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A comparison of *The Limits to Growth* with 30 years of reality

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ABSTRACT

In 1972, the Club of Rome's infamous report "*The Limits to Growth*" [Meadows, D.H., Meadows, D.L., Randers, J., Behrens_III, W. W. (1972). The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind. Universe Books, New York] presented some challenging scenarios for global sustainability, based on a system dynamics computer model to simulate the interactions of five global economic subsystems, namely: population, food production, industrial production, pollution, and consumption of non-renewable natural resources. Contrary to popular belief, *The Limits to Growth* scenarios by the team of analysts from the Massachusetts Institute of Technology did not predict world collapse by the end of the 20th century. This paper focuses on a comparison of recently collated historical data for 1970–2000 with scenarios presented in the *Limits to Growth*. The analysis shows that 30 years of historical data compare favorably with key features of a business-as-usual scenario called the "standard run" scenario, which results in collapse of the global system midway through the 21st century. The data do not compare well with other scenarios involving comprehensive use of technology or stabilizing behaviour and policies. The results indicate the particular importance of understanding and controlling global pollution.

1. Introduction

In 1972, a team of analysts from the Massachusetts Institute of Technology published "*The Limits to Growth*" (Meadows et al., 1972). This well-known and controversial book documented for the general public the results of the MIT study carried out by Meadows et al., who had been commissioned by The Club of Rome to analyse the "world problematique" using a computer model called World3 developed at MIT. The World3 model permitted Meadows et al. to examine the interactions of five subsystems of the global economic system, namely: population, food production, industrial production, pollution, and consumption of non-renewable natural resources. The time scale for the model began in the year 1900 and continues until 2100. Historical values to the year 1970 are broadly reproduced in the World3 output.

A description of the background that led to the *Limits to Growth* (subsequently abbreviated as: LtG) is given elsewhere (McCutcheon, 1979). This reference also briefly summarizes the LtG publication (pp. 7–14). A detailed description of the model, the supporting data, and an analysis of how the model behaves was also published (Meadows et al., 1974).

The release of the LtG in 1972 had immediate and ongoing impacts. Environmental issues and the sustainability debate were further popularized as millions of copies were sold, and translated into 30 languages. Scientifically, it introduced Jay Forrestor's newly founded computational approach of "system dynamics" modelling, and quantitative scenario analysis, into the environmental discipline. By linking the world economy with the environment, it was the first integrated global model (Costanza et al., 2007). The salient message from the LtG modelling was that continued growth in the global economy would lead to planetary limits being exceeded sometime in the 21st century, most likely resulting in the collapse of the population and economic system, but also that collapse could be avoided with a combination of early changes in behaviour, policy, and technology.

Despite these major contributions, and dire warnings of "overshoot and collapse", the LtG recommendations on fundamental changes of policy and behaviour for sustainability have not been taken up, as the authors recently acknowledge (Meadows et al., 2004). This is perhaps partly a result of sustained false statements that attempt to discredit the LtG. From the time of its publication to contemporary times, the LtG has provoked many criticisms which falsely claim that the LtG predicted resources would be depleted and the world system would collapse by the end of the 20th century. Such claims occur across a range of publication and media types, including scientific peer-reviewed journals, books, educational material, national newspaper and magazine articles, and web sites (Turner, unpublished). This paper briefly addresses these claims, showing them to be false.

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The main purpose of this paper, however, is to compare LtG scenario outputs of the World3 model produced in 1974 (the second edition of LtG) with 30 years of observed data covering 1970–2000. This comparison is made to distinguish between scenarios in terms of approximate magnitudes and trends of key variables, and is therefore commensurate with the purpose of the LtG modeling, i.e., to understand different global economic behaviour modes rather than being strictly predictive.

The World3 model was not intended to be predictive or for making detailed forecasts, but to provide a means for better understanding the behaviour of the world economic system. "In this first simple world model, we are interested only in the broad behaviour modes of the population-capital system." (Meadows et al., 1972, p. 91). Meadows et al. developed this understanding by experimenting with various settings of parameters reflecting different scenarios, and carrying out detailed sensitivity analysis, much of which is described in Meadows et al. (1974). The output graphs produced from the World3 model are predictive "only in the most limited sense of the word. These graphs are not exact predictions of the values of the variables at any particular year in the future. They are indications of the system's behavioural tendencies only." (Meadows et al., 1972, pp. 92–93).

A brief review is given in the next section of the LtG model, the output variables that will be compared with observed data, and the scenarios used in the comparison. The sources, uncertainties, and applicability of the historical data are described in the third section, and the data compared with the LtG scenario outputs. The comparison is discussed further in the fourth section. There are sufficiently large distinctions between the model output scenarios over this 30-year period to be able to:

- identify some scenarios appearing more likely than others, and therefore the extent to which a global sustainable pathway has been followed; and
- identify the main areas of uncertainty and key areas for research and monitoring.

2. The LtG model and output

2.1. The LtG model

There are four key elements to understanding the constraints and behaviour of the world system that was captured in the LtG study. It is the combination of these elements in the one study that gives the LtG analysis its strength above other comparable and critical work.

The first involves the existence of feedback loops, both positive and negative. When positive and negative feedback loops are balanced a steady-state outcome results; however, when one loop dominates an unstable state is the result, such as the simple case of exponential growth when there is a dominant positive feedback. When the dominance of the feedback loops depends on the level of the variable in question, then it is possible to produce oscillations in the variable over time.

A second key element is the presence of resources, such as agricultural land, whose function may be eroded as a result of the functioning of the economic system. The modeled resources can also recover their function, and the rate of recovery relative to degradation rates affects when thresholds or limits are exceeded, as well as the magnitude of potential collapse.

The third key element is the presence of delays in the signals from one part of the world system to another. For instance, the effects of increasing pollution levels may not be recognized on life expectancy or agricultural production for some decades. This is important because, unless the effects are anticipated and acted on in advance, the increasing levels may grow to an extent that prohibits or constraints feasible solutions whether technological, social, or otherwise.

Treating the world economic system as a complete system of sub-systems is the fourth key element. When considering the challenges of an individual sector such as energy or agriculture on its own, it is relatively easy to propose mitigating solutions. However, the solutions rarely come without implications for other sectors. The real challenge then becomes solving issues in multiple sectors concurrently.

