

# Complex Eco-economic Systems

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## ABSTRACT

In the past there has been a lot of research on the topic of economic growth. Nevertheless, the environment has been a bit abstracted by standard economics. Scarce natural resources and our choices to protect them or exploit them jointly determine economic and environmental systems. In this paper we describe a model with the particular focus on the relationship among income, pollution, and non-renewable resources. We want to combine both economic and environmental sectors. The system dynamics approach is used in analyzing these complex relationships. This paper yields insight into the possibilities for replacing non-renewable resources with more renewable ones. Next, we present the simulation runs of the model that are conducted with the help of existing system dynamics modeling tools. Only simulated so far relationships between variables ought to undergo yet more cautious examination

**Keywords:** Environmental Systems, Nonlinear Systems, Modeling, Simulation, System Dynamics.

## 1. Introduction.

Recently there is much of concern about consequences of environmental growth on environment. The authors and proponents of The Limits to Growth Report, continue to argue that economic growth must be lower with other changes [1]. Conversely, others claim that growth fuels social improvement. Most researchers take rather more moderate views, implicitly treating both sides of the argument as excessive, but presenting very little evidence to support the moderate view [2]. We take a step toward understanding of consequences of economic growth with non-renewable resources. Although the resulting simulations are crude approximations, they provide a first indication of future trends in some variables.

We have constructed a dynamic modelling framework incorporating many details of the flows inside each of two systems and specified connections between the two systems. Incorporating the particulars of these links makes the model better reflect trade offs between the economy and the environment.

The model presented in this paper uses some macroeconomic and ecological relations. First we will describe system dynamics with the burden on casual loops. We list the important and causal relationships among the levels and trace the feedback loop structures. A variable in that system can increase, decrease, remain constant, or combine several of those characteristic modes. Then, we will describe the functions of system dynamics in environment. Next section will provide overview of our simple model. We will add to this model new sectors, like non-renewable resources and other. Finally, we present simulation runs of this model and draw some

conclusion. The methods developed in this paper provide a framework for further analysis and discussion. We are interested only in the broad behavior modes of capital, population and non-renewable resources system.

## 2. System Dynamics and System Thinking.

A "system" is a collection of entities that operate together. In this context a system can be a human being in whom the parts of the body (the organs, bones, fluids, muscles and cells) operate together for human functioning. In an economic context, the variety of problems can create the system: aggregate supply and aggregate demand, analysis and the determination of equilibrium output (national income), given current technology, investment, savings, and many others. In each case, conventional economic analysis has a powerful set of tools for examining the equilibrium state, its stability under alternative exogenous changes, and the relationship between initial equilibrium and final equilibrium (assuming the model has a stable solution) in response to a variety of influences.

At first, system dynamics was invented to give managers a tool to understand the complex systems they were charged with controlling. A system dynamics definition was proposed by a group lead by Jay Forrester (1971) created at the Massachusetts Institute of Technology [3]:

*“System dynamics deals with how things change through time, which includes most of what most people find important. It uses computer simulation to take the knowledge we already have about details in the world around us and to show why our social and physical systems behave the way they do. System Dynamics demonstrates how most our own decision-making policies are the cause of the problems that we usually blame on others, and how to identify policies we can follow to improve our situation”*

*Jay W. Forrester*

The word "dynamic" implies continuous change and that is what dynamic systems do - they continuously change over time. The methodology of System Dynamics uses computer simulation models to relate the structure of a system to its behavior over time. Usually the simulation looks forward into the future, to predict possible future results, but sometimes it looks to historical results. The SD models are powerful tools to help understand and leverage the feedback relation of complex systems Decision makers can use the models to test various scenarios and explore consequences of their decisions.

Every level in a flow diagram is a state variable that requires a differential equation. Material flow into and out of a state variable requires an explicit algebraic expression. The sum of expressions associated with the inflow and out-flow arrows is the right-hand side of the differential equation. A system dynamics model can be specified as a system of coupled, nonlinear, first order differential equations, Equation 1.

$$\frac{d}{dx} x(t) = f(x, p) \quad (1)$$

Here  $\mathbf{x}$  is a vector of levels (stock or state variables),  $\mathbf{p}$  is a set of parameters, and  $\mathbf{f}$  is a nonlinear vector-valued function. This is a recursive formulation, because the vector  $\mathbf{x}$  is, among other things, a function of previous values of itself. System dynamics is methodology rather than technique.

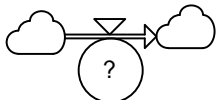
Simulation is a key aspect of system dynamics. It makes use of the ability of a computer to deal with many complex relationships so as to help decision makers and policy analysts who work with complex systems. A researcher can construct a model of a real system using computer software tools, and then use this model to simulate the outcomes of various options. System dynamics simulations are designed to correspond to what is, or might be, in the real world. A major limitation of simulation analysis is the assumption during the simulation, of

fixed changes in some variables, like exponential increases in population, industrial production, and the other economic activities.

