states thus making the complexity of the global hyper-system to increase. An international ruling body that emerged is the United Nations.

[15] http://discovery.ucl.ac.uk/1446515/1/U602440.pdf

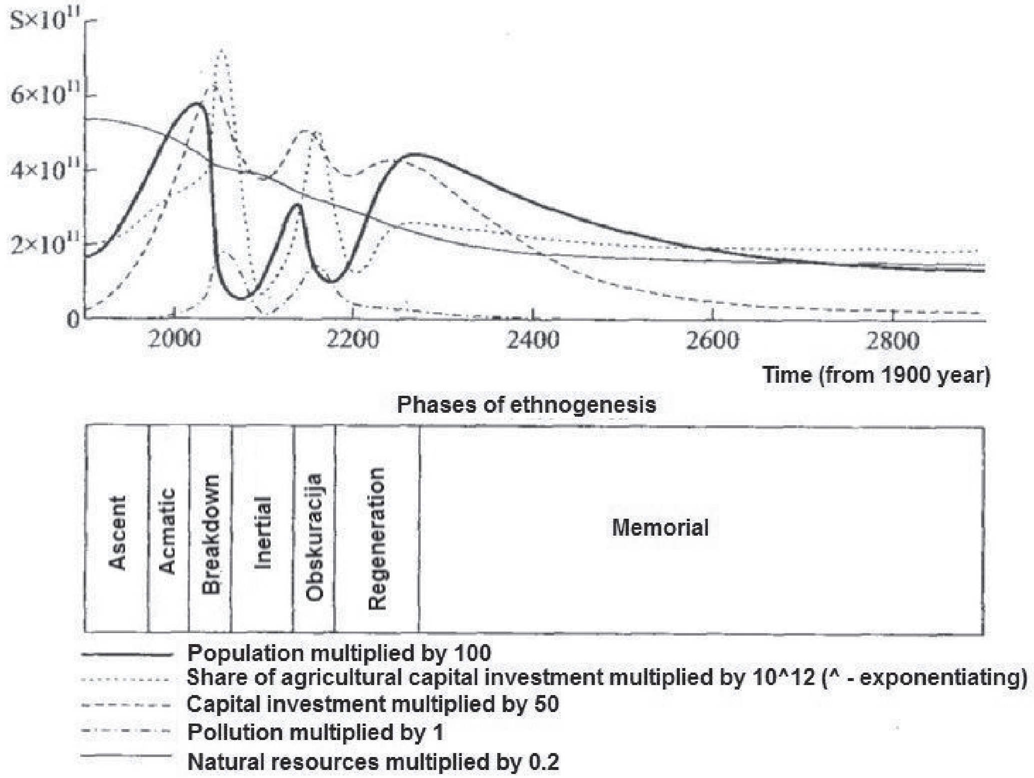

Рис. 14. Time-dependent changes in GSES components and the phases of a global hyper-ethnos development. See text for explanations

Increased activities of the economic agents of the hyper-ethnos at the manifest stage of its ascent are expressed in the transition from the pre-monopolistic to monopolistic capital investmentism, the emergence of transnational companies, and the explosive growth of the gross domestic and gross national products. The driving force of the market economy are businessmen, who are usually excessively energetic and striving for maximal gains at minimal expenses.

According to World2-MC, the capital investment of global economy increased from $0.44 \cdot 10^9$ CU in 1900 to $0.65 \cdot 10^9$ CU in 1990, that is 15.6 times. Population growth made it necessary to increase the share of the agricultural capital investment from 0.2 in 1990 to 0.32 in 1990. Environmental pollution gradually increased. The reserves of the nonrenewable natural resources decreased from $27 \cdot 10^{11}$ до $24 \cdot 10^{11}$ RU. Thus, only 10.8% of the initial reserves were spent during the manifest stage of the ascending phase of the development of the hyper-ethnos.

The acmatic phase of hyper-ethnos

The acmatic phase, according to L.N. Gumilev, is a fluctuation of the passionary intension that occurs at the ultimate level of passionarity following the ascending phase. The time when the ascending phase ends may be determined by changes in the type of relationship between the coefficient of population increase and population size: a positive correlation is replaced by a negative one. Formally, this corresponds to the bending point of population growth curve, where $(d^2P(t)) / (dt^2) = 0$. Upon a discrete representation with 1-year intervals, the bending point is determined by the equation $P_{i+1} - 2P_i + P_{i-1} = 0$. World2-MC suggests that the acmatic phase started in 1990. According to demographic statistics, global population size was 5 billion people in 1987, 6 billion on 2000, and 7 billion in 2012. Thus, the increase in global population was stabilized, in conformance with modeling results.