The World3 model was highly aggregated, treating variables as either totals, such as population being the total world population, or appropriate averages, such as industrial output per capita. No spatial or socio-economic disaggregation was directly employed in the model structure, although the values of parameters were informed by available data at suitable levels of disaggregation.

The LtG project was one of the early applications of computer-based system dynamics. Causal links were made mathematically to reflect the influence of one variable on another, both within and between various sectors of the global economic system. In this way, positive and negative feedback loops were established.

2.2. The LtG output variables to be compared with data

For each scenario, the output presented from the World3 model of LtG covered eight variables: global population; crude birth rate; crude death rate; services per capita; food per capita; industrial output per capita; non-renewable resources (fraction of 1900 reserves remaining); and persistent pollution (normalized against 1970 level). These are described below to clarify any issues of interpretation.

2.2.1. Population

The LtG World3 model simulates the global population as an aggregate total, using average birth and death parameters. Although this aggregate nature may complicate interpretation of the simulations, it does not necessarily invalidate the results of the model as long as suitable values for parameters are used, as described in Meadows et al. (1974).

2.2.2. Birth and death rates

Birth and death rates in the LtG are simply the crude numbers of these events in each year per capita. Like the other LtG variables presented here, birth and death rates are endogenously calculated, but also influenced by exogenous parameters, such as desired family size.

2.2.3. Services per capita

The LtG services per capita variable focuses on the health and educational contribution to the populace. Increasing services per capita were assumed in the LtG to raise life expectancy and lower the birth rate. Consequently, it is not appropriate to use observed data on the "service" sector as a whole (such as the proportion of world GDP that is attributed to the service sector) since such measures would encompass aspects that do not necessarily reflect health and educational benefits. For instance, increases in the tourism industry associated with greater travel by people in relatively wealthy countries could not be considered to contribute to longer lives and fewer children per family at a global level.

2.2.4. Food per capita

The issues regarding food per capita are similar to those for services in the sense that higher food per capita results in a

healthier population. The LtG modelled food per capita in terms of a uniform measure expressed as kilograms of grain equivalent.

2.2.5. Industrial output per capita

In the LtG study the industrial output per capita was used as a measure of the material wealth of the population, indicating the level of goods consumed by the population. This variable was also related to a number of components in the World3 model, such as capital made available for the provision of services and food production, resources consumed, and pollution generated.

2.2.6. Non-renewable resources

Non-renewable resources are expressed in the LtG World3 simulation as the fraction of non-renewable resources remaining, treating this as an aggregate. The LtG defines a non-renewable resource (Meadows et al., 1974, p. 371) as a "mineral or fossil-fuel commodity that (1) is essential to industrial production processes and (2) is regenerated on a time scale that is long compared with the 200-year time horizon of the model".[1] The fraction of non-renewable resources remaining is more difficult than demographic variables to quantify with measured data, since the fraction of what remains relies on estimates of what was originally in the ground. The LtG acknowledged this uncertainty and used a range of estimates, starting with a resource base with a static reserve index of 250 years in 1970 (which was approximately equivalent to that of iron), and increasing this ten-fold.

Before proceeding to describe the available data below, there are several aspects to non-renewable resources that should be outlined, namely the concepts of:

- ultimate resource base;
- extraction effort;
- aggregation of all minerals and fuels into one variable; and
- resource substitution.

The key quantity that creates the greatest degree of uncertainty in this analysis is the estimate of the original quantity of resources in the ground available for extraction and use over the 200-year timeframe of the LtG simulation irrespective of the extraction technology available.[2] This quantity, the ultimate resource or resource base (Rogner, 1997; McCabe, 1998), is always greater than estimates of reserves, which are essentially the resources that have been discovered (or anticipated near-term discoveries) that can be extracted economically using contemporary techniques; estimates of reserves generally increase cumulatively over time toward the ultimate resource as more discoveries are made or other techniques become economic. Estimates of the ultimate resource also vary depending on assumptions about relevant geophysics or long-term extraction possibilities. The approach in this paper is to determine from published literature upper and lower estimates of the ultimate resources that span a suitably wide range. Then it is reasonably straightforward to obtain the fraction of the non-renewable resource remaining, since there are relatively good data on the cumulative quantity of the resource that has been consumed over time.

Closely related to the estimate of ultimate resource is the issue of extraction effort, i.e., the capital and operational inputs required to extract the resources. For instance, while it is in principle possible to identify truly massive resources of minerals if this includes all molecules that are distributed in dilute concentrations in the crust of the earth (Interfutures, 1979), to do so on the basis of any technological extraction process for the foreseeable future would be prohibitively expensive (not just in economic cost but also in terms of energy, water, and other material requirements) (Meadows et al., 1992). Consequently, such "in principle" resource estimates are not included in the analysis presented here, since they are unlikely to contribute to the resource base in the timeframe covered by the World3 model.

The extraction effort associated with the resource base is explicitly included in the World3 model, implemented so that increasing capital and operating inputs are required as the fraction of non-renewable resources remaining (i.e., the portion of the ultimate resource yet to be extracted) decreases. In general, this is because further extraction takes place with resources of lower-grade ores and reduced accessibility. The LtG modeling incorporates an allocation of 5% of the industrial capital to extraction of resources, and remains at this level until nearly half the resource base is consumed (see Fig 5.18 of Meadows et al., 1974). This steady efficiency is in recognition of potential technological improvements in resource discovery and extraction. However, as the resources remaining drops below 50%, the LtG modeling assumes that the fraction of capital required rises steeply (for instance, at 25% of resources remaining, 60% of capital is diverted for use in the resource sector). This relation was based on data associated with accessing resources of increasing scarcity, such as US oil exploration costs. Sensitivity analysis in the LtG project showed that as long as there is increasing resource usage (at about 4% pa), even large errors in the fraction of capital allocated to resources cause only a small error in the timing of the eventual increase in resource costs (Meadows et al., 1974, p. 398).

A potentially confounding issue is the aggregate nature of the non-renewable resource variable in the LtG simulation. Resources are not considered separately, but as an aggregate. If there is little substitutability between resources then the aggregate measure of the non-renewable resources remaining is determined by the resource in shortest supply because economic growth within the model is affected by the increasing extraction effort associated with this resource. If there is unlimited substitutability, then the aggregate measure is determined by the sum of all resources including the most readily available resource because as other resources are diminished the industrial process can switch to more available resources without (in this case) significant impact.