### 3. Basic blocks in the system

System flow diagrams are generally attributed to Forrester and are thought to predate other diagramming methods. They use control-engineering symbology to distinguish flows of resources from the mechanisms that regulate them. Influence diagrams are drawn using arrows to link related concepts, with the arrow head showing the direction of influence.

We present basic building blocks of System Dynamics software (Powersim):



Auxiliary

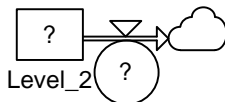
Flow with rate – rate equations describe rates of inputs to, or outputs from a state variable. The task of auxiliary variable is to control flows by mathematical expressions; primarily used to simplify the writing of rate equations.



Auxiliary\_1

Auxiliary\_2

Information link – shows which variable influence the other variable.



Level\_2

Auxiliary

Source or sink – origin or destination of a flow; on the picture we present outflow from the system. Rectangle (Level) means state variable; physical quantities that can be measured directly over time; dynamic quantities.

A stock is an accumulation, collecting whatever flows in, or losing what flows out. The purpose of the flow is to fill and drain an accumulation or stock. Levels are represented by rectangles, rates that influence those levels by valves, and auxiliary variables that influence the rate equations by circles. The arrow head on the flow pipe indicates direction of flow. The auxiliary holds values for constants, defines external inputs to the model, calculates algebraic relationship and serves as a repository for graphical function. The arrow between the auxiliary and the flow is called a connector. It represents a flow of information. Solid arrows show real flows of money, goods and people. Flows come from a cloud symbol and flow into a stock, or reverse is also true. The cloud symbol is used to represent system boundary and is not important to the model behavior.

We can present some hydraulic metaphors. Stock could be presented as a bathtub and a flow as a faucet and pipe assembly that fills or drains the stock as on the picture. State variables define the system; than information is transmitted to the decision variable (flow), which changes the system. Each of the arrows represents a general relationship that is important in the population-capital system. Most of the causal influences in the real world are non-linear; that is, a certain change in causal variable may affect another variable (for example life expectancy) differently, depending on the point within possible range of the second variable at which change takes place [4].

Causal loop diagrams, which are a form of system flow diagram, are drawn to highlight various feedback relationships in the system. Many practitioners prefer them for better understanding of underlying relationships. They show how change in one variable influences the other variable.

#### **4 System dynamics and environment.**

A systems dynamics approach can be used in modeling many systems. Outside of the mainstream system dynamics literature, some ecological economists have made use of system dynamics modeling techniques in the context of studying integrated economic ecological systems. Meadows et al. [1] used these dynamical models in their Limit to Growth Report, which started worldwide discussion about the idea of sustainable development. Although system dynamics has its limitations, it is quite powerful in analysing complex relationships between the economy and the environment. The modellers use all kinds of 'multipliers' to model positive and negative feedbacks. In the models such multipliers might change over time or because of policy decisions or economic and technical developments [5]. Evidence that the economy is in conflict with the earth's natural resources can be seen in the daily news that fisheries are collapsing, forests are shrinking and soils are eroding. The challenge of it is to change those trends before we experience the long term decline [6]. Ecologist claim that economic activity depends on ecosystem. They worry about limits, while economist do not see such constraints. Economist believe in market, while ecologist not. Economist look at the unprecedented growth of the global economy and international trade and investment and see a promising future. They see that global economy has expanded sevenfold since 50's. Conversely, ecologists view this process rather as burning vast quantities of artificially cheap fossil fuels, the process of destabilizing climate. They see more destructive storms, melting ice caps, and rising sea level that will shrink the land area even as population continues to grow. They view economy rather as altering climate with consequences that no one can foresee. Ecologist see that 480 million of the world population are being fed with grain produced by overpumping aquifers. Brown [6] argues that the economy, being in conflict with its support systems, is destroying these systems, consuming its endowment of natural capital.

One world's problems is lack of the clean water. Some rivers, like Colorado, are left without water and rarely reach the sea. Water tables in the world are falling as the demand for water outruns the sustainable yield of aquifers.. Thanks to new diesel and electric pumps we are able to pull water out from aquifer faster than it is replaced by precipitation.

Deforestation and fires of forest are another dilemma. The world is losing biodiversity and oceans are overfished. Daly [7] notes that the world "has passed from an era in which manmade capital represented the limiting factor in economic development to an era in which increasingly scarce natural capital has taken its place". According to Brown [6], the important challenge for us is to design eco-economy, one that respects the principles of ecology.