During the acmatic phase, passionaries develop a desire for maximal personal self-assertion even if the desire contradicts the interests of one's native ethnos. A recent example of such self-assertion may be found in the history of USSR breakdown, when the political leaders of Russia, Ukraine, and Belorussia at their meeting in Belovezhskaya Forest signed the treaty stipulating that their republics will come out of the USSR in spite of the results of general referendums in these republics. As a result, 15 new states have emerged in the former USSR territory.

Inflated individualism associated with increased passionary intension brings the hyper-ethnos to an "overheated" state. In this state, excessive passionarity is spent in interethnic conflicts, which may be exemplified with the sovereignty parades of FSU countries, Nagorno-Karabakh conflict, armed conflicts between Georgia and Abkhazia and South Ossetia, wars between former republics of Yugoslavia etc. During the acmatic phase, the number of ethnic subsystems and the frequency of significant events in ethnic history are maximum. The phase is not ended yet, and much may happen during the rest of its time.

According to World2-MC modeling, population must increase from 4.82 billion people in 1990 to 5.81 billion in 2022 during the acmatic phase. However, population growth rate must gradually decrease to zero. The capital investment of global economy continue to grow stably from $0.6565 \cdot 10^{10}$ CU in 1990 to $1.1 \cdot 10^{10}$ CU in 2022, that must increase 1.7 times. The continuing population growth requires further expansion of agriculture. The share of the agricultural capital investment during the acmatic phase must increase from 0.32 to 0.37. Environmental pollution also continues to increase. The reserves of the nonrenewable resources must decrease from $24.1 \cdot 10^{11}$ to $21.9 \cdot 10^{11}$ RU during 32 years.

The breakdown phase of hyper-ethnos

According to L.N. Gumilev, the breakdown phase is associated with a dramatic decrease in population size. The number of passionaries decreases proportionally. The passionary intention in an ethnic system decreases deeply. This is associated with ethnic field fracture, acute conflicts, and increasing number of indifferent people. The indifference is expressed in inability to control instinctive lusts and in asocial behavioral traits, parasitism, and insufficient care for progeny. Such people usually concentrate in cities and are responsible for increasing alcoholism, drug addiction, and criminality.

World2-MC modeling suggests that the time of transition from the acmatic to the breakdown phase is determined by the time of reaching the first maximum of population size. This must occur in 2022. During the next 55 years, global population will decrease from 5.81 billion people to 0.54 billion because of extremely low birth rates. This is nothing else but a profound demographic crisis.

For living standards improvement and demographic crisis prevention during the breakdown phase, global capital investment must increase from $1.1 \cdot 10^{10}$ CU in 2022 to $1.26 \cdot 10^{10}$ in 2040. The share of the agricultural capital investment must increase drastically, from 0.37 in 2022 to 0.72 in 2040. The intensification of economic development will result in a catastrophically increased environmental pollution, which must reach $1.8 \cdot 10^{11}$ PU by 2054. This is 1000 time more than in the year 1990.

The economic measures will not stop the depopulation process. Labor force deficit will lead to economic recession and then to stagnation. By the end of the breakdown phase, world capital investment will decrease to $0.88 \cdot 10^{10}$ CU, that is to 30% of the maximum. The share of the agricultural capital investment will decrease to 0.36, that is will two times less than its maximum.

The inertial phase

During the phase named by L.N. Gumilev as inertial, population grows again. Because of the genetic drift, the number of passionaries increases. A characteristic feature of this phase is the consolidation of governmental power and social institutes. Material and cultural treasures accumulate. Environmental landscape are actively transformed. The predominant personality traits are loyalty and workability. Labor is perceived as not a burden but a valuable prerequisite of wealth. Enormous useful work is carried out.

It is tempting to supplement this characteristic of the inertial phase according to L.N. Gumilev's analysis of the past with what follows from V.V. Olenyev's and M.P. Fedorov glimpse into the future: "The task of developing a controlled world may be fulfilled only based on a controlled and planned socioeconomic system, such as 'ecological socialism'" [21]. In L.N. Gumilev's theory of ethnogeny, one of the main factors that determine the development of an ethnos is the development of the productive forces, which transforms productive relations and, hence, social organization. It follows from the law of conformance of productive relations to productive forces and the law of decreasing potential of natural resources that the "environmental-social-economic development (of a socio-environmental system) corresponds to the formula [24]: (potential of natural resources) ↔ (productive forces) ↔ (productive relations).