2.2.7. Persistent pollution

The final variable for comparison—persistent pollution—is a difficult variable to quantify with appropriate data. Few measurements of pollutant amounts (volumes or concentrations) were found that span the last three decades and match the LtG criteria for this variable, namely:

- arising from industrial or agricultural production;
- distributed globally;
- persist for long times (on the order of decades or more); and
- damage ecological processes, ultimately leading to reduction of human life expectancy and agricultural production.

Aside from data availability, comparison with the World3 model output is complicated by the necessity of relating absolute pollution levels to damage of ecological processes. This aspect is explored further in the discussion comparing data with model output.

[1] The LtG definition did not include agricultural material inputs such as phosphorus and potassium, presumably so that the effect of resource constraint on the industrial sector could be isolated and understood.

[2] The World3 calculations actually used the resources in 1900 as the quantity of original resources, which is a very good approximation to the ultimate resource since a negligible amount was extracted prior to 1900. This is particularly true owing to the large uncertainties regarding estimates of the ultimate resource.

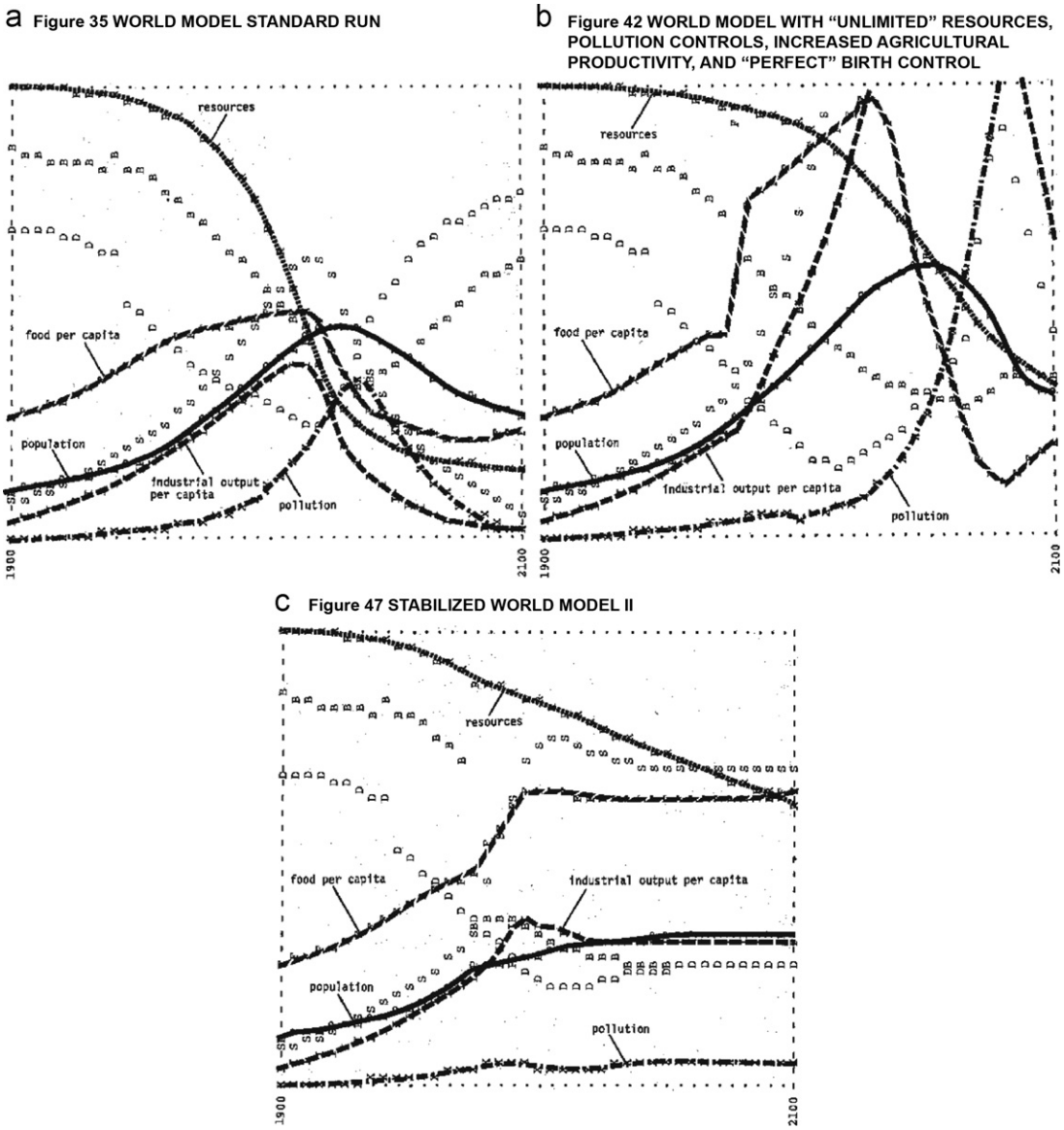

Fig. 1. Output from the LtG modelling for three scenarios ((a) standard run, (b) comprehensive technology, and (c) stabilized world) that effectively span the technological and social responses explored in the LtG.

2.3. LtG scenarios

To permit the design and testing of various scenarios in Meadows et al. (1972), a selection of variables were established as exogenous parameters. These could be set at different values throughout the time period of the simulation, allowing the study of the effects of different policies, technology, and behaviour. Exogenous variables were varied to create different scenarios, and endogenous parameters were varied to determine the sensitivity of the model output to key factors and uncertainties.

Three key scenarios from the LtG[3] are compared in this paper with data:

- "standard run" (Fig. 35 in the LtG);
- "comprehensive technology" (Fig. 42 in the LtG); and the
- "stabilized world" (Fig. 47 in the LtG).

[3] The scenario graphs are from the second edition published in 1974.

The three scenarios effectively span the extremes of technological and social responses as investigated in the LtG. The output from these scenarios is reproduced in Fig. 1. The graphs show the output variables described above on normalized scales, over a two-century timescale (1900–2100).