Brown writes that economic growth for the last half century was considerable. The economy expanded sevenfold Only Dow Jones index increased from 3000 to 11000 in 2000 year. But, as we develop, our economy is slowly destroying its support systems, consuming its endowment of natural capital. Demands of the expanding economy, as now structured are surpassing the sustainable yield of ecosystems. Easily a third if the world cropland is losing topsoil at the rate that is undermining its long-term productivity. Fully half of the land is overgrazed and deteriorating into desert. The forests are continuously shrinking. A sustainable economy respects the sustainable yield of the ecosystems on which it depends: fisheries, forests, rangelands, and croplands. Despite this ecological knowledge, many national governments have expanded economic activity with little regard for sustainable yields or the fragile balance in nature. The ecologists recognize that the value of services should be incorporated into market signals if they are to be protected. Forest for example may provide services such as flood control and the recycling of rainfall inland that are several times more valuable than its timber yield. Unfortunately it is not reflected by market. Higher price of scarce resource will not stop its exhaustion. Conversely, it can lead to even higher depletion. For example higher prices of fish encourage investment in additional fishing

trawlers. A similar problem will be with aquifers, forests, and rangelands. Once the climbing demand for water surpasses the sustainable yield of aquifers, the water tables begin to fall and wells go dry. The market says drill deeper. Evidence is accumulating that our global economy is undermining itself. If we want to continue growth, we should restructure global economy. One step towards sustainable economy was made by Denmark, which banned coal-fired power plants and the use of nonrefillable beverage containers. Moreover, it is getting 15 percent of its electricity from wind. Another country, Iceland, is planning to shift to hydrogen economy. In future cars and buses will run on fuel-cell engines powered by electricity produced with an electrochemical process using hydrogen instead of internal combustion engines.

## 5. Analysis of main relationships in the model

### 5.1 Basic sectors in our model

To create the dynamic model of a sustainable development following sectors are set: capital with population, non renewable fossil fuels, natural capital, carbon and green capital. Each of these sectors represents the principal variables in our model, which are connected together each other.

Especially carbon dioxide in atmosphere sector is presented in our model to reflect an impact of global pollutants on productivity. We assume, similarly to Yamaguchi [8], that increased amounts of pollutants in atmosphere is reducing productivity and output. We consider both non renewable resources together with alternative energies generated by hydrogen, sun and geothermal sources. Such alternative energies are generated by alternative capital stock, called green capital. Such capital is created by green investment, which in turn come from saving. Total amount of savings and investment is not affected by the green investment. The economy heavily depends on non –renewable fossil fuels that cause an emission of carbon dioxide and eventually global warming. We analyse that impact by setting a positive level of carbon contribution to the fossil fuels productivity, just for example 0.4. We can expect it will lead to great impact on capital level. Shifting the carbon-based economy toward a hydrogen one, just as proposed by Brown [6], can slow down economic collapse expected by depletion of non-renewable fossil fuels. Appropriate level of green investments can put economic growth on sustainable path.

### 5.2 Capital with population sector

First, we consider behavior of simple macroeconomic model, which comprise only capital, income, consumption, and savings, like in [9]. In a simple capital model, excluding population, we have two types of equations: one is a stock –flow relationship that specifies a dynamic movement. Another one is equation of causal relationship in which change in one variable is caused by other variable. The economy is considered as aggregate. A single variable  $K$  measures industrial capital.  $K$  changes over time according to the production  $Y$  of industrial capital, less consumption [10]

$$\frac{dK}{dt} = Y - C \quad (2)$$

or we can write that capital is accumulated by investments, first equation in the pair of equations, (3):

$$\begin{cases} K_{t+1} = K_t + I_t \\ Y_t = \frac{1}{v} K \\ C_t = c Y_t \\ S_t = Y_t - C_t \\ S_t = I_t \end{cases} \quad (3)$$

where:

$K_{t+1}$  is capital stock in time t+1,

$K_t$  is capital stock in time t,  
 $Y_t$  is income in time t,  
 $\nu$  is capital–output ratio,  
 $C_t$  is consumption in period t,  
 $c$  is marginal propensity to consumption,  
 $S_t$  are savings in time t,  
 $I_t$  is investment in time t.

These five equations become simple enough to describe the growth process of our economy in our model [9]. First Equation in (3) represents a capital accumulation process in which capital stock is increased by the amount of investment in a specified time unit, like one year. Second relationship is well known by economists as a production function. We assume all production comes about as a function of capital [10]. In these equation,  $\nu$  is the capital output coefficient, and  $I$  are investment. The amount of consumption is assumed to be proportional to output. It is usually assumed that 80 percent of income is consumed, and the rest is saved. Subtracting consumption from income leaves savings, forth equation in (3). In our case 20 percent of consumption is saved and invested. Saving can be changed into investments goods like raw materials, thereby increasing capital stock. At equilibrium, investments have to be equal to saving as shown in fifth equation of (3), otherwise output would not be sold out completely or would be in short supply.

