Simulating sustainability: a resources perspective

William Grace

Australian Urban Design Research Centre, University of Western Australia

Abstract

A global population – economy - resource model explores the future impact of declining resource availability on the world economy. The model tracks the likely future consumption of renewable resources, fossil fuels and non-renewable materials and the economic impact of availability. Scarcity will likely become evident during the latter part of this century and constrain economic production, reducing income per capita, living standards and ultimately population. Policy interventions involving a rapid transition from fossil fuels to renewable energy, reduced resource intensity and materials recycling are necessary to correct this trajectory and facilitate ongoing improvements in global average living standards.

Keywords

sustainability, population, resources, scarcity, limits, systems

1. Introduction

In order for people everywhere to attain and retain a reasonable quality of life (i.e. to achieve enduring human wellbeing), human society must live within the limits imposed by the bio-physical world. This is the essential message conveyed initially by the findings of System Dynamics research in the early 1970's (e.g. World Dynamics and Limits to Growth) and numerous researchers since.

Using the technique of System Dynamics, the World Dynamics and Limits to Growth models establish a causal structure linking living standards (the basic constituent of wellbeing) to production and consumption of renewable and non-renewable resources and pollution absorption capacity. These models operate at the global scale. However, effective management of production and consumption cannot occur (presently) at that scale. The near-term system behaviour at the global scale will "emerge" from interactions at smaller scales – nations, regions and cities. However no country can be "sustainable" in isolation and so any model that operates at that scale must reflect the key exogenous variables arising from the global scale resource flows.

The work described here uses a relatively simple population – economy - resource model to explore the trajectory of the world system and the implications for enduring human wellbeing. The purpose of the model is not to provide an alternative to the Limits to Growth World 3 model but rather to establish a simplified version that uses readily available metrics for which data is available at national and regional scales. The same model architecture can then be used as a basis for smaller scale versions of the model which, while being reflective of the global dynamics, facilitates exploration of high level policy options with respect to resource use at that scale.

2. A global sustainability model

Jay W. Forrester's landmark work, World Dynamics(Forrester, 1971), was the predecessor of better-known global models that followed. Forrester's World 2 model, which used the System Dynamics technique in the DYNAMO programming language, linked population, natural resources use, capital investment, food and pollution. The model highlighted the potential limits to population growth arising from crowding, food supply, pollution and natural resources[1]. A number of other global models have been produced since, as documented by several authors (Castro & Jacovkis, 2015; Meadows, Richardson, & Bruckmann, 1982).

Included in these is the famous Limits to Growth study (Meadows, Meadows, Randers, & Behrens, 1972) which built on Forrester's work in World Dynamics via the World 3 model using the STELLA software. Key variables in the World 3 model included world population, industrialization, pollution, food production and resource depletion. The model explored various scenarios for the future of the world system. Several of the scenarios saw "overshoot and collapse" of the global system during the 21st century, while others resulted in a "stabilized world". The study was updated initially in 1992 (Meadows, Meadows, & Randers, 1992) with the World3-91 model and more recently (Meadows, Meadows, & Randers, 2004) with a further iteration of the model, World3-03. The essential conclusion of the latest study, now a decade old, is that humanity is dangerously in a state of overshoot.

Scenario 1 of the World 3-03 model is the reference point for the other scenarios presented in Limits to Growth: The 30 Year Update. This scenario produces overshoot and collapse in the world system around 2025 due to a "non-renewable resources crisis". In Scenario 2 the model assumes higher stocks of non-renewable resources which delays the onset of population collapse to around 2050, although living standards begin to decline around 2025, as in Scenario 1. The collapse in Scenario 2 is triggered by pollution.

The model I present here is highly simplified in comparison to the World 3-03 model. It does not contain many of the sectors (i.e., sub-models) in World 3-03, including the disaggregation of the economy into industrial and agricultural sectors. Furthermore, it only accounts for carbon pollution, while World 3-03 includes persistent pollution from industry and agriculture. These simplifications allow the model to focus on the influence of resource constraints on aggregate global output. Thus it seeks to capture the essential resource crisis reflected in Scenarios 1 and 2 of World 3-03 but using more accessible data.

One advantage of this simplified model is that it uses metrics that can easily be calibrated against readily available data, which facilitates a quasi-quantitative analysis of system trajectory. The model has been constructed to project the current trajectory of population, economic production and associated resource use into the future. By definition therefore, it does not reflect any changes that may occur to the underlying relationships in the future, whether due to scarcity or policy.

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[1] As the name implies, there was also a World 1 model, developed earlier by Forrester as the behest of the Club of Rome to help investigate '*the predicament of mankind*'.

A high level causal loop diagram[2] for the model is set out in Figure 1. Causal loop diagrams indicate the influence over time of interacting variables on system behaviour, and are the building blocks of a stock and flow model.

The model, which is simulated in the Vensim software, explores the 350-year period of 1960-2310 using a one-year time step and Euler's Method for numerical integration.

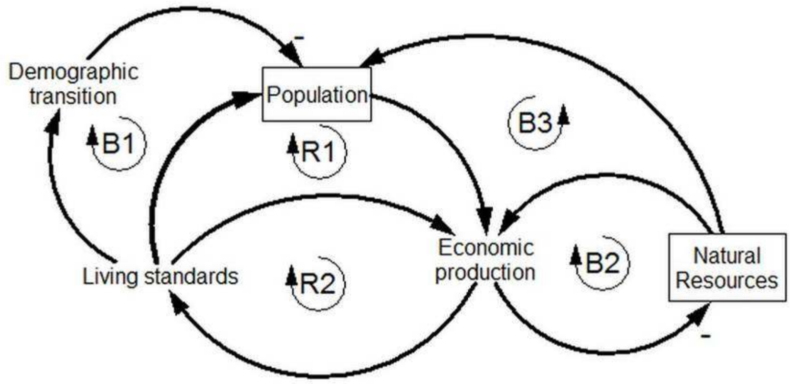

Figure 1 Causal loop diagram of global sustainability model. Key stocks are shown in boxes with inflow and outflow rates as arrows. Arrow polarity is positive unless noted as negative. 'R' and 'B' represent the overall polarity of a loop as either reinforcing or balancing.

Rapid growth in economic production has facilitated the massive increase in global population over human history (Loop R1), particularly since the rise of agriculture some 10,000 years ago. However economic production is not linked purely to population growth. GDP per capita growth (the main influence on basic living standards) also reinforces population growth (Loop R2), and has been growing in both developed and developing nations for centuries. More recently, however, the rise in living standards in developing nations has led to reduced birth rates (the so-called demographic transition) – Loop B1.

Economic production, in turn, depends on the use of natural resources (Loop B2), some of which are renewable (e.g. food and fibre) and some of which are non-renewable (e.g. metals and fossil fuels). Of course the human population also relies more directly on natural resources for survival (e.g. productive soils and clean water) – Loop B3.

Among the five loops in Figure 1, R1 and R2 have been dominant to date, as suggested by the - similar trajectories of global population (Figure 2a) (United Nations, 2004) and global gross domestic product (Figure 2b) (Groningen Growth and Development Centre, 2010).

[2] An explanation of causal loop diagrams is included in Appendix 2 and further explanation is available at http://www.public.asu.edu/~kirkwood/sysdyn/SDIntro/ch-1.pdf.

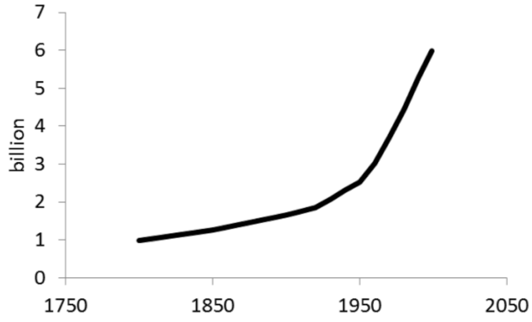

Figure 2a World population

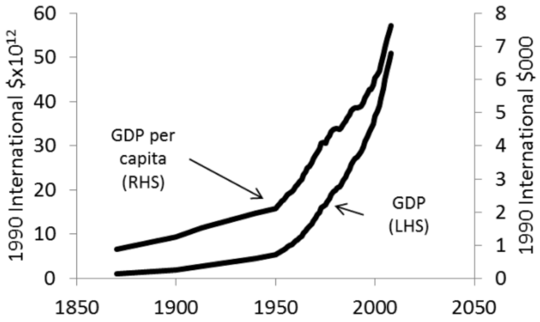

Figure 2b World GDP

A key question for the future is whether global population and living standards can be stabilised at levels that deliver enduring well-being given available flows of natural resources.

2.1 The Economy

The economy is modelled here in line with Robert Solow's growth model (Solow, 1956) as developed by Michael Radzicki (2004). Specifically, the economy's output or Gross Domestic Product (GDP) is determined by the Cobb Douglas production function.

$$GDP = K^{\beta} \cdot L^{1-\beta} \tag{1}$$

where GDP = Global Gross Domestic Product (a measure of economic output)

K = stock of capital in the world economy

L = stock of effective labour in the world economy

β = output elasticity of capital

Radzicki has shown that the Solow model can only explain all of Kaldor's so-called stylized facts[3] (Kaldor, 1957) if (as Solow posited) it includes technical progress. In Radzicki's model, technology is modelled as a stock that acts as a multiplier on labour, representing productivity improvements due to technological development in the world economy.

