MATHEMATICAL MODELS OF GLOBAL TRENDS AND TECHNOLOGICAL CHANGE

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Summary

Human activities cause negative global changes, such as climate change (global warming), environmental pollutions, extinction of some species, degradation of whole geographic areas, and others. The expected growth of human population and economy can lead to more dangerous global trends. Unfortunately, current scientific knowledge is insufficient to accurately predict environmental consequences of human impact. On the other hand, forecasting global trends and modeling global change are scientific problems of great complexity as well as of great importance.

First global models (*models of world dynamics*) were developed by J.W. Forrester and D.H. Meadows in the 1970's. They produced mostly qualitative results and represented first systematic attempts to analyze global trends. These models evolved into a more quantitative *integrated assessment* (*IA*) approach in global modeling.

The interdisciplinary *IA* approach reflects the interactions among various global components (the environment, society, economics, and others). This framework employs sets of reduced module-models – one for each component - which are then linked.

Technological change (*TC*) is an essential driving force behind economic development that considers different environmental and social factors. Modeling hypotheses include exogenous, autonomous, embodied, endogenous, and induced technological change. Models of *embodied TC* (*vintage capital models*) focus on the relations between the TC and investment and consider heterogeneous production factors (capital and/or labour). The models of *endogenous* TC explain the TC sources and drivers.

1. Global Trends and Global Change

Global trends provide a flexible framework to discuss and debate the future. Governmental and nongovernmental institutions, academia and private sectors are working intensively to identify and model major global trends that will "shape" the world. Some of the identified trends will persist, others will become less important and may change over the time, and new global trends may appear. For example, globalization, cooperation between government and private organization, and the role of science and technology have recently emerged as powerful components. A variety of methods are used to analyze and model global trends, for instance, extrapolation of existing trends and available statistics are used to explore demographic and natural recourse trends and experts' opinions are used to forecast science and technology, economic growth, and conflict trends.

In a narrow sense, "*global change*" is often related to the climate change and the linked environmental issues, e.g., stratospheric ozone depletion, acid rain, etc. However, the underlying meaning of global change is much more than the climate change. It reflects changes in the environment, society and economics, and their impacts on each other. Human activities have caused many *negative* global-scale changes in the environment such as the pollution of water, land, and air; the extinction of some species; the degradation of whole geographic areas; and others. The *positive human impact* on the environmental improvement and protection is very limited. Reduced availability of clean water, fertile soils, and clean air may harm human populations as well as the well-being of other species.

Nowadays, global trends and global changes have become the centerpiece of numerous conferences, briefings, protocols, and public addresses.

1.1. Global Trends

Depending on goals and objectives, the global trends can be classified in *categories*, such as:

- Natural resources including the environment, food, water, energy.
- Climate change. Energy and climate.
- Demographics. Population and society.
- Health and disease.
- Agricultural resources.
- Science and technology.
- Communication and transportation.
- Global economy and globalization.
- National and international governance.
- Future conflicts.
- War and conflicts.
- The role of a specific country or region.

Examples of current global trends in the environment include (Global Trends 2000, Steffen et al, 2005):

- Average atmospheric carbon dioxide CO_2 concentrations have climbed 20% since its measurements began in 1959. CO_2 emissions from fossil fuels increased a record 4.5% in 2004.
- More nitrogen is now fixed into available forms through the production of fertilizers

and burning of fossil fuels than is fixed naturally in all terrestrial systems.

- More than half of all accessible freshwater is appropriated for human purposes.
- The concentrations of several important greenhouse gases, such as CO_2, N_2O and ClH_4, have substantially increased in the environment. The CO_2 level of Antarctic ice is 27% higher than its first measurement.
- Almost 40% of known oil reserves have already exhausted in the last 150 years. It took the nature hundred million years to generate this amount.
- Nearly 50% of the land surface has been transformed by direct human action, with significant consequences for biodiversity, nutrient cycling, soil structure and climate.
- Up to 50% of fish stocks are fully exploited, 15-18% are overexploited, and about 10% have been depleted.

1.2. Climate Change Trends

The warming trend is accelerated. The observed changes of the atmosphere indicate the increase of concentrations of greenhouse gases (CO_2, CH_4, and others), which may change the global climate.

1.2.1. Global Warming.

The average global temperature is 14.6°C in 2005. It has risen nearly 1°C in the past century, and has an increase of .6°C in the past 30 years. It leads to changes in the environment and affects all aspects of a population life. Just in one 2005 year, sea ice in the northern hemisphere reached its lowest levels, Greenland's glaciers lost 53 cubic miles of ice, the Gobi Desert expanded 26000 km^2. These events have forced millions of Chinese farmers to move to find more fertile land and natives of the Arctic region to go further north to follow prey. Tourism industry is losing millions of dollars because of the extreme heat and followed it consequences: Kuala Lumpur closed some harbors as a result of wild fires, drought, and heat; the US Gulf Cost had to reduce popular tourist activities because of intensive algal blooms; thousands of residents in different parts of the world were asked to leave their homes due to wild fires.

