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Limits to growth redux: A system dynamics model for assessing energy and climate change constraints to global growth

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ABSTRACT

This study investigates the notion of limits to socioeconomic growth with a specific focus on the role of climate change and the declining quality of fossil fuel reserves. A new system dynamics model has been created. The World Energy Model (WEM) is based on the World3 model (*The Limits to Growth*, Meadows et al., 2004) with climate change and energy production replacing generic pollution and resources factors. WEM also tracks global population, food production and industrial output out to the year 2100. This paper presents a series of WEM's projections; each of which represent broad sweeps of what the future may bring. All scenarios project that global industrial output will continue growing until 2100. Scenarios based on current energy trends lead to a 50% increase in the average cost of energy production and 2.4–2.7 °C of global warming by 2100. WEM projects that limiting global warming to 2 °C will reduce the industrial output growth rate by 0.1–0.2%. However, WEM also plots industrial decline by 2150 for cases of uncontrolled climate change or increased population growth. The general behaviour of WEM is far more stable than World3 but its results still support the call for a managed decline in society's ecological footprint.

1. Introduction

The notion of limits to growth is based on the premise that exponential growth of human population and physical output cannot continue forever on a finite planet (Lovejoy, 1996). Such concerns have been raised for centuries and were further popularised by the Limits to Growth (LTG) research; the original LTG publication (Meadows et al., 1972) sold over 12 million copies and has been described as the founding text of the modern environmental movement (Jackson and Webster, 2016).

The LTG approach is distinguished by its use of a global system dynamics model called World3 to create projections of the future. World3 projected that, having overshot the Earth's carrying capacity, humanity was left facing two futures – involuntary collapse driven by physical limits or a controlled reduction of the ecological footprint by deliberate social choice.

In response to growing environmental and energy concerns, the UK government recently launched a parliamentary group on LTG to "*create the space for cross-party dialogue on environmental and social limits to growth*" (Jackson and Webster, 2016). The LTG argument remains relevant but few researchers have taken up the mantle laid down by the LTG team to improve the underpinning World3 model.

This paper presents a new system dynamics model, entitled the World Energy Model (WEM), to investigate how climate change and the declining quality of fossil fuel reserves will affect socioeconomic growth in the 21st century. The study compares the projections of WEM to the World3 model, investigates the impact of climate change policies on the state of the world and considers the likelihood of industrial decline. The results support broad policy themes and will hopefully stimulate further attempts to improve the process of model making.

2. Background

2.1. Limits to growth summary

The LTG research is documented in three publications for the general public (Meadows et al., 1972, 1992, 2004) and one detailed technical report (Meadows et al., 1973). The LTG researchers believe that three features of the world system make it unstable and prone to future collapse; exponential growth in human activity, limits in the Earth's system and delays in societies reaction. These features were built into a global system dynamics model called World3.

World3 projects the flow of five key variables to the year 2100; human population, industrial capital, non-renewable resources, agriculture, and pollution. Global averages are used for all parameters and complex measures such as pollutants and non-renewable resources

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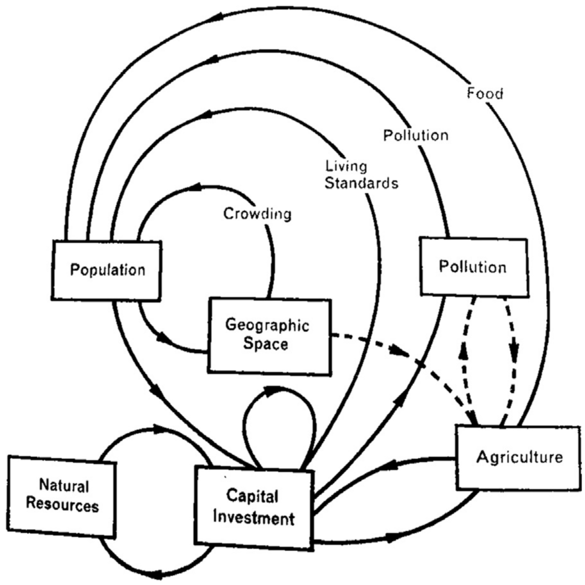

Fig. 1. World3's Main Feedback Loops – The boxes represent the main subsystems and the arrows show the causal links (Cole et al., 1973).

aggregated to a single value. Fig. 1 presents a simplified diagram of the model. The numerous nonlinear relationships and feedback structure make the whole model dynamically complex.