The Solow growth model with technological progress describes well the historical exponential growth in the world economy. However, nothing limits growth in this model and so it continues to produce GDP growth over time (even with zero population growth) as long as there are stocks of labour and capital. The version of the Solow model presented here includes factors that facilitate production reaching a dynamic stability. This is achieved through balancing loops that constrain savings, and hence investment, when GDP per capita reaches a threshold value. The threshold occurs when GDP per capita reaches the global average of around $7,000 per person per year compared to the present figure of around $6,000 (constant 2000 US$). Exceeding this threshold ultimately reduces Investment to $0 at around $35,000 per person per year which is about 40% higher than that of OECD countries presently (World_Bank, 2013).

[3] Kaldor's six "stylized facts" are empirical observations related to economic growth that appear to apply to the economic trends in many different industrialized countries.

The model is further modified to account for natural resources. Specifically, the economic sector is unaffected until Resource Availability (the ratio of available resource flows[4] to demand for resources) falls below 1. Furthermore, when Resource Availability falls to zero, Savings/Investment and Technology growth also fall to zero. The causal loop diagram of the economy is shown in Figure 3.

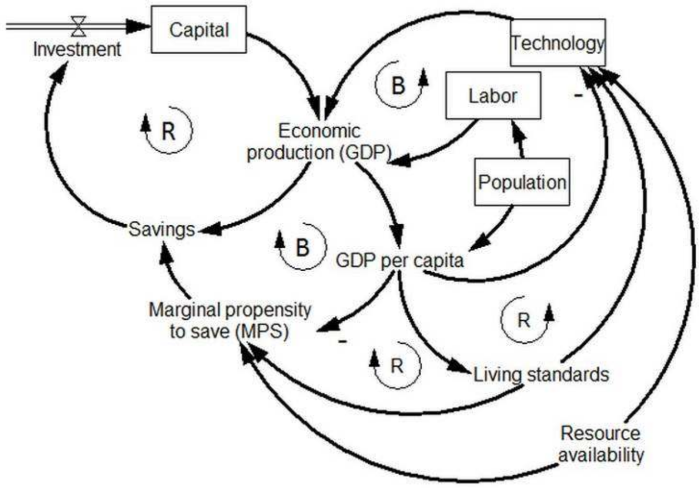

Figure 3 Causal loop diagram of the economy sector

2.2 Population and Living Standards

As described before, the model assumes that living standards have a causal relationship to population growth (Figure 1). However at higher levels of living standards, the demographic transition is triggered and the rate of population growth reduces, ultimately to zero. The United Nations Human Development Index (HDI) is used as a proxy for living standards. The current global average HDI is around 0.68 (UNDP, 2012). In the model, I assume population growth becomes zero at an HDI of around 0.90, which is slightly higher than the existing index for very high HDI countries. I also assume that population growth begins to slow when natural resource stocks fall to around 40% of their initial value.

The causal loop diagram for population and living standards is shown in Figure 4, which expands the structure shown in Figure 1 to incorporate loops for both GDP and GDP per capita. The demographic transition balances the GDP loop (as depicted in Figure 1), but reinforces the GDP per capita loop. Accordingly the demographic transition loop is depicted as both reinforcing and balancing, as population changes have opposite effects on GDP (positive causation) and GDP per capita (negative causation).

[4] Resource flows (and hence consumption of resources) are constrained as the stock of resources is diminished.

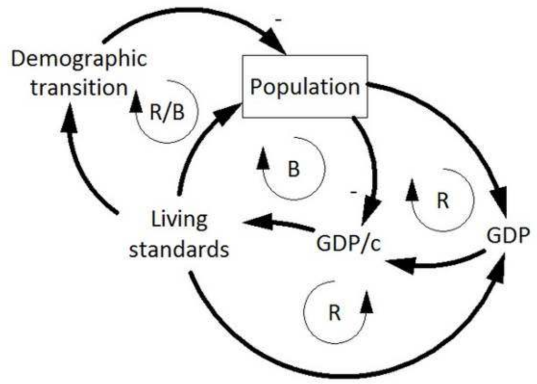

Figure 4 Causal loop diagram of the population and living standards sector

2.3 Natural Resources

Natural resources are represented in the model through three subsectors: fossil fuels (as a specific subset of non-renewable resources); renewable resources; and other non-renewable materials.

2.3.1 Fossil fuels

Economic activity across the globe is driven by energy, which remains largely derived from the combustion of fossil fuels – a finite natural resource. The model assumes that demand for fossil fuels is a function of the demand for energy across the economy, taking into account the fraction provided from nuclear energy and renewable resources such as solar energy, wind energy, biomass, etc. The current fraction from these sources is around 19% of global energy use (International Energy Agency, 2009). Non-energy use of fossil fuels (e.g., fertilizer, plastics) has been simply modelled at around 30% of that used for energy purposes, which is the average split since 1980. The causal loop diagram for the fossil fuels sector is shown in Figure 5.

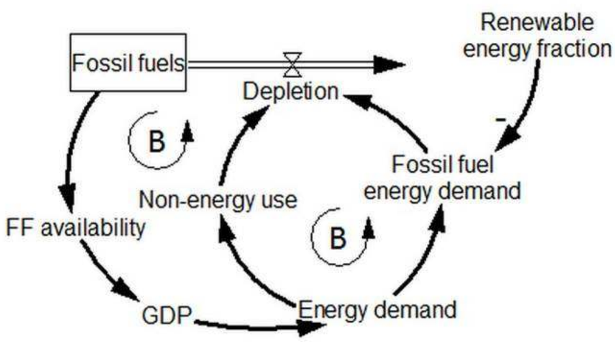

Figure 5 Causal loop diagram of the fossil fuels sector

2.3.2 Renewable resources

Renewable resources are those defined by The Global Footprint Network and used in the calculation of the Ecological Footprint (GFN, 2012). Ecological Footprint represents the consumption rate of renewable resources, specifically: cropland, grazing land, forest land, fishing grounds, and built-up land. The demand for forest land also includes that sufficient to sequester carbon after accounting for the oceans' sequestration capacity (referred to hereafter as the carbon footprint).

Distinct from Ecological Footprint, Biocapacity is a measure of the regeneration rate of renewable resources. Both Biocapacity and Ecological Footprint are expressed in units called global hectares (gha) per year, where 1 gha represents the productive capacity of 1ha of land at world average productivity. For example, data from 2010 indicate a global Biocapacity of 11.6×10^9 gha/yr.

Finally, the Ecological Footprint Ratio is the ratio of Ecological Footprint to Biocapacity; hence, it is a measure of resource exploitation relative to regeneration. Stated another way, Ecological Footprint is a depletion flow, whereas Biocapacity is a regeneration flow. These two flows modify a stock that I have referred to as Ecological Capacity. In turn, Ecological Capacity determines the ability of ecosystems to provide services to society from renewable resources.

Conventional analyses typically assume that Biocapacity is a constant, i.e. the regenerative capacity of ecosystems is unaffected by the stock of Ecological Capacity. My model, in contrast, (optionally) allows Biocapacity to reduce as the stock of Ecological Capacity declines, ultimately to zero if the stock is depleted entirely.

The total ecological footprint has been disaggregated into components of renewable resources and the carbon footprint (derived here from energy demand and fossil fuel use). The carbon footprint is converted to a resource consumption (in gha/yr) by calculating the amount of productive land and sea area required to sequester carbon dioxide emissions.

The causal loop diagram for the Ecological Footprint Ratio is shown in Figure 6.

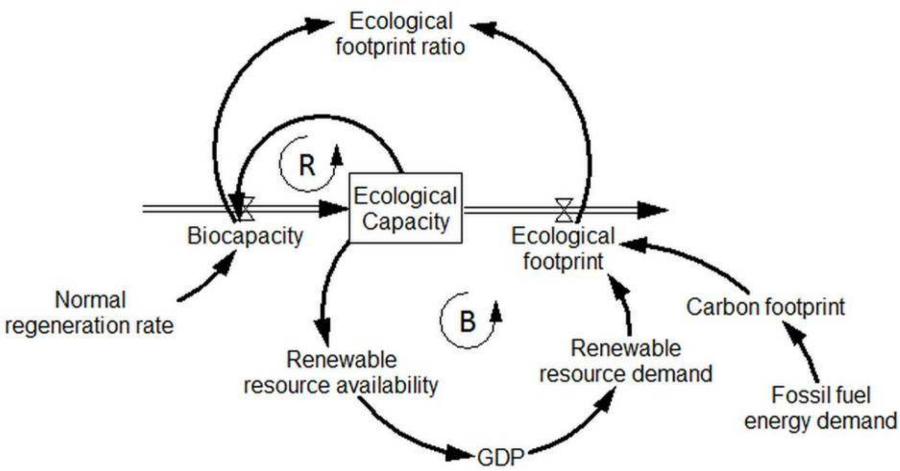

Figure 6 Causal loop diagram of the renewable resources sub-sector

2.3.3 *Other non-renewable materials*

Other non-renewable materials are defined here as metal ores and the minerals used in industry and construction. These resources are finite and stocks are being consumed at a rate determined by economic demand. Many metal ores can theoretically be recycled continuously, although in practice the myriad ways metals are incorporated in products limits the potential opportunity (UNEP, 2011). Construction and industrial minerals are mainly "down-cycled" rather than recycled (e.g. re-use of waste concrete as aggregate). For simplicity, all non-renewable resources are assumed here to be recyclable, albeit with a 10% loss in each cycle. A service life of 25 years is assumed. The causal loop diagram for other non-renewable materials is shown in Figure 7.