The "standard run" represents a business-as-usual situation where parameters reflecting physical, economic, and social relationships were maintained in the World3 model at values consistent with the period 1900–1970. The LtG "standard run" scenario (and nearly all other scenarios) shows continuing growth in the economic system throughout the 20th century and into the early decades of the 21st. However, the simulations suggest signs of increasing environmental pressure at the start of the 21st century (e.g., resources diminishing, pollution increasing exponentially, growth slowing in food, services, and material wealth per capita). The simulation of this scenario results in "overshoot and collapse" of the global system about mid-way through the 21st century due to a combination of diminishing resources and increasing ecological damage due to pollution.

The "comprehensive technology" approach attempts to solve sustainability issues with a broad range of purely technological solutions. This scenario incorporates levels of resources that are effectively unlimited, 75% of materials are recycled, pollution generation is reduced to 25% of its 1970 value, agricultural land yields are doubled, and birth control is available world-wide. These efforts delay the collapse of the global system to the latter part of the 21st century, when the growth in economic activity has outstripped the gains in efficiency and pollution control.

For the "stabilized world" scenario, both technological solutions and deliberate social policies are implemented to achieve equilibrium states for key factors including population, material wealth, food, and services per capita. Examples of actions implemented in the World3 model include: perfect birth control and desired family size of two children; preference for consumption of services and health facilities and less toward material goods; pollution control technology; maintenance of agricultural land through diversion of capital from industrial use; and increased lifetime of industrial capital.

The LtG authors explicitly emphasized uncertainty about the timing and extent of any "overshoot and collapse" of the global system. Nevertheless, substantial sensitivity analysis (Meadows et al., 1974) showed that the general behaviour (if not the detail) of overshoot and collapse persists even when large changes to numerous parameters are made (such as the relationship of health and the environmental impacts with increasing pollution).

2.4. Previous reviews of LtG from an historical perspective

Numerous reviews of the LtG appeared mostly in the decade of years following the publication of the original report (Weitzman, 1992; Hardin and Berry, 1972). Since these reviews were made relatively shortly after the 1972 publication, there was little scope for analysing the LtG scenarios against actual world developments and the reviews therefore focused on technical issues associated with the modelling approach.

Somewhat surprisingly, very few reviews of the LtG modelling have been made in recent years using the "benefit of hindsight" (Costanza et al., 2007). Perhaps this can be attributed to the effectiveness of the number of criticisms attempting to discredit the LtG on the basis of present availability of resources (Turner, unpublished). A common claim made about LtG is that the 1972 publication predicted that resources would be depleted and the world system would collapse by the end of the 20th century. Since any such collapse has not occurred or been imminent, the claims either infer or explicitly state that the LtG is flawed. In contrast, few publications have noted the falsity of these criticisms (e.g., Norton, 2003; Lowe, 2002; Meadows, 2007).

Shortly after the LtG appeared, *The New York Times Sunday Book Review* magazine published a general critique by three economists of the LtG and of two earlier books by Jay Forrester (Passell et al., 1972). Among a series of incorrect statements, they attributed the LtG with the statement that "World reserves of vital materials (silver, tungsten, mercury, etc.) are exhausted within 40 years", which is clearly attributed in the LtG to a US Bureau of Mines' publication. Passell et al. also state "all the simulations based on the Meadows world model invariable end in collapse" (Meadows, 2007). Neither of these statements is borne out in the LtG, as can be seen by the scenarios reproduced in this paper. Nevertheless, it appears that these criticisms have been promulgated widely (Turner, unpublished). Some critiques, such as that in Lomborg (2001) and McCabe (1998), specifically identify a table (number 4) of non-renewable natural resources and inappropriately select data (from column 5) that fits their criticism while ignoring other data (column 6) that illustrate extended resource lifetimes due to expanded reserves.

Other notable references include places of high profile or influence, such as presentations to the UK Royal Society of Arts (Ridley, 2001), and educational material for children (Sanera and Shaw, 1996) and university economic students (Jackson and McIver, 2004). Similarly, false claims have also been adopted by sceptical, independent, or environmentally aware people and organizations. For example, in its Global Environment Outlook (GEO3, Chapter 1, pp. 2–3) (UNEP, 2002) the United Nations Environment Programme quotes the LtG as concluding world collapse by the year 2000. Inaccurate and exaggerated statements such as those following from a book (Moffatt et al., 2001) on sustainable development do not help to maintain a clear and logical analysis: "Some earlier estimates from computer simulation models such as the discredited LtG models…suggested that during the next 250 years (i.e., by about 2195) the human population and most other life forms will cease to exist." In reality, the LtG scenarios finished in 2100, and the simulations did not indicate that the human population will cease to exist, but rather that a dramatic decline in numbers might result.

Some studies that are relevant to the historical review of LtG in this paper are summarized below. While all are useful additions to the sustainability debate for various reasons, none explicitly compare a comprehensive set of observed historical data with the original LtG analysis.

Several of the original LtG authors published two revisions: 20 and 30 years after the original study. "*Beyond the Limits*" (Meadows et al., 1992) and "*Limits to Growth: The 30-Year Update*" (Meadows et al., 2004) are updates of the original work using better data that had become available in the intervening years. They determined that the three overriding conclusions from the original work were still valid, and needed to be strengthened [pp. xiv–xvi].

In "*Beyond the Limits*" for example, updates were made using empirical data and relatively minor changes were made to seven parameters. In some cases, such as agriculture and population, errors in two parameters had opposite effects that tended to cancel out, with the result that the model output of the original study remained in reasonable agreement with historical data. The most obvious example of this is in the birth and death rates (actually underlying parameters) producing the same aggregate population as originally calculated. In addition to updating parameter values, Meadows et al. also changed how new technologies were implemented, from being driven exogenously to being determined by an adaptive structure within the system dynamics model that sought to achieve a system goal (such as a desired level of persistent pollution). However, this was a feature explored in the original work and published in the accompanying technical report in 1974 (Meadows et al., 1974).

With these changes, Meadows et al. reran the World3 model over the same time period (1900–2100) as the original study. The model output was presented graphically in a manner similar to the 1972 publication. Consequently, they did not compare the historical data over the period 1970–2000 with the original simulations published in Meadows et al. (1972).