It is essential to find a steady state equilibrium for structural consistency of the model. Steady state implies that all stocks stop changing, which, in turn, means that there are no flows among them. In our model, a steady-state equilibrium of capital accumulation is attained for  $K_{t+1} = K_t$ . To calculate the steady state analytically, five equations of the model have to be first reduced to a single equation of capital accumulation (4):

$$K_{t+1} = \left( 1 + \frac{1-c}{\nu} \right) K_t \quad (4)$$

Then, a steady state is reached only when all the income is consumed and there are neither saving nor investments, i.e. coefficient  $c$  must equal one. In our numerical example, a steady-state equilibrium could be attained at the example values of capital  $K^*=1000$ , consumption  $C^*=cY^*=250$ , and  $S^*=I^*=0$ .

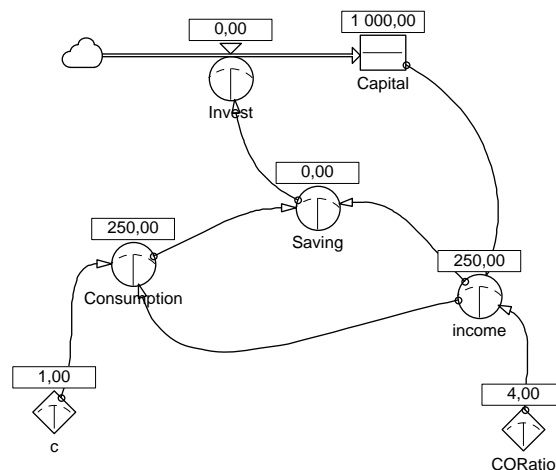


Figure 2. A steady state equilibrium diagram of simple capital model when coefficient of marginal propensity to consume equals one. Diagram in Powersim software

We observe that in this state all income is consumed and there is neither saving nor investment, Figure 2. In fact, we have not yet applied depreciation. By assuming that coefficient  $c$  is lower than one (for example 0.8), a growth path can be found easily. Then 20 % of output (or income) is saved for investment, which, in turn, increases the capital stock, and consequently contributes to the increase in output in the next period, driving the economy toward indefinite growth.

Although capital value is not fixed, but is decreasing over time. Let us introduce capital depreciation in the macroeconomic growth model. Equation (3) of capital accumulation is expanded for capital depreciation, yielding Equations (5).

$$\begin{cases} K_{t+1} = K_t + I_t - D_t \\ D_t = \delta K_t \end{cases} \quad (5)$$

where:

$D_t$  is capital depreciation over time  $t$ ,

$\delta$  is coefficient of capital depreciation.

In our model capital depreciation is simply made by adding an outflow arrow of depreciation from the capital stock. A given amount of industrial capital, operating at constant efficiency, will be able to produce a certain amount of output each year. Some of that output will be more factories, machines etc., which are investments that increase the stock of capital goods. At the same time, some capital equipment will depreciate or be discarded each year. To keep industrial capital growing, the investment rate must exceed the depreciation rate.

In a steady-state equilibrium investments must be equal to depreciation ( $I_t = D_t$ ), as it can be easily concluded from (5). To obtain the steady state analytically, all equations in the model have to be reduced to a single capital accumulation, (6):

$$K_{t+1} = \left( 1 + \frac{1-c}{v_t} - \delta \right) K_t \quad (6)$$

A steady state condition is then easily obtained as follows (7) (asterisks are added to the constants that meet this condition):

$$\frac{1-c^*}{v^*} = \delta^* \quad (7)$$

At the steady state, marginal propensity to consume becomes less than unitary, (8):

$$c^* = 1 - \delta^* v^* < 1, \quad (8)$$

which implies that a portion of output has to be saved to replace the capital depreciation [7]. One possible combination of numerical values for the steady state is  $(v^*, c^*, \delta^*) = (4, 0.8, 0.05)$ .

To simulate economy growing out of the steady state; that is, for  $K_{t+1} > K_t$  we improve capital maintenance by setting  $\delta < \delta^*$ , for example at  $\delta = 0.02$ . The results of simulations show that during 100 time units capital stock will be kept increasing from  $K_T = 1000$  to  $K_{100} = 19218$  and keeps growing output from 250 to 4805.

Next, we consider population which we embodied in the model, (9):

$$\begin{cases} N_{t+1} = N_t + \Delta N_t \\ \Delta N_t = \alpha N_t - B N_t \end{cases} \quad (9)$$

where:

$N_{t+1}$  population over time  $t+1$ ,

$N_t$  population over time  $t$ ,

$\Delta N_t$  - net birth,

$\alpha$  birth rate,

$B$  death rate,

$t$  time.