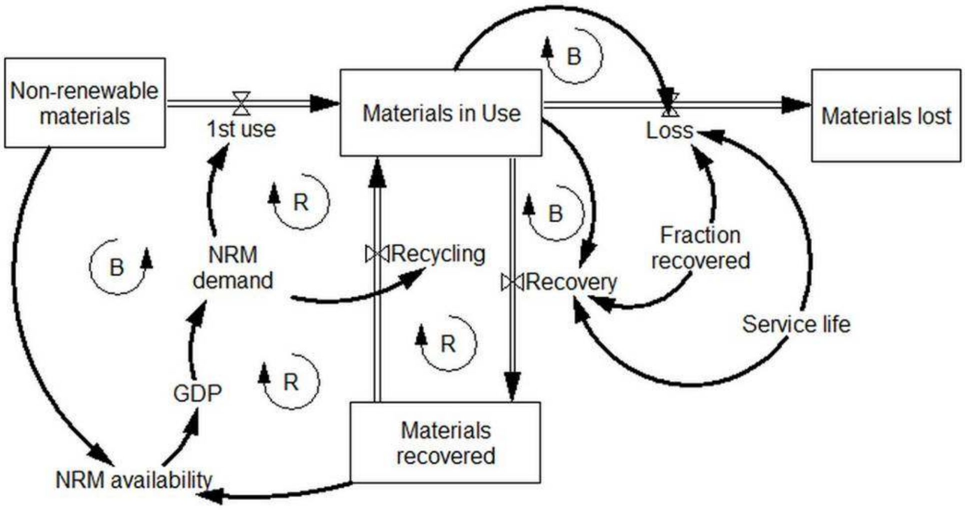

Figure 7 Causal loop diagram of the other non-renewable materials sub- sector

3. Model Calibration

The model was calibrated for an initial period (i.e. 1960 through 2010) by selecting initial stock levels and constants from historical records (Table 1). Causal relationships and graphical functions have been constructed such that the simulated results match the real data as closely as possible for this period (graphs included in Appendix 1).

Table 1 Data sources

Data used in model	Source	Reference
GDP and Investment	World databank	(World_Bank, 2013)
Population	World databank	(World_Bank, 2013)
Human development index	United Nations	(UNDP, 2012)
Ecological footprint and Biocapacity	Global footprint network	(Ewing et al., 2010)
Energy and fossil fuels	World databank	(World_Bank, 2013)
Non-renewable materials	Sustainable Europe Research Institute (SERI)	(SERI, 2013)

4. Initial Model Run

Scenario 1 (Infinite resources)

The model was initially run for the years 1960 to 2310 assuming unlimited resources (by selecting very high initial stock values for ecological capacity, fossil fuels and other non-renewable materials). This run represents a future in which infinite resources allow for continuous economic growth and improvement in living standards, unhindered by scarcity. The purpose of this scenario is to approximate the annual flow of resources required to achieve this outcome, as a point of reference for further scenarios. This scenario, if it were possible, represents a “smooth landing” for humanity (Figures 8a to 8d).

Population, GDP and living standards

Continued economic growth improves living standards, which enables the demographic transition that slows and then halts population growth. Global living standards (HDI) and GDP per capita achieve levels similar to those of currently high income countries (over 0.9 and US$25,000 respectively) at a population of around 11 billion people (Figure 8a). The resulting global GDP is around 3.75 x 10^{14} constant US$2000, about 9 times the current value.

Energy and fossil vs. non-fossil fuels

Scenario 1 assumes non-fossil-fuel energy consumption remains at the current value of around 19%, and materials recycling remains at low levels (10%). Because a majority of energy demand remains derived from fossil fuels, fossil fuel demand follows a similar path as overall energy demand (Figure 8b). Energy demand stabilises at around 35 million kilotonnes oil equivalent per annum, over 3 times the current rate.

Ecological Footprint

In the model, the ecological footprint contains two parts: a renewable resources footprint (from consumption of cropland, grazing land, forest land, fishing grounds, and built-up land) and a carbon footprint (from consumption of fossil-fuels). Figure 8c depicts these footprints under the “no-limits” simulation (Scenario 1). The 2007 renewable resource footprint of 8.4 billion global hectares per year grows quite modestly to 12 gha per year in 2310. However the carbon footprint grows rapidly from 8 billion gha per year in 2007 to around 40 billion gha per year in 2310. The combined ecological footprint of 50 billion global hectares per year is over 3 times the 2007 value and represents an ecological footprint ratio of over 4.

Other non-renewable materials

As identified in the figure in Appendix 1 panel g, the consumption of metal ores and industrial/construction materials has been recently growing at a greater rate than renewable resources or even fossil fuels. Figure 9 shows the global consumption[5] of these materials and the share of consumption by the USA and China since 1980 (SERI, 2013).

Global consumption is being driven significantly by growth in the Chinese economy and associated demand for materials. When this relationship is translated into the model and projected forward, global consumption grows by more than 9 times compared with consumption in 2010 (Figure 8d). This may in fact be a conservative figure because the graphical function controlling materials use per unit of GDP has been set to plateau.

[5] In fact SERI reports these figures as ‘used extraction’ which approximates consumption.

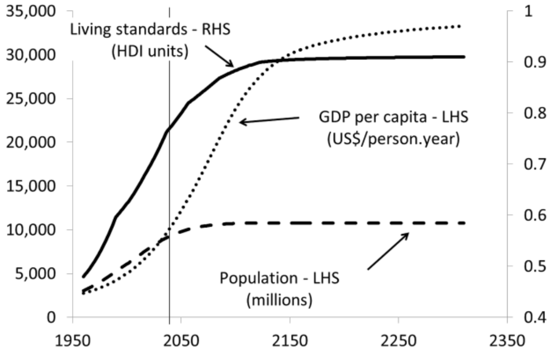

Figure 8a) Simulated population, GDP per capita & living standards – Scenario 1
(RHS and LHS refer to right hand and left hand scale respectively)

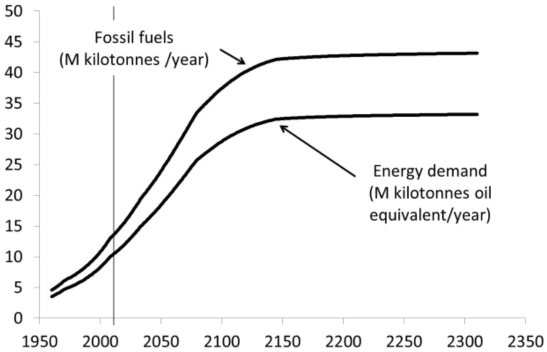

Figure 8b) Simulated energy demand and fossil fuel demand – Scenario 1

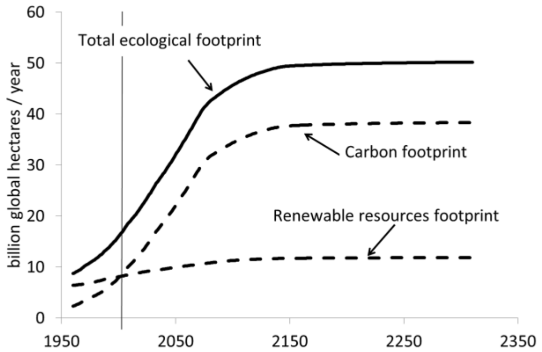

Figure 8c) Simulated ecological footprint – Scenario 1

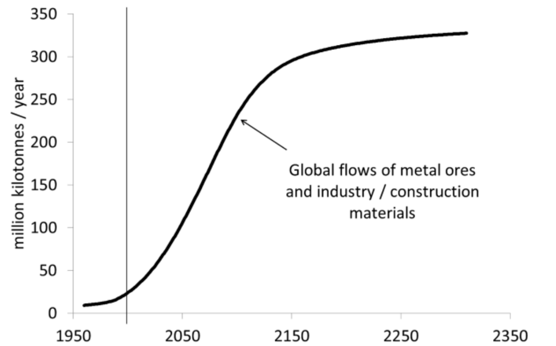

Figure 8d) Simulated consumption of other non-renewable materials – Scenario 1

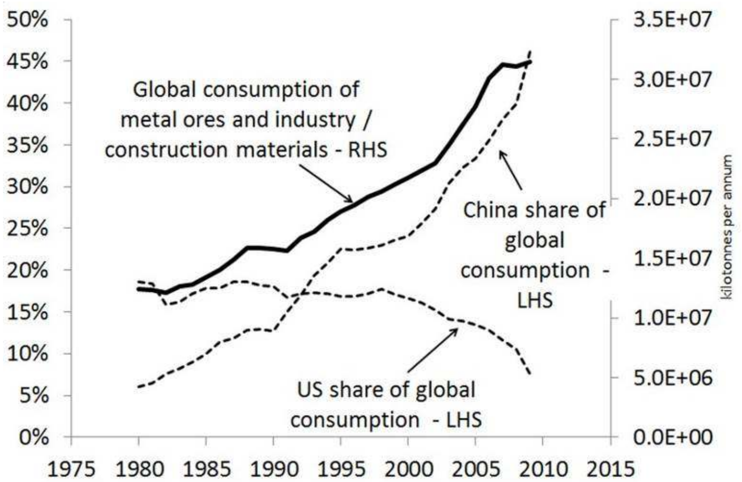

Figure 9 Actual global consumption of other non-renewable materials, 1980-2009

5. Introducing Natural Resource Limits

Next, the model is modified to set limits for each of the resources of interest, in turn: renewable resources, fossil fuels and other non-renewable materials.