One of the original authors also published a review paper (Randers, 2000), stating "Interestingly, history since 1970 has shown that the surprise free scenario—the "standard run" of LtG—has proved to be a good description of actual developments this far." Data are not presented to accompany this view; instead, the paper focuses on the continuing relevance of feedback loops.

In an energy white paper, Simmons (2000) notes how accurate many of the trend extrapolations are 30 years after the original LtG publication. He specifically presents global population figures,

and generally reviews the production and consumption of energy for broad comparison with the LtG.

In 2001 a special issue of *Futures* was published with articles focused on the LtG (Cole and Masini, 2001). Although this issue had a retrospective aspect, it was oriented to the social impacts of the LtG and did not compare historical data with the LtG simulations.

A good summary of the LtG scenarios is provided by Jancovici, available on the Internet (Jancovici, 2003). Some historical data are presented, such as population growth and concentrations of global air pollutants, and general observations about driving forces related to the "standard run" scenario of LtG. However, specific comparisons with the output of LtG scenarios were not made.

3. Observed data and comparison with LtG scenario outputs

In this paper, independent historical data generally covering the period 1970–2000 are compared with the output of the World3 simulation (Meadows et al., 1972). Publicly available sources were used, such as WorldWatch Institute's "Vital Signs" (Brown et al., 2002), World Resource Institute Earthwatch database (WRI, 2002), and UN publications (UN, 2001a). There are no other publications that the author is aware of that compare independent historical data with the original World3 outputs (Costanza et al., 2007). This includes revisions by several of the original LtG authors 20 and 30 years later (Meadows et al., 1992, 2004), which were implemented by updating model settings. Although it should be possible to also compare the World3 output over 1900–1970 with historical data, this would not provide a good test of the LtG analysis since the World3 model was calibrated by data for 1900–1970, and therefore historical data are not necessarily independent of that used by the model.

In keeping with the nature of the LtG modeling and accuracy of the global data, a simple graphical and quantitative comparison is made between the observed data and the modeled output of the three scenarios. This comparison may provide insight into the validity of the LtG World3 model, as a predictive validation (or positive economics) technique (Sargent, 1998). In the discussion section, the comparison is summarized using the root mean square deviation (RMSD) for each variable, for each scenario. However, the extent of any model validation is constrained since the comparison with data is complicated by the reported model output being limited to the set of scenarios previously published. Lack of agreement between data and model output may arise if the assumptions embodied in the settings of the exogenous parameters in a scenario are not commensurate with the evolution of the global system from 1970 to 2000. The comparison presented here is as much a test of the scenarios as it is of the model. Further statistical analysis (such as graphical residual analysis, degenerate tests, or traces (Sargent, 1998)) could be considered beneficial in the context of more detailed data and global models, particularly if random variations are consequently introduced.

The variables used for comparison are those that were displayed in the LtG output graphs, described above. These variables collectively represent the state of the global system as calculated in the World3 model. The following sub-sections detail the data used for the comparison, and explore the comparison between data and LtG model output.

Careful consideration of what constitutes appropriate data was required since the concepts (or level of aggregation) of several of the LtG variables require interpretation. For example, the persistent pollution variable is meaningful when considered in terms of the effect that the level of total global pollution has on the human or environmental system. Details on the source of observed data are provided to aid further independent comparisons. Estimates of uncertainty or ranges of alternative data are given. Observed data have generally been normalized to the LtG output at 1970.

Following a description of the observed data, a graphical comparison with the LtG scenario output is provided. The LtG model output for each scenario is shown in each figure using open symbols ("standard run" with open diamonds ◇, "comprehensive technology" with open triangles △, and "stabilized world" with open squares □), compared with observed data as solid circles ●. In each graph the shaded portion shows the period 1900–1970 over which the World3 simulations were calibrated with historical data available then, and the model output over 1900–1970 is shown with open cirlces ○.

3.1. Population data

Total global population was obtained from the on-line "EarthTrends" database of the World Resources Institute (http://www.wri.org/) (WRI, 2002). The source of this population data was the: Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, 2002. World Population Prospects: The 2000 Revision. Dataset on CD-ROM. United Nations, New York.

Among the data presented in this paper, global population is likely to be one of the more accurate, being based on a process of regular censuses. There will be some degree of error due to issues such as some countries not undertaking censuses (for example "during 1985–1994 202 of 237 countries or areas conducted a census" (UN, 2001b)) and limitations in the census-reporting mechanisms. However, global population data are widely reported and referenced without significant variance and any errors will be negligible with respect to the precision of the World3 model output. The observed data were normalized at 1970 to be equal to the World3 output.

3.2. Population comparison

Observed global population (WRI, 2002) using UN data closely agrees with the population for the "standard run" scenario, as shown in Fig. 2. However, as shown next, this is a result of compensating discrepancies in the birth and death rates. Comparison with the "comprehensive technology" scenario is even better, while the "stabilized world" population is significantly lower (about 25%) than the observed population.

3.3. Birth and death rates data

Birth and death rates were obtained from the on-line "EarthTrends" database of the World Resources Institute (http://www.wri.org/) (WRI, 2002). The source of the crude birth rate was given as the: United Nations (UN) Population Division, Annual Populations 1950–2050 (The 1998 Revision), on diskette (UN, New York, 1999). For the death rate, the reported source was the same as for total population (above).

Both birth and death rates have been normalized to the LtG World3 output at the year 1955, rather than 1970 since a departure between the observed data and the World3 output for the crude death rate should be made explicit for proper comparison.