Each year the population is increased by the total number of births that year and decreased by the total number of deaths that that year, (8). The absolute number of births per year is a function of population. For example, in 1650, world population numbered about 0.5 billion, and initially it was growing at a rate of approximately 0.3 percent per year. In 1970 world population totaled 3.6 billion, and the rate of growth was 2.1 percent per year. In 2001, world population was equal to 6.1 billion.

The average number of deaths is a function of total population size, consumption, and pollution. For any society to maintaining a wholesome living standard of a minimum amount of consumption has to be guaranteed. Let  $c_m$  be such a subsistence-consumption level. Then, consumption per capita is defined as minimum from subsistence consumption level and income per capita, (10).

$$c_p = \text{Min}(c_m, Y_t/N_t) \quad (10)$$

where:

$c_p$  consumption per capita,

$c_m$  subsistence consumption level

This formula enables per-capita consumption to be lowered from the level of subsistence. A decrease in per-capita consumption may increase the death rate, because of food shortage. In this way, a negative feedback loop is completed for per capita consumption. Then, the total amount of consumption has to be defined, (11).

$$C_t = c_p N_t \quad (11)$$

where:

$C_t$  is total consumption.

With the introduction of a minimum amount of consumption that is demanded irrespective of the output level, the amount of saving defined in the saving function might become negative, as population and consumption increase. To warrant a non-negative amount of saving, the saving function should be defined as maximum from zero and as the difference between output and consumption.

Now, we define in our model labor force as percentage of population, (12).

$$L_t = k N_t \quad (12)$$

where:

$L_t$  is labor force,

$k$  is fraction of working population

The introduction of this equation allows us to redefine production function in (3) as a Cobb Douglas form from capital and labor, (13).

$$Y_t = A P K_t^\alpha L_t^{1-\alpha} \quad (13)$$



where

$A$  is technological factor,

$P$  is productivity parameter depended on fossil fuels and green capital factors and  $a$  is a Cobb-Douglas production factor.

We assume conversely to [9], that  $A$  equals 0.7. The Cobb Douglas function allows substitution between capital and labor.

### 5.3 Nonrenewable Fossil Fuels Availability.

Next, we add to our model non-renewable fossil fuels, necessary for industrial production. As the world's population and capital grow, the demand for nonrenewable resources will increase accordingly. The amount of resources consumed each year can be found by multiplying the output (input) by usage rate. As population becomes wealthier, it tends to consume more fuels per person per year. The following equations represent non-renewable fossil fuels and their input, (14).

$$\begin{cases} R_{t+1} = R_t - \Delta R_t \\ \Delta R_t = \lambda Y_t \end{cases} \quad (14)$$

where

$R_{t+1}$  non-renewable fossil fuels over time period  $t+1$ ,

$R_t$  non-renewable resources over time period  $t$ ,

$\Delta R_t$  is non-renewable fossil fuels depletion,

$\lambda$  is input amount of fossil fuels necessary for producing an unit of output.

Let us next consider the existence of steady state equilibrium of initial simple model with non-renewable resources. There are two state variables,  $K_{t+1}$  and  $R_{t+1}$ , in the model. A steady state of capital accumulation is not affected by the introduction of non-renewable fossil fuels, since a steady state of non-renewable fossil fuels implies  $R_{t+1}=R_t$ , which in turn means  $\Delta R_t=\lambda Y_t=0$  or  $Y_t=0$ . On the other hand, a steady state equilibrium of capital stock implies a positive amount of output, that is  $Y_t>0$ . Hence we conclude that macroeconomic growth model with non-renewable resources cannot have a steady equilibrium. Non-renewable natural resources are limited, but they are continuously depleted even at a steady state equilibrium of capital accumulation, contrary to the general belief that they are not depleted in a non-growing economy.

At steady-state equilibrium set by condition (8), the initial non-renewable resources  $R_t=1000$  constantly diminishes over one hundred years later, that is,  $R_{100}=500$ . This result can be examined by simple calculation. Since the economy is at the steady state, the output level remains constant at  $Y_t=100$ . Hence  $\Delta R_t=\lambda * Y_t=0.5*100=5$ , and non-renewable resources are depleted by five tons per every year. After a hundred years half of resources will be depleted and over two hundred years, they will be totally exhausted [9].