LTG did not make an explicit prediction about the future state of the world but instead presented a series of World3's scenarios, each based on varying social and environmental assumptions. The majority of these scenarios projected global industrial output to peak within the 21st century. Industrial decline occurs because increasing capital is drained into either extracting resources, adapting to pollution, producing sufficient food or developing technologies to offset these physical limits. The post peak trajectories are described as highly speculative due to the unpredictable response to industrial decline. Fig. 2 presents a typical scenario, where pollution grows exponentially and drives industrial collapse.

World3 only projects a sustainable future when a deliberate constraint is placed upon population and material growth. LTG argued that society should target a form of equilibrium state, where material consumption no longer grows. The LTG researchers also hoped that their work would lead to a new movement of justifying views with explicit and examinable computer models. World3 was "both a demonstration of what can be done and a challenge to do it better" (Meadows et al., 1973).

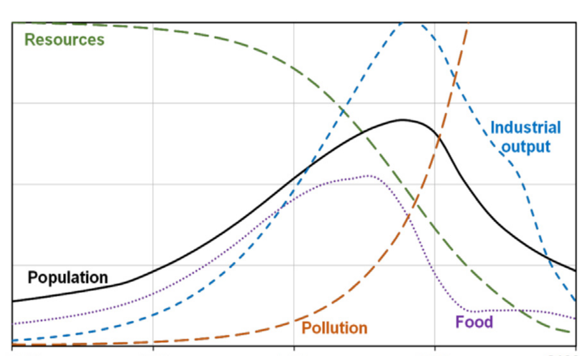

Fig. 2. World3-03 Scenario 2 – Global industrial collapse is projected due to increasing pollution costs (Meadows et al., 2004).

2.2. System dynamics

World3 remains the most well known example of system dynamics modelling; using stocks, flows, internal feedback loops and time delays to investigate complex and non-linear behaviour.

The basis of system dynamics is recognition that the behaviour of a system is dependent on the system structure as much as the individual components. Whilst most scientists study the world by breaking it up into smaller and smaller pieces, system dynamics encourages a whole and continuous view; striving to look beyond events to see the dynamic patterns underlying them (MIT, 1997). Many global forecasts are inconsistent, one part of the forecast contradicts another, because they fail to consider these underlying relationships (Randers, 2012).

2.3. The LTG argument today

The LTG research raised environmental awareness but ultimately failed to lead to the political actions called for. Critiques of World3 tended to focus on the level of aggregation and political bias within the model. Continued socioeconomic growth over the last 45 years has led to calls to relegate the work to the "dustbin of history" (Lomborg and Rubin, 2002). Many critics either misinterpret the LTG message or perpetuate the myth that LTG was flawed because it had forecast collapse to have occurred by the end of the 20th century (Turner, 2012).

An assessment of events over the last 40 years actually shows that major variables such as population, industrial output and food production are closely following the LTG 'business as usual' scenario (Turner, 2012). In order to assess the likelihood of the world further following World3's scenario into industrial decline, it is important to consider the state of the underlying physical constraints.

Food and general resource scarcity appear no closer to materialising into significant constraints to industrial growth than 45 years ago. Food production per capita has steadily increased and that trend is expected to continue to 2050 (Alexandratos and Bruinsma, 2012). The cost of raw materials has remained relatively constant with continued technological advances offsetting the diminishing quality of reserves (Yamada and Yoon, 2014; Eastin et al., 2011).

The depletion of fossil fuel reserves is arguably the most significant example of resource scarcity in the modern world. Oil and gas reserves are falling in quality rather than quantity, as demonstrated by the shifts to first offshore and now unconventional resources. Despite technological advances, real oil prices are approximately three times higher than the average price through the mid-20th century (BP, 2016). Increasing energy costs could drain industrial capital in the same manner that LTG hypothesised the increasing cost of resource extraction would.

Meanwhile, environmental issues have turned out *"considerably worse than the Club of Rome's projections"* with concerns that climate change, biodiversity loss, damage to nitrogen cycles and land use could all threaten the maintenance of the Earth system (Jackson and Webster, 2016). Policy attention and social discourse have increasingly shifted emphasis from general growth concerns to climate change (Eastin et al., 2011). Climate change and the depletion of fossil fuel reserves appear to be the most threatening examples of physical constraints in the modern world and are the main focus of this paper.

3. Methodology

The World Energy Model (WEM) is a systems dynamics model, written in STELLA, and based on the World3-03 model (private communication from Jorgen Randers, 2016) that was created for the latest LTG publication (Meadows et al., 2004). The core change from World3-03 to WEM is the replacement of generalised resource and pollution terms with specific energy and climate change factors. WEM's five main variables are human population, industrial capital, food production, energy production and global warming.

WEM recreates historical data from 1900 to 2016 and projects