5.1 Renewable resources

The model structure described in Figure 6 was invoked by assuming an initial value of the stock that represents Ecological Capacity. While conceptually we can envision a stock of global hectares from which renewable resources flow, there is no physical stock that can be directly measured. Accordingly the Global Footprint Network (GFN, 2012) does not report the stock level, only the flows to and from this stock. For the purposes of modelling, however, it is necessary to estimate the initial level of stock in the year 1960.

Scenario 2a (Limited stock of Ecological Capacity)

For this simulation, I assume an initial Ecosystem Capacity of 3,680 billion global hectares in 1960, equivalent to about 500 years of the 1980 net depletion rate (7.36 bn gha/year)[6]. This run also assumes that Biocapacity is constant (11.6 bn gha/yr), i.e. unaffected by the status of the stock. Later simulations vary these assumptions. All other resources remain unlimited.

Figure 10a shows the status of Ecological Capacity (specifically the ratio of the resource stock in a given year to its initial stock) and the availability of renewable resources (specifically the ratio of available resources to the demand for those resources). The imposition of an upper limit on Ecological Capacity results in rapid depletion of Ecological Capacity after the ecological footprint exceeds unity, i.e. around 1980. This decline ultimately leads to renewable resource scarcity around the end of the twenty-first century. As is evident from Figure 10a, the model assumes renewable-resource availability begins to fall short of demand (i.e. its ratio dips below 1.0 for the first time) when Ecological Capacity is reduced to half of its initial value.

This scarcity of renewable resources acts as a brake on economic production, impacting adversely on GDP per capita and hence living standards. As living standards drop, and resources diminish, population growth plateaus, and then reduces rapidly (Figure 10b) to around 600 million at the end of the simulation period. Figure 10b is directly comparable to Figure 8a.

Because the regeneration of renewable resources is constant in this scenario, ecological capacity begins to recover around 2150 (Figure 10a) as population declines. However this recovery is not sufficient to stop the decline of GDP and population[7]. This scenario represents an overshoot and collapse situation.

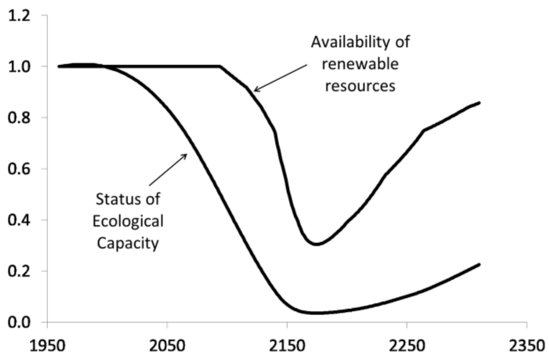

Figure 10a Simulated renewable resources availability – Scenario 2a

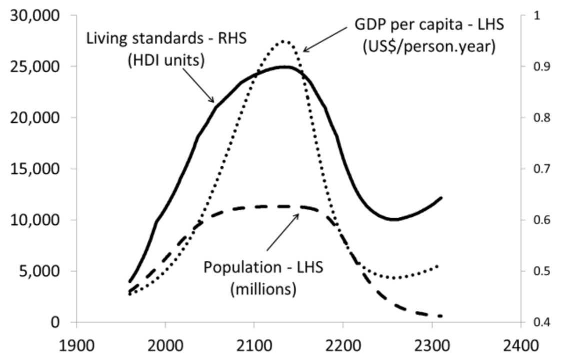

Figure 10b Simulated population, GDP per capita & living standards – Scenario 2a

Scenario 2b (Double the initial stock of Ecological Capacity)

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[6] 500 years is an arbitrary figure chosen to reflect the possibility that considerable ecological reserves may remain even after the ecological footprint exceeds 1, beginning in the 1980s.

[7] GDP per capita and living standards begin to rise around 2250 but only because declining population reduces more quickly than declining GDP.

To test the model's sensitivity to assumptions about Ecological Capacity this scenario doubles the initial stock level to 1,000 years of the 1980 net depletion rate. Doubling the Ecological Capacity delays the onset of the thresholds noted above but does not change the system's essential behaviour (Figure 11).

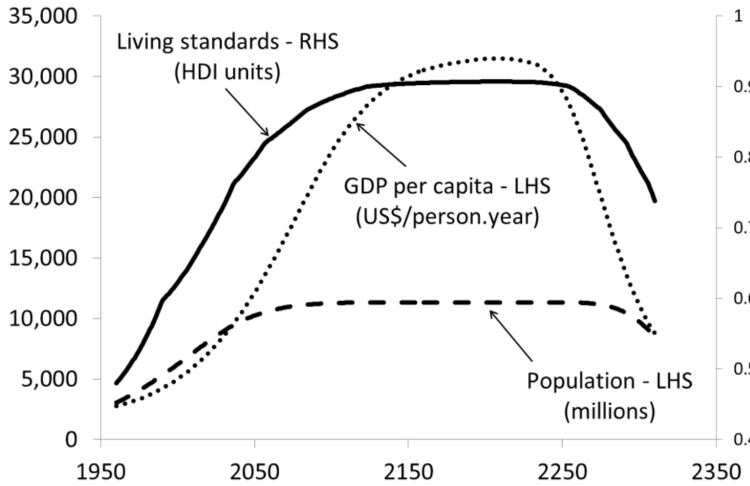

Figure 11 Simulated population, GDP/c and living standards – Scenario 2b

Scenario 2c (Half the initial stock of Ecological Capacity)

Of course it is equally possible that the initial stock is less than the arbitrary value assumed in Scenario 2a. Halving the initial Ecological Capacity to 250 years of the 1980 net depletion rate brings forward the peaks in Figure 11 by around 50 years to 2085 (graph not shown).

Scenario 2d (Degrading Biocapacity)

The next run of the model invokes the reinforcing loop shown in Figure 6, which modifies Biocapacity (the regeneration rate of renewable resources) in accordance with the stock level of Ecosystem Capacity. A convex graphical function controls this feedback, reducing Biocapacity to zero when Ecosystem Capacity reaches 10% of its initial value (which is returned to the Scenario 2a value for this run).

Results from this modification of the model (Figure 12a) initially follow the paths in Figure 10a. But instead of recovering, Ecological Capacity is completely depleted, resulting in availability of renewable resources falling to zero in the middle of the twenty-second century.

The implications of this scenario for population, GDP per capita, and living standards are depicted in Figure 12b. The path is similar to Figure 10b initially, but population falls towards zero as renewable resources are completely depleted. Thus, Scenario 2d also represents an overshoot and collapse situation.

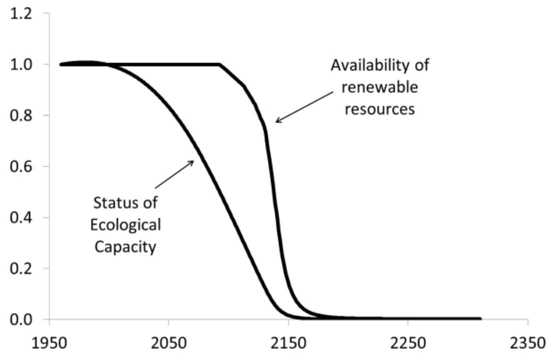

Figure 12a Simulated renewable resources availability – Scenario 2d

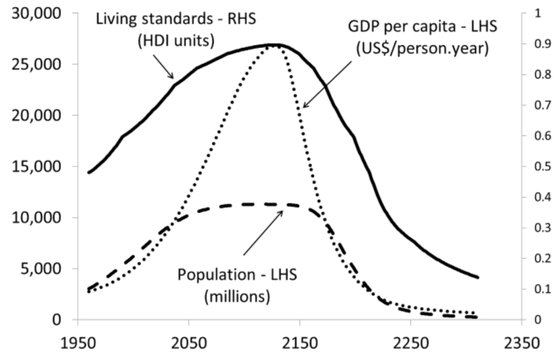

Figure 12b Simulated population, GDP per capita & living standards – Scenario 2d

5.2 Fossil Fuels

In the next round of simulations, the renewable resource limit is removed but a limit on the stock of fossil fuels is introduced. The limit assumed for fossil fuels is based on Maggio & Cacciola (2012), in which historical data on oil (crude and NGL), natural gas, and coal production are combined with three possible scenarios to estimate the global quantity of resources (i.e. ultimate realisable resource = cumulative production plus remaining reserves plus undiscovered resources). Their values for ultimate resources, based on a comprehensive literature survey, are as follows (Table 2).