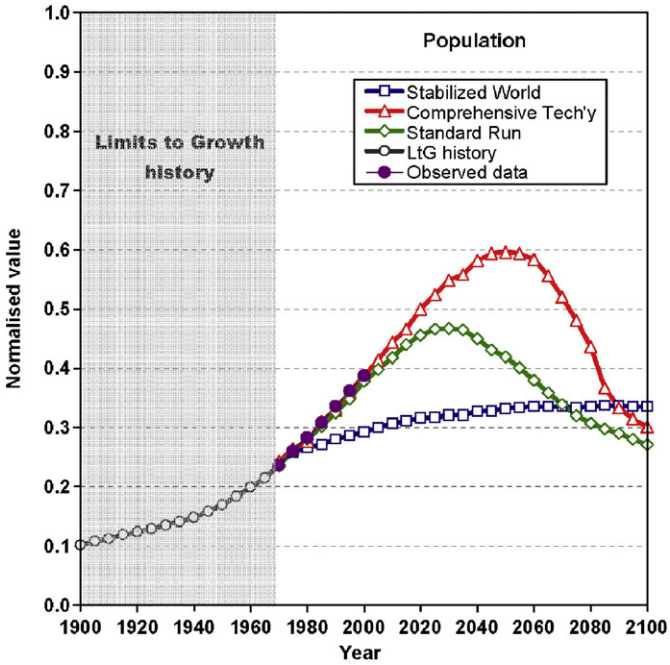

Fig. 2. Comparison of observed data (solid circles ●) for global population with the LtG model output for each scenario ("standard run" with open diamonds ◇, "comprehensive technology" with open triangles △, and "stabilized world" with open squares □). The calibrated model output over 1900–1970 is shown with open cirlces ○.

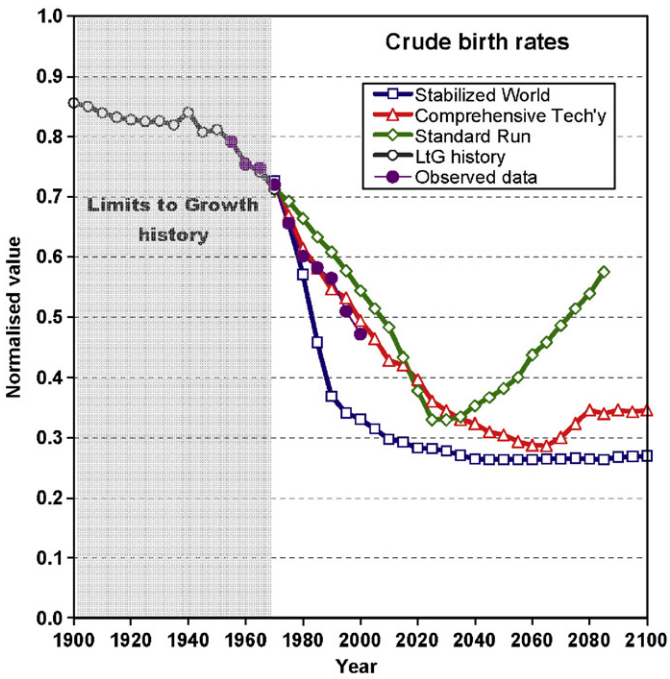

Fig. 3. Comparison of observed data (solid circles ●) for crude birth rates with the LtG model output for each scenario ("standard run" with open diamonds ◇, "comprehensive technology" with open triangles △, and "stabilized world" with open squares □). The calibrated model output over 1900–1970 is shown with open cirlces ○.

3.4. Birth and death rates comparison

Both the observed birth and death rates drop rapidly (Figs. 3 and 4), though the death rate has a saturating trend. The rate of decrease of both variables is such that the overall rate of growth of

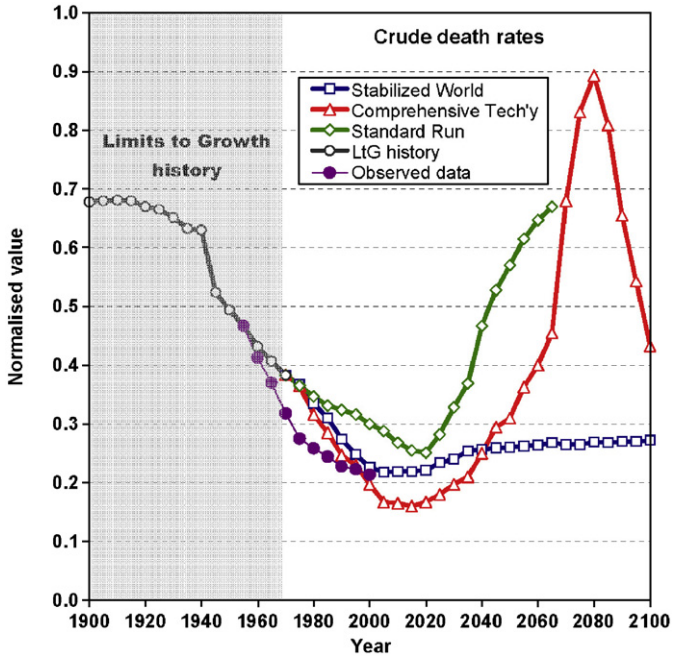

Fig. 4. Comparison of observed data (solid circles ●) for crude death rates with the LtG model output for each scenario ("standard run" with open diamonds ◇, "comprehensive technology" with open triangles △, and "stabilized world" with open squares □). The calibrated model output over 1900–1970 is shown with open cirlces ○.

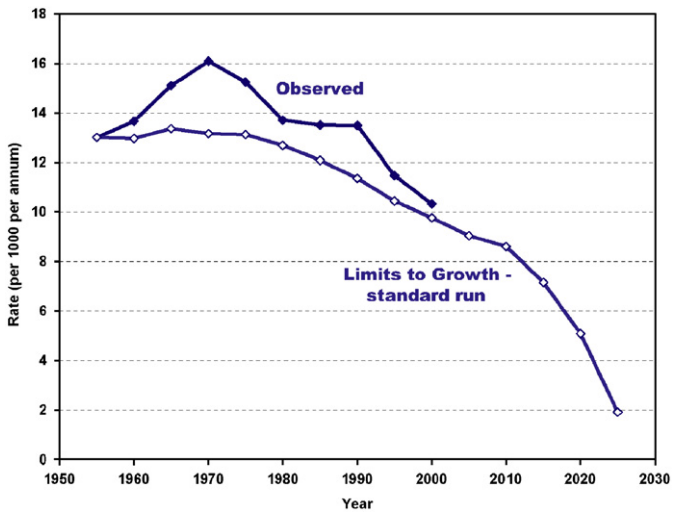

Fig. 5. Observed (solid symbols) and World3 calculated (open symbols) "net" birth rates (the crude birth rate less the crude death rate).

the population remains as calculated in the World3 "standard run". The "comprehensive technology" scenario has a good agreement with birth rates, while the "stabilized world" scenario involves birth rates that fall substantially faster than the observed data. All of the scenarios show death rates that fall over time (until later this century), but are higher than the observed data for most of the period of comparison. The death rate in the "stabilized world" scenario appears to approximate the observed data with an offset of about two decades.