To show how fast non-renewable resources deplete under a growing economy, when the depreciation rate is 0.02, the economy starts growing at the rate of 3%. In this case, non-renewable resources will be totally depleted after 66 years. We will give now a practical example. Easter Island, one of the most remote spots on the earth is a small island of 160 km<sup>2</sup> in the Eastern Pacific. Around the year 400, some sailors of Polynesian origin arrived there. Population has grew slowly until the year 1100, when growth accelerated dramatically, perhaps doubling every century until 1400. Before the arrival of people, Easter Island was very forested and supported a diverse set of fauna, particularly birds. As the human population grew, the forests were progressively cut to provide wood and fiber for boats, structures, ropes, and tools.

By about 1400, deforestation was nearly complete. The loss of tree cover dramatically reduced the island's carrying capacity. Soil erosion increased with deforestation as rain washed away the unprotected soil. Without tree cover, wind speeds at ground level increased, carrying still more valuable soil into the sea. Fishing also

declined, as boats could no longer be maintained. As the capacity declined, population growth slowed, reaching a peak generally estimated to be between 6,000 and 10,000 people around year 1600. In many other documented cases population growth led to deforestation, the extinction of native species and changes in climate, all of which were followed by a population collapse [11].

#### 5.4 Demand for nonrenewable energy and green energy.

Depletion of non renewable resources depends on the demand for fossil fuels. In turn, demand for non renewable fossil fuels depends on demand for energy minus green energy generation. We assume, similarly to Yamaguchi [8], that at least 10 percent of energy comes from energy generated from fossil fuels.

Let  $\Delta GI_t$  be an inflow amount of renewable substitutes (green investment) that can be added to the green capital stock, and the  $\mu$  can be level of the substitutes, (15). We assume, for simplicity, that the green investment come from saving, therefore only investment is lower, without relinquishing consumption. Therefore, a higher level of substitutes decreases only investment in conventional capital, (15). The coefficient of substitutes for non-renewable resources was chosen as 0.07. A low level of substitutes allows higher depletion of non-renewable resources, lowering in this way both productivity and output. Non-renewable resource depletion is changed by allowing an inflow of renewable resources to the equation of non-renewable resources, (15).

$$\begin{cases} \Delta GI_t = \mu S_t \\ GK_{t+1} = GK_t + \Delta GI_t - \Delta GD_t \\ \Delta GD_t = \pi GK_t \end{cases} \quad (15)$$

where:

$\Delta GI_t$ -amount of renewable substitutes (green investment),

$\mu$  - be level of the substitutes,

$\Delta GD_t$ -depreciation of green capital),

$S_t$ -saving,

$\pi$ -coefficient of green capital depreciation,

#### 5.5 Pollution as an Effect of Economic Development

The relationship between economic development and pollution is very complex issue. Natural resources serve as inputs to the production of many goods and services. If the methods of production were not changed, then damage to the environment would be linked to the scale of global activity. For this reason, in the last few years several studies have tried to characterize this problem as an empirical reduced-form relationship [12,13,14]. According to some theories, at very low levels of economic activity, environmental impacts are generally low; but as development proceeds, pollution increases rapidly. At higher levels of development, structural changes lead to a decrease in pollution. Economic growth eventually redresses the environmental impact of the early stages of economic development, and that growth leads to further environmental improvements in developed countries or tends to fix environmental problems. These results are similar to those that would be predicted by the environmental Kuznet's Curve. It proposes there is an inverted U-shaped relation between various indicators of environmental degradation and income per capita.

At present, let us assume that production and consumption activities, in addition to capital accumulation, generate as by-products consumer garbage, industrial wastes, and depreciation dumping. We assume these by-products are accumulated as an artificial environmental stock called sink, first equation in (16). These by-products

are, in turn, dumped to the earth or they are scattered in the atmosphere. The amount of industrial wastes (mainly pollution) is proportionate to an income, second equation in (16).

$$\begin{cases} S_{t+1} = S_t + \Delta S_t \\ W_t = \varphi Y_t \\ G_t = \chi C_t \\ M_t = \zeta D_t \\ W_t + G_t + M_t = S_t \end{cases} \quad (16)$$

where:

$S_{t+1}$  is sink of pollutants and garbage over time  $t+1$ ,

$S_t$  is sink of pollutants and garbage over time  $t$ ,

$W_t$  is amount of industrial wastes created during producing a unit of output,

$\varphi$  is coefficient of industrial wastes,

$C_t$  is amount of garbage coming from consumption,

$\chi$  is coefficient of garbage,

$D_t$  is amount of dumping created during using of capital in production,

$\zeta$  is coefficient of depreciation dumping,

We assume also that existence of carbon in atmosphere is decreasing productivity and output. We treat carbon as a sink. Flow of carbon into the atmosphere depends on use of fossil fuels in production. Some part of carbon is certainly fixed in the atmosphere. Productivity maybe decreased b droughts and storms that are in turn triggered by an increased temperature and a high sea level., therefore it is very important to apply renewable green energy (instead of fossil fuels).