The global average temperature is expected to continue to rise in the years ahead. Global warming may be a result of emissions of greenhouse gases. Some experts warn that the consequent climate change will be difficult to reverse. This lead to more severe storms, reduction in agricultural yields, biodiversity loss, and threats to human health.

1.2.2. Greenhouse Effect

The Earth receives short-wave solar radiation from the sun. Approximately 70% of incoming solar radiation is absorbed by the Earth's surface and atmosphere and warms it. Although the Earth's surface emits some of long-wave (infra-red) thermal radiation back into space, the essential part of radiation is absorbed by *greenhouse gases* (water vapor H_2O, carbon dioxide CO_2, methane CH_2, nitrous oxide N_2O, chlorofluorocarbons CFCs, and ozone O_3) that lead to the increase of the Earth's surface temperature up to 15^0C instead of -18^0C (the '*natural greenhouse effect*').

During past centuries, atmospheric concentrations of the greenhouse gases have increased because of anthropogenic activities. This increase leads to an increase of the global average surface temperature of the Earth (the '*enhanced greenhouse effect'*). It is still unknown where and how fast such temperature increases will occur and how it will impact the biosphere and human society. In general, scientific knowledge of global system is insufficient to predict results of human impact locally. Certain human activities create multiple interacting effects in nature in a complex and unpredictable way.

1.2.3. Unexpected Trend: Stratospheric Ozone Hole over Antarctica

Stratospheric ozone acts as a filter for ultraviolet radiation, which is harmful for life. A spring time stratospheric ozone hole is a result of the widespread use of chlorofluoro-hydrocarbons such as aerosols in spray cans, solvents, refrigerants and as foaming agents in the 70's. When they react with sunlight, they form chlorine atoms that react with ozone reducing its concentration and creating ozone holes. The ozone hole allows significantly more ultraviolet radiation to penetrate to Earth's surface. Fortunately, the ozone hole forms over Antarctica; so its effects are limited to that sparsely populated part of the Earth. The ozone hole could have covered the entire Earth if chlorine had been replaced with bromide that is 100 times more effective in destroying ozone. Such a global trend would be catastrophic.

1.3. Demographic Trends

Populations in developed and developing countries are changing dramatically. These changes can radically impact local and global environments as well as economies and future development.

The life expectancy is increased all over the world (compare 25 and 60 years for babies born in India in 1881 and 2006), but it is still different in poor and rich countries (84 vs. 46 years for girls born Japan and Kenya). The current life expectancy in the developing world is 63 years. Also, 18% of the developed-world population is 60 years or older compared to 6% in 1900. The US Census Bureau predicts that the number will increase up to 28% by 2050. This process is reflected by a phenomenon called *squaring of demographic pyramid*, which shows changes of a population age in dynamics and emphasizes that the number of productive workers in developed countries is approaching the number of their dependants (retirees and youngsters) who are non-productive consumers. On the other hand, the globalization of the world economy increases international competition. To survive and prosper, developed countries have to innovate and provide a higher labor productivity using new efficient technologies (see Section 5.1.4).

The fertility rate in the developing world has declined in the past 50 years from 6.2 to 3.3 children per one woman. However in some countries it is increasing, for instance, from 7.7 to 8 children in Niger. Even in countries with a decreasing fertility rate the population continues to rise due to the increasing number of young people. This phenomenon is known as a *population momentum*. The average fertility rate in the developed world is 1.5 children per one woman. Moreover, none of the developed countries have the replacement-level fertility. If the current fertility rates do not change, then the population increases up to 11.6 billion people in the developing world and up to 12.8 billion in the entire world by 2050. However, the rate of the population growth has declined from 1.7% in 1985 to 1.3% in 2005, and predicted to be 1% in 2015 (US Census Bureau). Currently, 40% in the developing world and 76% in the developed world live in urban areas. By 2030, 60% in the developing world is projected to live in cities. With the urbanization trend, changes in consumption patterns may create new environmental problems.

These demographic trends create new challenges. High levels of consumption from freshwater to fossil fuels may damage the environment, put pressure on natural resources, and increase pollution. An impact on the environment varies from one region to another. While in rich countries transport-sector emissions are growing most rapidly and they consume more energy, poor rural families engage in slash-and-burn agriculture and pollute local water and other resources. At the same time, according to the ***environmental Kuznets theory*** as nations industrialize, pollution levels initially rise, but then peak and decline. As a country gets richer, a middle class develops, demands a cleaner environment, and replaces older equipment and production methods with more expensive but environmentally cleaner ones.