The "net" birth rate (i.e., the difference between the crude birth and death rates) is shown in Fig. 5 for both the observed data and the World3 standard run scenario. Simply extrapolating trends for the latest observed data suggests that birth rates may equal death rates in about 2030 give or take a decade, at which

time the population would stabilize. In this case, the population would peak at a value higher than that of the "standard run" scenario.

3.5. Services per capita data

Several data measures have been used here to compare with the World3 model of services (per capita) provided to the global populace. Literacy and electricity data were used for comparison with the LtG output because of the relevance to health and educational contribution to the populace. Electricity consumed (per capita) globally and the literacy rate (as a %) for both adults and youths were obtained from the WRI EarthTrends database. These latter two data sets were available only from 1980 onwards and were sourced from the United Nations Educational Scientific, and Cultural Organization (UNESCO) Institute for Statistics, Literacy and Non Formal Education Sector (2002). For the graphical comparisons, the literacy data were normalized to the LtG value at 1980, and electricity per capita normalized at 1970. No attempt was made to aggregate the observed data into one data set.

Uncertainty ranges are likely to be potentially greater than $\pm 10\%$ since these data will combine the uncertainty of global population estimates with those of literacy rates or electricity consumption. Literacy rates in particular will be subject to errors associated with survey methods taken across numerous countries. Using both electricity and literacy measurements without combining them provides an explicit indication of the degree of uncertainty in measurements of services per capita: by the year 2000 these data are some 20% divergent.

3.6. Services per capita comparison

The comparison between observed and modeled services per capita illustrated in Fig. 6 is mixed. The observed data on adult and juvenile literacy per capita (lower services curves) show significantly lower growth than modeled services in Fig. 6. For electricity, the services per capita for the "standard run" scenario is close to the observed data. In this case, the modeled services per capita is growing in a near-linear manner between 1970 and 2000 (subsequently saturating after 2000), whereas all observed data indicate diminishing growth already.

The "comprehensive technology" and "stabilized world" scenarios do not compare well with the observed data, significantly over-estimating services per capita. In the "stabilized world" scenario, however, the saturating trend of the modeled services per capita roughly approximates that of electricity per capita. The modeled output is a result of simulating deliberate policies of directing preferences toward services, among other things, whilst constraining system growth that would otherwise lead to deleterious effects. In the "comprehensive technology" scenario by contrast, the large compounding growth in the World3 model output results in services per capita being some 35% higher than the observed electricity per capita and 80% higher than literacy rates.

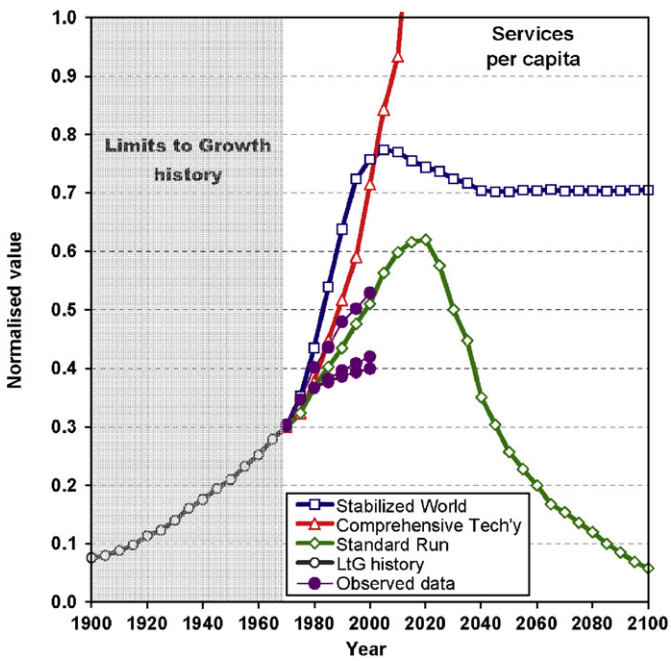

Fig. 6. Comparison of observed data (solid circles ●) for services per capita (upper: electricity; middle: adult literacy %; lower: youth literacy %) with the LtG model output for each scenario ("standard run" with open diamonds ◇, "comprehensive technology" with open triangles △, and "stabilized world" with open squares □). The calibrated model output over 1900–1970 is shown with open cirlces ○.

3.7. Food per capita data

For the observed data on food per capita it is appropriate to use the average supply per person of total energy content in food, obtained as kilocalories per capita per day from the WRI EarthTrends database, which identifies the source as the Food and Agriculture Organization (FAO) of the United Nations—FAOSTAT on-line statistical service, Rome, 2002. Using this data set is preferable to using selected food types (such as meat, grain, and fish) since these entail more specific issues of distribution and use (e.g., grain production may or may not include supply of grain to meat production). Nevertheless, using other data sets results in similar trends and magnitudes (e.g., see world grain production per capita (Lomborg, 2001, Fig. 50), and world meat production per capita (Brown et al., 2002, p. 29)). Of course, the supply of the energy content of food is not itself a complete measure of the nutritional contribution to humans of agricultural production, but it is a necessary component for which there is good data. The observed data were normalized to the LtG value at 1970 and observed data from 1960 were also included.

In the case of food, in contrast to services, the observed data are arguably more precise given that there are considerable efforts to record agricultural production. Accompanying notes to the data source state: "data from the FAO on food supply are governed by established accounting practices and are generally consider[ed] to be reliable"; and "Data are available for most countries and regions from 1961". They also note that these data refer only to supply and should not be used as a measure of consumption. For the purposes of comparing global averages, this means that the observed data are an effective upper limit for comparison with the food per capita variable.