## 6. Results of Simulation Using A Sustainable Development Model

Main relationships in our model are presented as causal loop diagram, Figure 3. The results of simulation conducted for a period of two hundred years show that capital is increasing from 400 at the start of our simulation in 2001 year to about 21426 units in year 2128, so after 127 years, and then continuously decreases, reaching value of 16014 in 2200 year, Figure 4. Output increases from around 141 units at the beginning of our simulation in 2001 year to about 807 units in year 2075, so after more than 70 years, and then continuously decreases, reaching value of 480 in 2200 year, Figure 5. Output must decrease, since capital in our economy is depreciated and there are no assets to renew it (investments are falling together with income since 2055 year, after an initial increase) an initial increase of output It should be remarked that both investment and green investment are falling with decreasing output. Conversely consumption, which is assumed to be proportionate to the population, is showing slightly increasing tendency, Figure 5. Population growth is lowered by a decrease in the birth rate due to decreased food consumption. Population cannot grow permanently because also natural resources will continue to be depleted as long as there is any amount of population to consume it. Natural resources are decreasing from 1000 at the start of our simulation in 2001 year to 400 in year 2200.

At first decrease in resources has no decreasing effect on capital. Because of their existence in large amounts, output and, consequently, capital can be increased. After significant decrease of resources capital starts declining. As the resources continues its inexorable decline, the decline rate races by the growth rate. Thus, the outflow from capital becomes greater than the inflow, and it will always remain so. Consumption or erosion of the carrying capacity by the population creates a negative feedback, which limits growth. Economic growth and

population increase cut resources. When resources are initially ample, positive growth dominates and the system grows exponentially. As the economy grows, and resources are depleted, the negative loop gradually gains in strength.

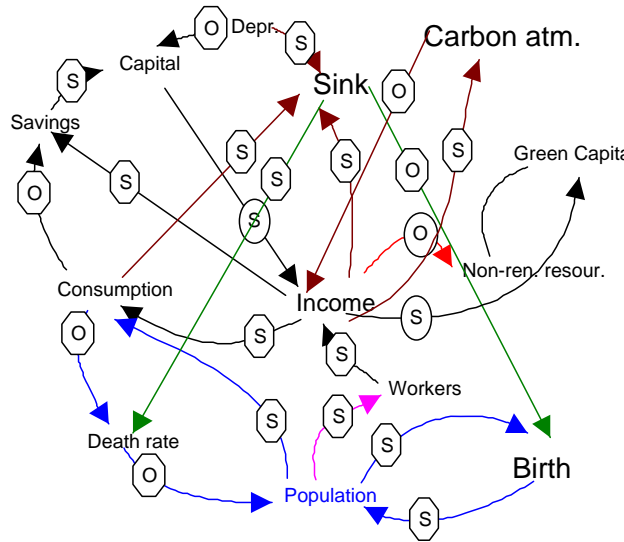


Figure 3. Causal loop diagram of main relationships in our model. S is change in the same direction and O is change in the opposite direction.

The results agree with many previous research. Malthus was the first who pointed out the possibility of growing relative scarcity of natural resources, cited by Solow [10]. Another source, The Report of Rome Club, cited by [12], was underlining, not only about a food crisis, but also about natural resources exhaustion and environmental degradation as a result of development. Also, the report predicted that, if this exponential growth was not curbed, industrialization would halt economic growth, [15]. Then, world population would be curtailed as a result of an increase in the death-rate caused by food shortages and environmental pollution. Those results draw public awareness to the need for saving and conserving the environment and natural resources. Meadows [15] writes:

“One can cut a forest beyond its annual growth rate for quite long time, because there is a standing stock of wood in the forest and that has grown over decades or centuries (...). The larger the accumulated stocks, the higher and longer the overshoot would be.”

Because we have feedback delays, the global economic system is likely to overshoot and collapse.

Such idea of limits to growth is difficult to accept by many people. Limits are politically difficult to recognize and economically unthinkable. Rather many tend to assume there is no limits thanks to power of technology and free market. With increasing income comes an increasing amount of wastes and pollution. We can circumvent such a fast depletion of non-renewable resources and stay within a limit of resource availability by limiting the inefficient use of non-renewable resources. To accomplish this circumvention, an introduction of long-term management resources is necessary. Further, substitutes for non-renewable resources have to be discovered or newly invented through technological development. It is essential to use more renewable sources of energy, like biomass instead of fossil fuels, together with less capital-consuming technology. To do this, there is a need for development of new modern technologies.