Table 2 Fossil fuels – ultimate realisable resources (Source: Maggio & Cacciola, 2012)

	Range	**Units**	**Upper value (ktoe)**
Oil & natural gas liquids	2,250-3,000	Gigabarrels (GB)	409,200,000
Natural gas	9,500-15,400	Trillion cubic feet (Tcf)	362,208,000
Coal	550-750	Gigatonnes of oil equivalent (Gtoe)	750,000,000
		Total	1,521,408,000

The upper values in Table 2 represent 177%, 234% and 125%, respectively, of the proven reserves of oil, gas and coal reported in BP's "Statistical Review of World Energy" published in mid-2014. These upper values are adopted for the purposes of this study, after being converted to kilotonnes of oil equivalent (ktoe) and totalled.

Scenario 3 (Limited fossil fuels)

The ultimate realisable fossil-fuel resource is incorporated in the model as the initial total stock, reduced by the fraction used by the commencement of the model in 1960 (approximately 10% from the historical production data), leaving 1.38×10^9 ktoe as the initial value of the Fossil Fuel stock. This quantity represents about 110 years of production at 2012 rates (12.6×10^6 ktoe/year; see Appendix 1 panel h).

The results of this run are summarised in Figures 13a and 13b. Figure 13a shows the status of the fossil-fuel stock (stock value / initial value) and the availability of fossil fuels (the ratio of available resources to the demand for those resources). The availability of fossil fuels becomes constrained around 2035 and the resource is exhausted by the end of the twenty-first century.

As in previous model runs, this resource scarcity has a dramatic effect on the economy, leading to overshoot and collapse (Figure 13b). Doubling the initial stock of fossil fuels delays the onset of the peaks in Figure 13b by around 40 years (graph not shown).

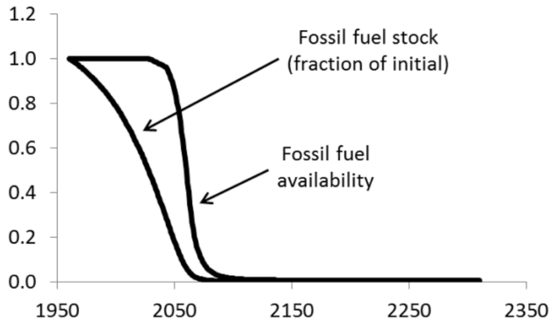

Figure 13a Simulated fossil fuel and stock – Scenario 3

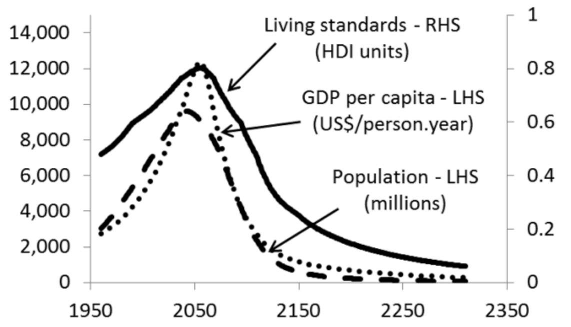

Figure 13b Simulated population, GDP per capita & living standards – Scenario 3

5.3 *Other non-renewable materials*

A similar approach was taken to modelling the impact of initial availability of other non-renewable materials, specifically metal ores and industry/construction materials. After removing the fossil fuel limit, a cap was placed on the total quantity of other non-renewable materials available to the economy. Unlike fossil fuels, some of these materials are not fully-consumed and remain available for recycling and reuse, although the viability of doing so varies from material to material.

In the 30-year update of the Limits to Growth study (Meadows, et al., 2004, p. 105), an estimate for the life expectancy of various metals is quoted assuming an annual production growth rate of 2% per year from 1999. These life expectancy figures range from 530 years for nickel to 1,070 years for aluminium. No guidance is available, though, for total global stocks of industry and construction materials.

Scenario 4 (Limited stock of other non-renewable materials)

It is assumed (conservatively) that the initial stock of all other non-renewable materials (in 1960) is equivalent to 1,000 years of production at 1980 rates. It is further assumed that 25% of these materials had already been exploited by 1960, leaving 75% available for first economic use. Of the materials already exploited, it is assumed that 60% were "in-use", 20% "lost", and 20% "recovered" and available for recycling in 1960. For simplicity the recycling rate is set to 10% for this initial simulation.

Figure 14 depicts the changing status of other non-renewable materials stocks throughout this simulation. It indicates a rapid rise in the quantity of materials lost, due to rapid depletion of available materials and a low recovery rate.

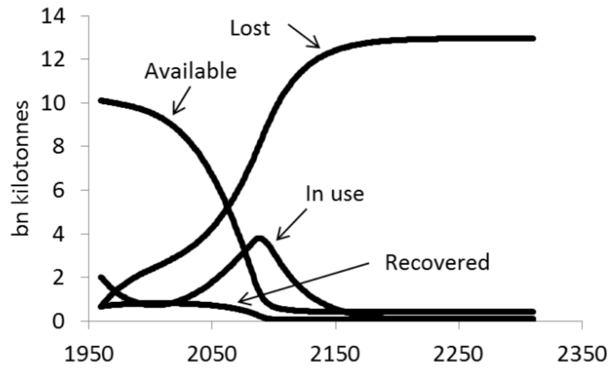

Figure 14 Simulated stocks of other non-renewable materials – Scenario 4

The rapid consumption of other non-renewable materials (a continuation of the historical trend observed in Appendix 1 panel g) leads to a particularly sharp reduction in availability (the ratio of available materials to demand for those materials) as stocks become depleted after mid-century (Figure 15a). Availability is limited ultimately by recovered rather than virgin materials. The resulting system behaviour is similar to previous cases, involving overshoot and eventual collapse (Figure 15b). Furthermore, doubling the initial stock of other non-renewable materials delays the onset of peak conditions (as observed in Figure 15b) by 30-40 years (graph not shown).

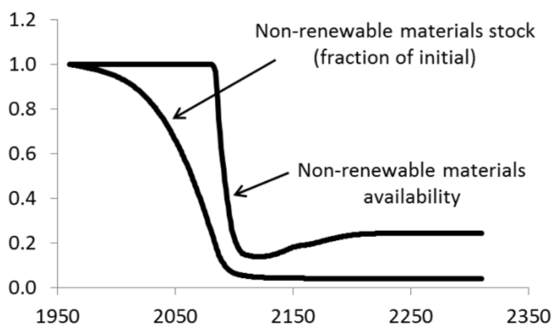

Figure 15a Simulated other non-renewable materials availability and stock – Scenario 4

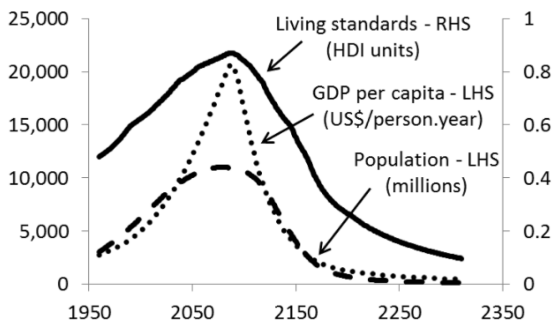

Figure 15b Simulated population, GDP per capita & living standards – Scenario 4

6. Discussion of Results

Like all System Dynamics studies, the timing and exact numeric values are the combined effects of initial conditions, posited causal relationships, and in particular, the equations and graphical functions that regulate them. Therefore the timing and values predicted by the simulations are not to be taken as accurate. However the basic behaviour of the system is predictable from our understanding of the dynamics of growth-limited systems, i.e. that depleting resources at a faster rate than their regeneration or substitution must eventually lead to their exhaustion, giving rise to overshoot and decline or collapse. Given that the model shows reasonable calibration with actual data from the past fifty years, the near-term results are likely to be closer to reality than those for later periods of the model.

These results, when taken together, suggest peaks somewhat later than those suggested by Scenario 1 of World 3-03 (the reference case of Limits to Growth - The Thirty Year Update).

More specifically, my results suggest GDP per capita and living standards may peak as follows (Table 3), noting that the model presented here is more simplistic, and initial stock values more conservative.

Table 3 Peak GDP per capita and living standards under various scenarios

Limit Assumed [Relevant Scenario]	**Timing of Peak [Relevant Figure]**
Stock of Other non-renewable materials [Scenario 4]	Towards the end of the 21st century [Figure 15b]
Stock of Fossil fuels [Scenario 3]	Second half of the 21st century [Figure 13b]
Flow of Biocapacity [Scenario 2d]	First half of the 22nd century [Figure 12b]

It is worth stressing again that the results presented here should not be considered as 'predictions.' Nor should they be considered more accurate in magnitude or timing than the World 3-03 Scenario 1, noting that even the authors of that work '*do not believe it represents the most likely real world outcome*' (Meadows, et al., 2004, p. 171). Rather, the intent is only to show that this simplified model produces similar trajectories, yet was easier to parameterize.