The pressure humans put on the environment depends on population, consumption, and technology (see Section 2.1). Both population and consumption will almost certainly rise. Hence, the development of new, environmentally friendly and more efficient technologies will have much greater influence and importance than it has been assumed. Advances in science and technology may generate major breakthroughs in agriculture and health, protection of the environment and quality of life. On the other side, it is unclear whether the technology can compensate the environmental damages it causes.

Mathematical modeling and ***computer simulation*** are essential in making forecasts, preventing possible negative impacts, studying interrelation and interaction among various ecological, economic, demographic, social, and other phenomena. The next sections consider basic models of global changes, global trends, and technological changes.

2. Modeling of Global Trends and Global Changes.

Mathematical models are a useful tool to analyze global changes and trends. The global models should involve three modeling components:

- Modeling of biota (biological communities);
- Modeling of inorganic nature (the natural environment, excluding biota);
- Modeling of human activity (includes economic, social, and demographic processes).

Population models or *mathematical models of biota* have been successfully developed starting with the investigations of Malthus, Verhulst, Lotka, and Volterra during 19th and early 20th centuries. Such models have been well studied and modified to consider various real-life phenomena. Modern population models take into account delays and joint influence of different exogenous and endogenous population factors. They use various mathematical tools such as ***deterministic*** and ***stochastic models***, differential, integral and difference equations, ***optimization*** and ***computer simulation***, and so on.

Modeling of inorganic nature is often identified with modeling of the environment at whole. It can be subdivided into the modeling of different components of the environment (atmosphere, water, soil, etc.). One of major applied aspects is modeling of pollution propagation and climate change.

Modeling of human activity captures human impact on surrounding. It is a subject of mathematical economics and social sciences. The influence of economic activity on the environment is considered by environmental economics.

An integrated modeling of interrelationships among the environmental, biologic, economic, and social components of a global system is a scientific problem of a great complexity. Many attempts to estimate global development of such systems have failed and no satisfactory solution has been obtained. Nevertheless, large scientific projects on global trends have been implemented since 60's. The corresponding models are known as *global models*. Different modeling schools have common concepts as well as their own theories and mathematical techniques for constructing and testing models. The ***system dynamic*** and *complex* ***adaptive methods*** are among the main techniques. There are thousands of references on global models. Because of space limitations, we restrict ourselves to a brief description only of well-known global models.

2.1. Simple Models

Human population growth correlates with many environmental changes at global scale and over long time scales. There are basic human needs for food, water, shelter, community health, and employment that are related to the population size. The way in which society meets these needs determines environmental consequences at all scales.

Historically, the first ***mathematical model*** of a global change was suggested by the Englishman R. Malthus in "An Essay on the Principle of Population" in 1798. Following the model, the human population size would double every twenty-five years, and the food production as a land-limited resource could not possibly be increased quickly enough to keep pace with the growing population. Malthus' expectation did not come true for various reasons including a sharp increase in agricultural productivity and smaller than projected average birth rate.

This most simplified model of human impact on the environment is captured by the *IPAT identity* suggested by Ehrlich and Holdren in 2002:

$$I = P \times A \times T ,$$

where the environmental impact I is the product of the population P, the affluence A and the technology T (see Section 1.3).

Although the relation is not useful for small space and time scales, it provides some practical insights into the role of human activities in general. Indeed, it is estimated that, historically, the population growth has accounted for 38% of the emissions from the developed world and 22% in the less developed world. The affluence A reflects the human wealth and material comfort and generates higher levels of consumption. Thus, people in the developed world consume much more material and energy during their lives than do those in the less developed world. On average, people living in a developed nation consume twice as much grain, three times as much meat, nine times as much paper, and 11 times as much gasoline as the rest of the world. The environmental impact I correlates with the technology T, which increases the production efficiency and can reduce waste per output unit. The latter effect is usually associated with the ***environmental Kuznets curve.***

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Biographical Sketches

Dr. Natali Hritonenko received her Ph.D. from Byelorussian University (Minsk, Belarus). She joined Prairie View A&M University (Texas, USA) in 2002. Her research results in the areas of control theory, mathematical modeling in life sciences and economics, theory and applications of integral equations, and mathematical education are outlined in four monographs and 70 papers. She is in the Editorial Boards of five international scientific journals and in the organizing committees of numerous conferences and workshops. Her biographical profile appears in 2006-2007 Edition of Marques “Who's Who in Science and Engineering” and many others.

Yuri Yatsenko is a professor at College of Business and Economics, Houston Baptist University, USA, where he teaches economics and information systems. He has 150 scientific publications, including six books. His four latest monographs (Kluwer, Netherlands, 1996, 1999, 2003; Science Press, China, 2006), co-authored with N. Hritonenko, explore a wide spectrum of applied mathematical models in economics, industry, population ecology, and the environment. Professor Yatsenko taught at the universities of four countries and was listed in "Who's Who in the World - 1995", "Dictionary of International Biography" and other international reference directories. He also served as a senior consultant for several international companies in Canada and USA. He is in the Editorial Boards of four scientific journals.