When economic growth discontinues (deep depression during the breakdown phase), market economy becomes needless. The capital investmentistic mode of production, which is based on achieving maximum gains at minimum expenses, most often operates at the expense of destruction of the biosphere and thus is dangerous for the humankind.

Modeling suggests that the time of the end of the breakdown phase and of the beginning of the inertial phase is determined by the date of achieving of the first minimum of population size (the year 2075, 0.54 billion people). In the subsequent years, population will increase due to a decrease in death rate and an increase in birth rate. The capital investment will increase again after their short-term decrease to $7.52 \cdot 10^{9}$ CU in 2097. The share of the agricultural capital investment increases again after its drastic reduction to 0.07 in 2095. Environmental pollution decreases to $1.22 \cdot 10^{10}$ PU in 2097 and starts to gradually increase again.

If the hypothesis that ethnogeny phases are associated with GSES cycles is true, then the transition to the logistic growth of population size is possible without economic, social and environmental cataclysms. The negative experience of the breakdown phase and the transition of dominant personality traits from sub-passionary to harmonized in the inertial phase will facilitate birth control ensuring the maintenance of a current population size.

Conclusions

The World2-MC scenarios of global development lead to conclusions, which, although do not forecast the development of GSES, still point at significant trends:

1. In the XXI century, the humankind will experience not a catastrophe forecasted by Wold2 and World3 models, but rather a series of profound crises followed by recovery. Less profound regional crises having other origins have been experienced by the humankind not once in the past.

2. The global socio-environmental system (GSES) has the potential to develop in a cyclic manner during the third millennium. The number of cycles must increase proportionally to energy availability for humankind. Each cycle ends with a crisis. When the resource and energy potential is limited by the traditional fossil fuels reserves (oil, gas, and coal), three to four cycles may be expected. Upon expanding the potential due to shale oil, there may be up to 15 cycles followed by stationary (in Lyapunov's sense) developmental trends of GSES components.

3. Upon widely used controlled thermonuclear synthesis, the number of cycles must increase infinitely, and GSES must enter a harmonic oscillator regimen and thus experience fluctuations around an equilibrium state.

4. The humankind is the ecological dominant of the biosphere within each separate cycle of GSES development. Capital investment, food, and environmental pollution, which are the products of the socioeconomic metabolism of the humankind and depend on the current reserves of energy resources, limit human population size within a cycle but do not determine the number of cycles.

5. In the five model scenarios, which differ in their initial reserves of fuel resources, the stationary levels of population size reached by GSES after its final cycle range from 1.3 to 1.6 billion people. Population size that corresponds to a 1% threshold of primary product consumption, which provides for the stability of the biosphere, amounts to 1.7 billion people. A similar calculated population size (1.63 billion people) is sustainable by the biosphere in the scenario that implies the complete recovery of the present-time agricultural lands. Thus, the threshold population size, to which the logistic curve of population size approaches asymptotically, ranges from 1.3 to 1.7 billion people.

6. Computations suggests that the restoration of the ecological systems that are currently substituted with agricultural lands and urbanize territories, which is proposed in the biospheric concept of sustainable development as an alternative to the reduction of human population size, is unfeasible without the proportional and simultaneous reduction of the latter. Means to restore ecosystems are discussed in the biospheric concept, whereas means to reduce human populations are ignored.

7. The cyclic trajectory of changes in global population is a manifestation of the spiral shape of the curve that reflects the dependency of the coefficient population growth on population size. In population ecology, this is known as Olley curve. The curve explains the existence of several stable and unstable local stationary states of the cyclic development of population. The stable states provide for the possibility of an accelerated transition of GSES to stationarity.

8. GSES may transit from the cyclic to the stationary mode of its development starting from a stable local stationary state via the logistic growth of population size, its saturating size being 1.5 billion people.

9. A smooth transition is possible, by all appearances, only after the formation of a global hyper-ethnic system featuring a common mentality, i.e. common mental traits and general outlooks, of all people in a controlled and planned socioeconomic system of an "ecological socialism" type.

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