The essential behaviour of the system is controlled by the rates of resource consumption and regeneration or recycling, and the variables that affect these rates. The key variable affecting the overall consumption of resources in the model is the ratio of resource demand to GDP (hereafter referred to as resource intensity).

For most of the calibration period of the model (1960-2010) real world data shows that worldwide resource intensity has been declining. Much of this decline can be attributed to growth of the service sector. By the mid- 1990s, services accounted for almost two-thirds of world GDP (Figure 16), up from about half in the 1980s (Soubbotina, 2000, p. 50). As developing countries become wealthier, the proportion of materials and energy per unit of output declines significantly as economic production shifts away from industry and agriculture towards services. China, for example, has achieved a 65 % decline in energy intensity in between 1970 and 2000 (Soubbotina, 2000).

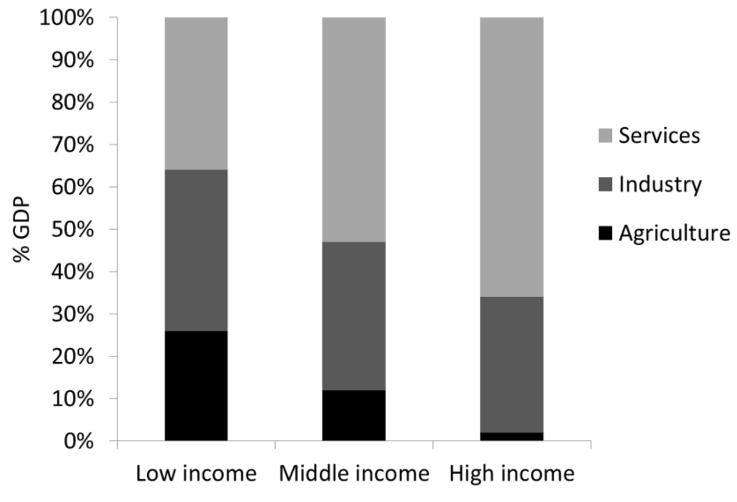

Figure 16 Sectorial structure of world economies in 1995 (Source: Soubbotina, 2000)

Data on GDP and the global Ecological Footprint from 1961-2007 support the hypothesis that reductions in resource intensity are mainly attributable to changes in the structure of the world economy. Figure 17 illustrates the percentage of total Ecological Footprint attributable to different resource-use categories over this period. The contribution of cropland and grazing has reduced markedly and has been replaced by carbon (a proxy for fossil-fuel-based energy consumption). By 2007, carbon contributes more than 50% to the total Ecological Footprint[8]. If carbon is deducted from the footprint measurement, the subsequent Ecological Footprint Ratio reduces to well below 1 (depletion is less than renewal), and is increasing at a much slower rate than if the carbon footprint is included. This point is often neglected in media presentations of the Ecological Footprint.

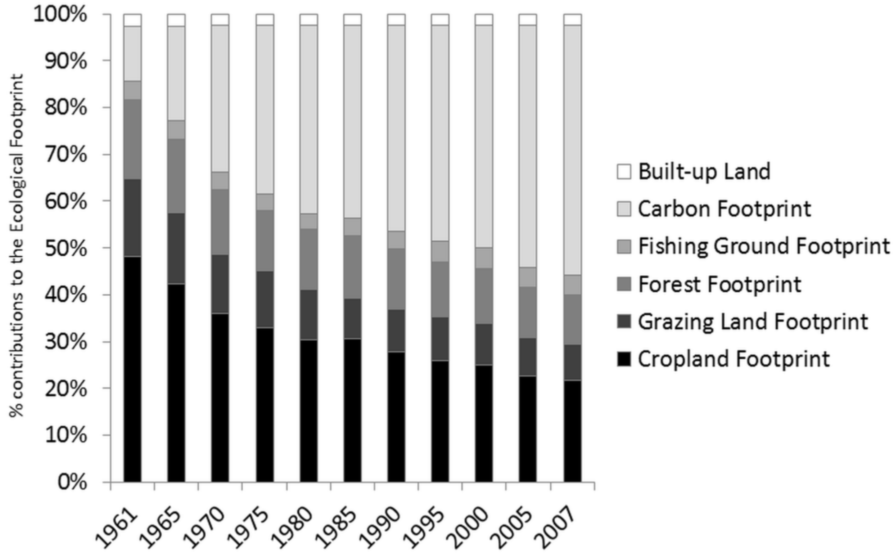

Figure 17 Make up of the ecological footprint 1961-2007

Although the economic intensity of renewable resource use has been steadily declining (Figure 18), there seems to have been some changes in the relationship between GDP and non-renewable resources since the year 2000. First, there has been a sharp upturn in the resource intensity of other non-renewable materials (i.e. excluding fossil fuels). Second, energy intensity seems to have stabilised, rather than continuing its recent decline. Finally, the carbon footprint intensity has returned to 1990 levels after a gradual decline since around 1980.

[8] Noting that the carbon footprint is the amount of productive land and sea area required to sequester carbon dioxide emissions. The required quantity of land and sea is the ‘resource’ in this case.

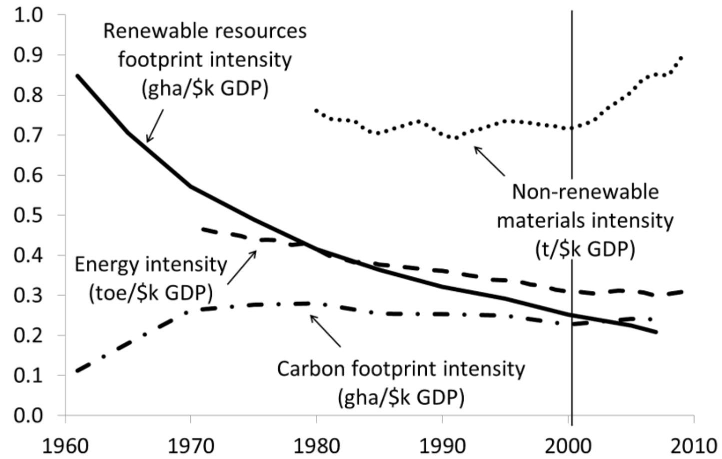

Figure 18 Natural resource intensity 1960-2010

The shapes of these intensity curves are the basis of the model's assumed relationships between resource use and GDP. Thus, as the latter grows exponentially, resource use is increased accordingly.

In the simulations described earlier, consumption of resources is constrained only by availability, i.e. whether or not there are sufficient resources to match demand at any point in time. As shown in Figures 10a, 12a and 13a, such resource constraints take effect well after depletion of the resource stocks begin. Although the associated balancing loop eventually takes effect -- to reduce GDP and thus resource demand -- it is too late to avoid overshoot and decline. This result challenges the conventional wisdom that market economics will help avoid depletion, i.e. that scarcity will induce a price signal that incentivises technology improvements that in turn lead to reductions in resource use or substitution. Acknowledging that my simplified model does not allow price signals to directly affect resource demand, its results suggest that the rapid onset of economic scarcity will preclude our ability to avoid overshoot. As Sterman (2012) puts it:

> "Even with significant potential for new technical solutions, a prosperous and sustainable future can only be built if growth of both population and material throughput cease voluntarily, before growth is stopped involuntarily by scarcity or environmental degradation."

7. Introducing Voluntary Measures

The Limits to Growth – the 30 Year Update (Meadows, et al., 2004) include scenarios that avoid collapse (Scenario 6, 8, 9 and 10) through the adoption of various policy measures. Other authors have produced similar credible outcomes from global models. Developers of the Human and Nature Dynamics (HANDY) model (Motesharrei, 2014) found that:

> ".. collapse can be avoided and population can reach equilibrium if the per capita rate of depletion of nature is reduced to a sustainable level, and if resources are distributed in a reasonably equitable fashion."

To investigate the voluntary policy measures necessary to avoid overshoot and decline or collapse, I expand the model to incorporate further balancing loops (i.e. endogenous behaviour). Modifications are specifically applied to the fossil fuels and other non-renewable materials sub-sectors only. No changes are made to the renewable resources sector, although this sub-sector is affected indirectly by the carbon footprint of energy.

7.1 Fossil Fuels

An additional balancing loop is added to the model which increases the renewable energy fraction as fossil fuel stocks are depleted (see Figure 19).