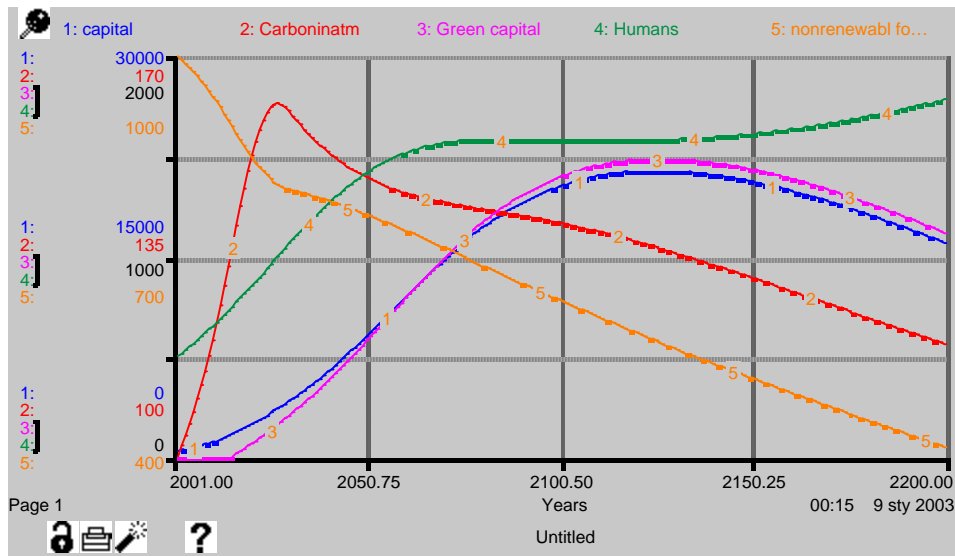


Figure 4. Results of our simulation: conventional capital, green capital, carbon in atmosphere, non-renewable fossil fuels, and population (humans).

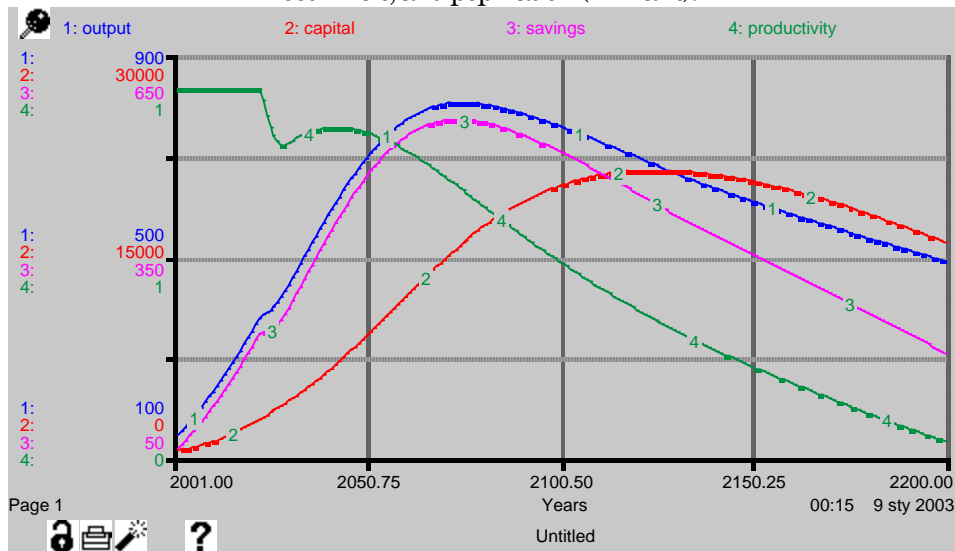


Figure 5. Results of our simulation: Output, capital, productivity and savings.

## 7. Conclusions

This paper examined the impact of economic development on environmental quality. Certain plausible assumptions about the response of some variables were made. It was shown that when the economy grows pollution and depletion of natural resources increases. A depletion of non-renewable fossil decreases output and leads consequently to lower population growth. Application of renewable capital can slow down this process. A constructed system dynamics model is so far very comprehensive and we used mainly theoretical, not empirical, data. The greatest value of model is not in prediction and forecasting, but developing our basic understanding of the relationships between economy and the environment. From this basic model we do not expect to get exact predictions of the outcome of different policies nor exact numbers about population, capital, etc. in a concrete year. The goal of that work was to increase the knowledge about system behavior under different circumstances; to increase understanding about inside development potential and choosing best outside projects for increasing

strengths of the community. However, the results of conducted research are rather pessimistic, but we must look into the possibilities for replacing non-renewable resources with more renewable ones, like renewable energy. Relationships between variables simulated so far ought to undergo a more careful examination. An important policy implication that comes from our simulation results is that short-term sustainability is possible with the use of non-renewable resources. This implication points out a key issue for future generations.

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