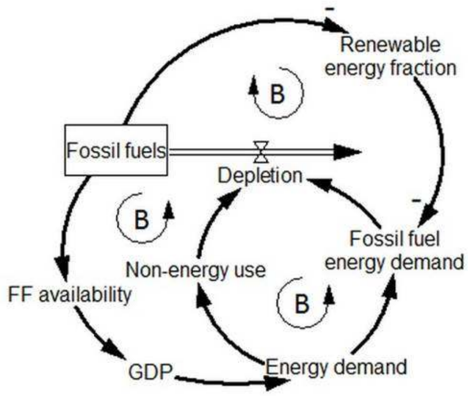

Figure 19 Causal loop diagram of the modified fossil fuels sub-sector

7.2 Other non-renewable materials

Additional balancing loops are added to the other non-renewable materials sub-sector. These balancing loops are triggered by the decline of other non-renewable materials stocks. In response to this decline, they cause a gradual reduction in overall demand for these materials, and a gradual increase in the fraction of materials recovered and reused. The modified causal loop diagram is depicted in Figure 20.

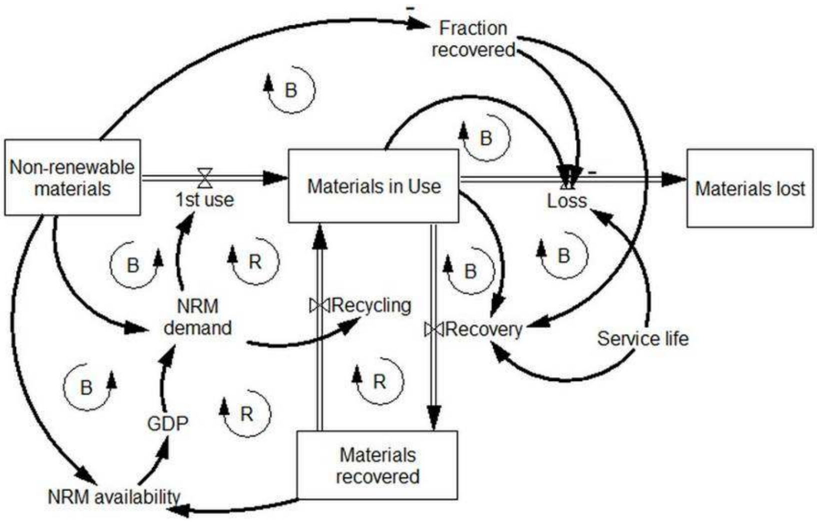

Figure 20 Causal loop diagram of the modified other non-renewable materials sub- sector

Scenario 5 (Voluntary mitigation measures)

The strengths of the additional balancing loops in Figures 19 and 20 are varied iteratively until they offset the overshoot behaviour and reinstate the “smooth landing” evident in the no-limits scenario. This smooth landing is ultimately achieved through addition of the following policies.

With respect to fossil fuels:

- Increasing the fraction of renewable energy rapidly from the present level to 1 by the time fossil fuel stocks deplete to 25% of their initial value.

With respect to other non-renewable materials:

- Reducing demand for other non-renewable materials by 75% (per unit of GDP) as their stocks decline; and simultaneously increasing the fraction of materials recovered from 10% to 70% as stocks decline.

The application of these modifications returns the system behaviour to something close to the “smooth landing” of the no-limits scenario, as shown in Figure 21a. In this scenario, living standards reach the same high values as the no-limits scenario but GDP per capita is slightly lower and population stabilises at less than 9 billion, compared to 11 billion previously. This changed behaviour is due to reductions in resource intensity triggered by the voluntary measures. The resource intensity with respect to fossil fuels and carbon footprint is depicted in Figures 21b and 21c.

This modification also returns the Ecological Footprint Ratio to unity as the Carbon Footprint reduces to zero (Figure 21d). Note that the ‘voluntary measures’ simulation did not include any direct reduction in the renewable resource intensity (it is indirectly reduced by reducing fossil fuel use). This result therefore implies that current patterns of renewable resource intensity may be sustainable if the carbon component can be eliminated through a transition to renewable energy. However there is an important caveat on this conclusion which is discussed below.

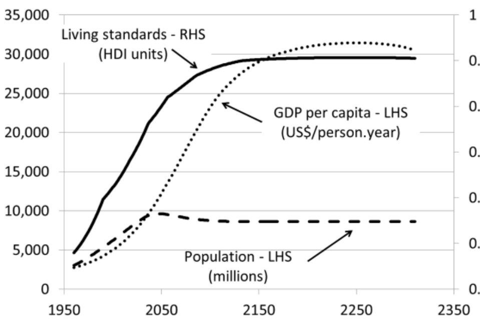

Figure 21a Simulated population, GDP per capita & living standards – Scenario 5

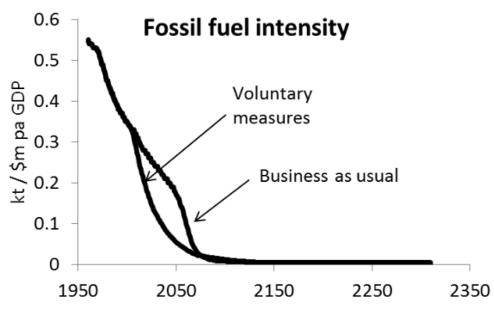

Figure 21b Simulated fossil fuels intensity – Scenario 5

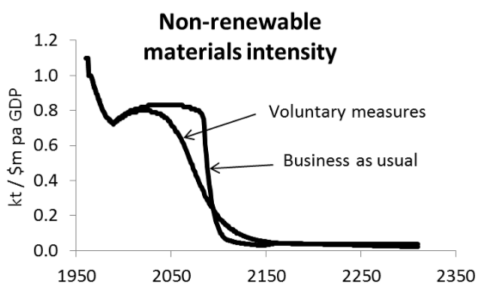

Figure 21c Simulated other non-renewable materials intensity – Scenario 5

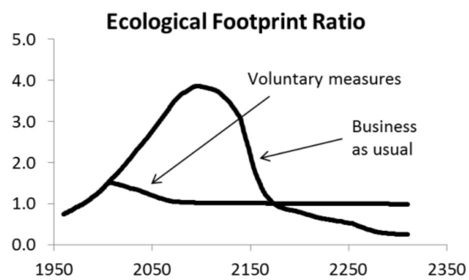

Figure 21d Ecological footprint intensity – Scenario 5

Closer inspection of Figure 21a (Scenario 5) suggests that, towards the end of the simulation period, GDP per capita is dropping, and living standards (which are modelled as a direct function of GDP per capita) are on the verge of decline. Extending the timeframe of the model reveals that equilibrium has not in fact been achieved; overshoot has been merely delayed, and occurs thereafter. The reasons for this behaviour are clear from consideration of Figure 20, which depicts the other non-renewable materials causal structure.

The total stock of other non-renewable materials at any time is the sum of: virgin materials, materials-in-use, materials recovered, and materials lost. As virgin materials are used for the first time, they are converted to materials-in-use according to the rate of demand. The time they reside in that stock depends on the life of the materials, or rather the life of the products that embody the materials. Clearly this varies significantly, from a very long period (e.g. concrete in transport infrastructure) to a very short time (e.g. materials in consumer goods). At the end of their life they are either recovered or discarded. It is impossible to recover 100% of materials because they are bound together in products that make their separation very difficult in many situations (UNEP, 2011). In the case of some metals, very high recovery rates are at least theoretically possible. However, even if it is assumed that 90% of the materials in use can be recovered, the balance is lost to the economy.

Because the laws of thermodynamics preclude 100% recovery, the act of reducing demand and increasing the recycling fraction only delay the inevitable, albeit considerably. Eventually, stocks of viably obtainable virgin materials will be depleted completely. Accordingly in the long term the consumption of materials must equal their recovery or recycling rate. Because some proportion will be lost through each cycle, the availability of materials must diminish over time with consequences for economic use of those materials.

In the long term, the proportion of materials that are lost must be substituted with renewable materials, if the same economic demand is to be met. If we further assume that the recovery rate itself will likely diminish in the long term, as materials go through multiple cycles of recovery and recycling, this substitution towards renewable materials will need to increase over time. The impact of this on the Ecological Footprint must be considered in any modelling of future economic use of other non-renewable materials.

8. Policy Response

The voluntary measures outlined above with respect to fossil fuels and other non-renewable materials only achieve global stability if all of the following conditions apply:

- Continuing improvements in living standards in the developing world deliver the demographic transition (and thereby constrain net global resource consumption);
- Fossil fuel use for energy is completely eliminated;
- 70% of other non-renewable materials are ultimately recovered and recycled;
- Demand for other non-renewable materials is ultimately reduced by 75%; and
- All measures occur simultaneously and without delay.

Absent these conditions, the model produces overshoot and collapse behaviour during the simulation period. Although easy to configure in a mathematical model, the implementation of these or similar policies at anywhere near the scale and timeframe required, appears presently infeasible. Although some action is being taken with respect to greenhouse gas emissions and recovery or recycling of materials, the scale of these actions does not reflect the urgency of the task. Almost no action is being taken on reducing the economic demand for other non-renewable materials, and it is highly questionable whether it is even possible to reduce demand per unit of GDP for such materials by 75%, let alone in the timeframe identified.

There is presently little focus on the problems set out in this article at the international or national level. Although the United Nations Environment Program's International Resource Panel[9] recently produced a report on de-coupling resource use from economic growth[10], even this document is tentative about recommending national policies. Recommendations relate to leadership, institutional frameworks (changing the mindsets of decision-makers), and the adoption of price signals. Even this agenda has virtually no momentum in national politics in the countries that matter most. There is no reference to the work of this panel, for example, on the websites of the US Environmental Protection Agency, Natural Resources Canada, or the UK Department for Environment Food & Rural Affairs. Policies in these and most countries remain focussed on waste management and recycling, rather than the economy-wide transformations needed.

Policy change will only follow much greater public awareness of the issues and translation of this awareness into political action. Accelerating this process is imperative if we are to avoid the present state of global overshoot progressing to serious decline or collapse. Urgency has only grown in the nearly half a century since the original Limits to Growth study (Meadows, et al., 1972) came to this same conclusion.

9. Further Work

The model presented here averages global stocks and flows. Accordingly it does not account for the large disparities between developed and developing nations' resource demand and access to resources. The next phase of the study will seek to explore interactions between the "haves" and "have-nots" due to resource distribution across nations. Further phases of modelling will be based on OECD GDP groupings, nations, and cities. Development of these models will need to address a variety of complexities related to the import and export elements of local economies. Accommodating these complexities will necessarily involve a number of assumptions, the results of which can only realistically be tested through sensitivity analysis. Accordingly the models will (like the model presented here) include 'sliders' that facilitate such sensitivity testing.

An open source online version of this model is available at https://forio.com/simulate/williamrgrace/sustainable-world to facilitate exploration of the system dynamics and policy options. Future models will similarly be made available online.

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[9] http://new.unep.org/resourcepanel/

[10] It is not physically possible to completely decouple economic production and resource use. The thrust of the report is really about reducing the economic intensity of resource use.

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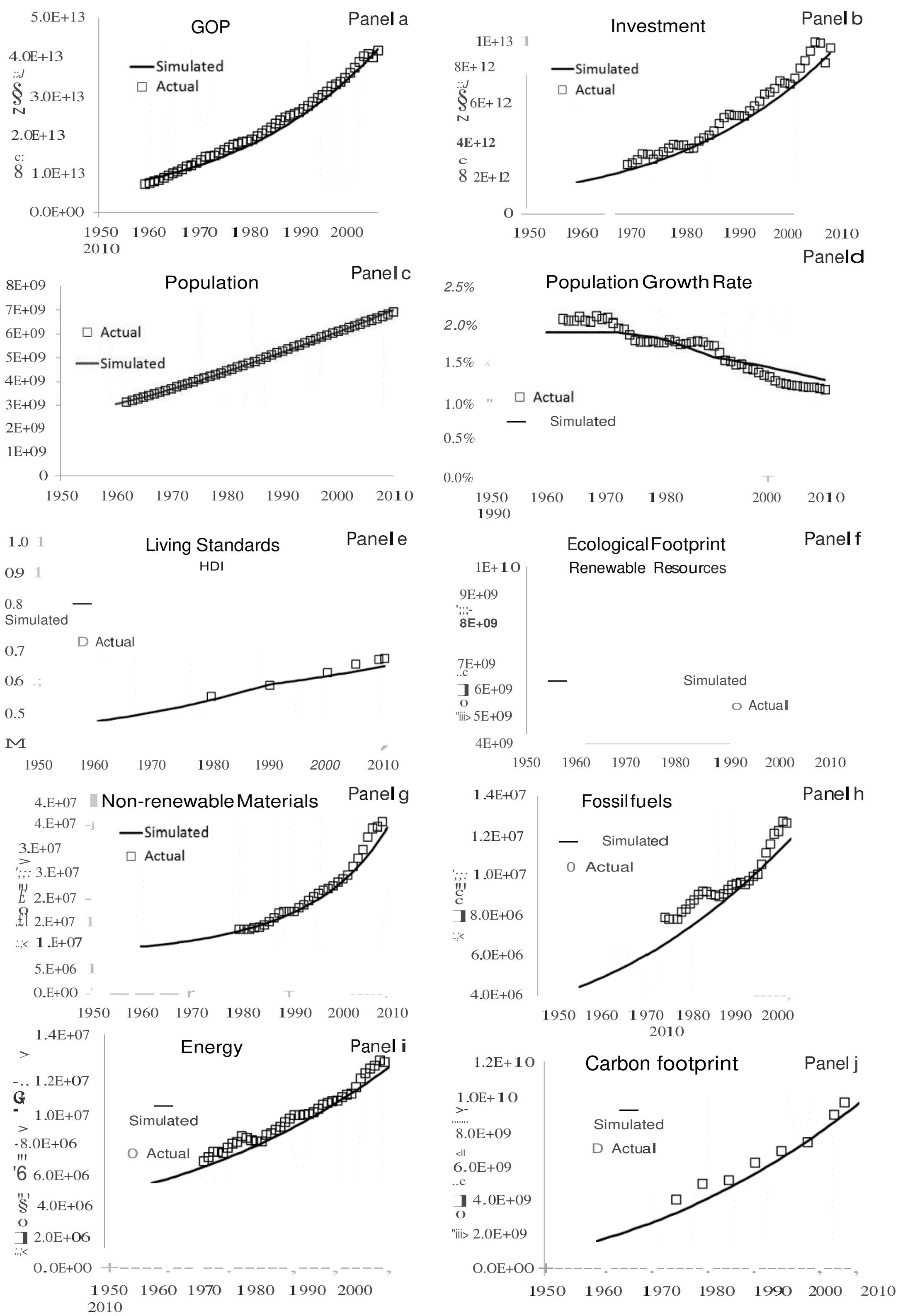
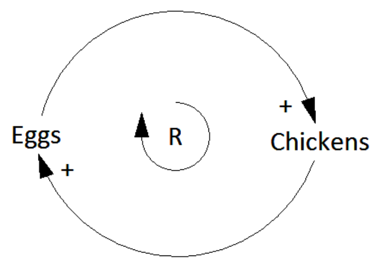
Appendix 1 – Simulated vs observed data for causal relationships and graphical functions assumed in the model.

Appendix 1. Simulated vs observed data for causal relationships and graphical functions assumed in the model



Appendix 2 - Causal Loop Diagrams

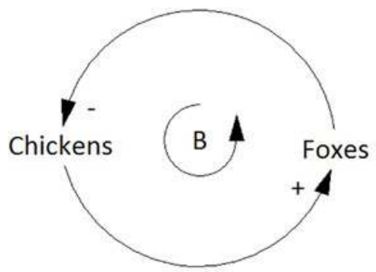
All systems with feedback are made up of combinations of so-called reinforcing and balancing loops. These can be characterised by causal loop diagrams. In the following, the arrows indicate the direction of causality, e.g. chickens come from eggs. The polarity indicates that the causation is positive.



More chickens lead to more eggs, which lead to more chickens …… and so on.

This is a reinforcing loop and leads to exponential chicken population growth (in the absence of other influences)

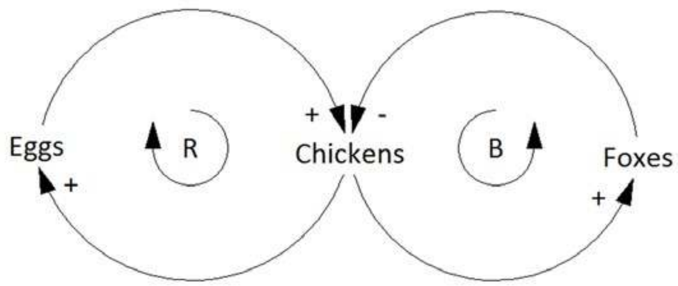
However nothing grows forever, so in real systems there are factors that limit growth or decline. We could assume, for example, that chickens live in an area inhabited by foxes.



The more chickens there are the more foxes there will be (positive polarity). However the more foxes there are the fewer chickens there will be (negative polarity).

This is a balancing loop because it counteracts the growth of chicken and fox numbers. If this loop operated in isolation from the first loop, chicken numbers would fall to zero.

When the two loops operate in tandem, we have both reinforcing and balancing loops influencing the number of chickens over time, one that causes growth and one that causes decline.

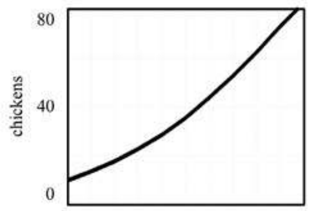


The resulting behaviour of the system over time depends on:

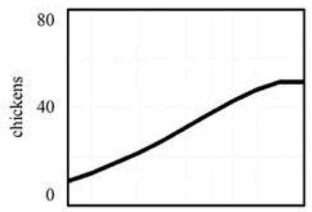
- the number of eggs hatched per chicken per year; and
- the number of chickens consumed per fox per year.

Depending on these parameter values, the number of chickens may:

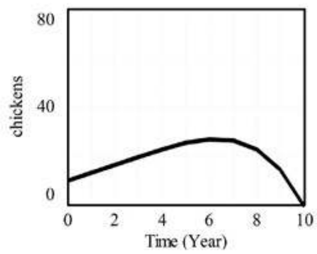
- grow exponentially;



- stabilise at an equilibrium level; or



- grow exponentially initially and then collapse to zero.



All of these outcomes are possible, demonstrating that complex behaviour can result from a simple system structure.