3.8. Food per capita comparison

The observed food per capita (average supply per person of total energy content in food (WRI, 2002) using FAO data) shows signs of diminished growth (Fig. 7), most similar to that in the "standard run" scenario—by year 2000 there is only about 5% difference between observed and modeled data. Comparisons with other data sets provide similar indications: global meat production per capita has increased approximately linearly by 40% (Brown et al., 2002); world grain production per capita peaked in the 1980s and has increased

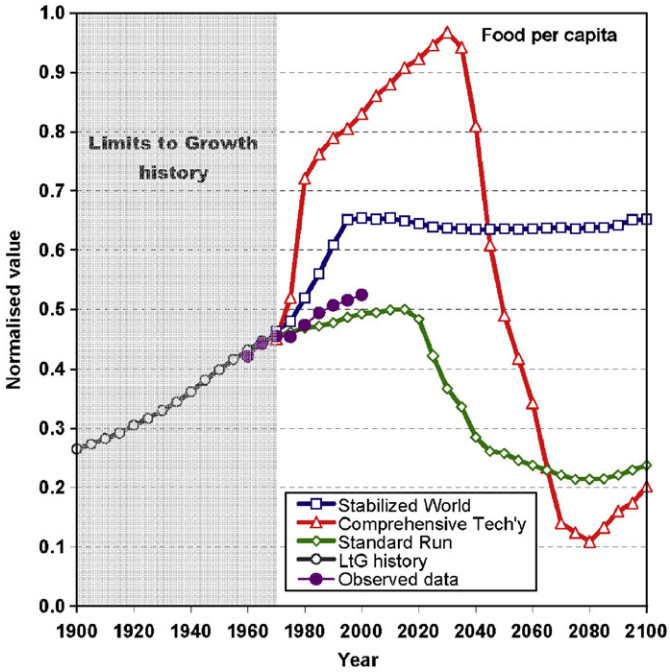

Fig. 7. Comparison of observed data (solid circles ●) for food per capita with the LtG model output for each scenario ("standard run" with open diamonds ◇, "comprehensive technology" with open triangles △, and "stabilized world" with open squares □). The calibrated model output over 1900–1970 is shown with open cirlces ○.

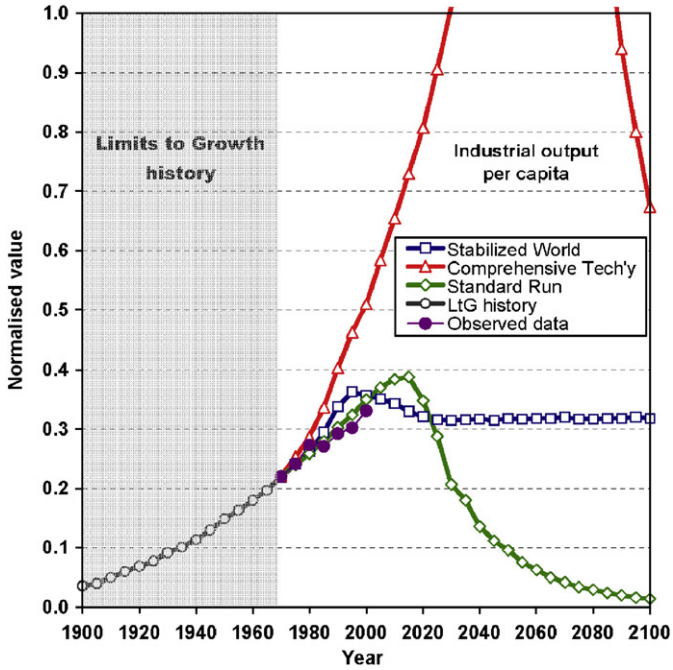

Fig. 8. Comparison of observed data (solid circles ●) for industrial output per capita with the LtG model output for each scenario ("standard run" with open diamonds ◇, "comprehensive technology" with open triangles △, and "stabilized world" with open squares □). The calibrated model output over 1900–1970 is shown with open cirlces ○.

only a few percent since 1970; and a smooth curve of the developing countries grain production per capita has increased about 20% (Lomborg, 2001).

The food per capita outputs of the "comprehensive technology" and "stabilized world" scenarios are substantially higher than the observed data. Any of the scenarios that include pollution control and increased agricultural productivity (such as the "comprehensive technology" scenario) show food per capita increasing at a rate of growth to levels well beyond that observed. This indicates that this combination of technological initiatives is not being implemented or realized at a rate that is greater than the population growth rate.

The "stabilized world" scenario shows a higher level of food per capita than the observed data, due to the simulation of soil enrichment and preservation in the scenario. This scenario also diverts capital to food production even if this is "uneconomic" so that sufficient food is available for all people (where the population has been stabilized at less than the current world population).

3.9. Industrial output per capita data

Recorded data for industrial output (Meadows et al., 1992, p. 5) were obtained directly from UN Department of Economic and Social Affairs Statistics Division figures, which are provided as a global aggregate (and for regions) (UN, 2001a). Several yearbooks were used to cover the period 1970–1999. The data are presented as "Index numbers of industrial production". This data source over earlier years was used by the LtG study to help establish the historical simulation relating to industrial output per capita (Meadows et al., 1974). It is unclear what level of uncertainty is associated with these data, but the per capita output will have at least the same relative error as the population total. The observed data were normalized to the LtG value at 1970.

3.10. Industrial output per capita comparison

The "standard run" scenario produces an industrial output per capita that is very close (e.g., within 15% at the year 2000) to the observed data (UN statistics on industrial output (UN, 2001a)) in Fig. 8. Except for the time period 1980–1984, there is a very close match between the rate of increase in the simulated and observed data; the difference may be due to the oil shock of the early 1980s, producing a slow-down in industrial output. Evidently, the oil shocks in the 1970s (or those of 1990 and 2000) did not impact on industrial output to the same degree. Other research may shed light on the reason for the different impacts, including the role of real price increases of oil, creation of strategic petroleum reserves, early fuel efficiency gains, and development of additional locations of oil and alternative fuels. Rather ironically, the relatively quick recovery from the early 1970s oil shocks may have counteracted the initial public concern about sustainability raised by the LtG when published at about the same time (Simmons, 2000).

The application of technological improvements in all sectors of the World3 model in the "comprehensive technology" scenario results in rapidly accelerating growth of material wealth and capital substantially beyond that observed. In the "stabilized world" scenario, industrial output per capita is brought toward an asymptote through policies that direct excess industrial capability to producing consumption goods rather than re-investing in further capital growth, and a preference for services over material goods. While the industrial output per capita is similar to that observed at year 2000, the decreasing trend toward stabilization contrasts with continued growth in the observed data.

3.11. Non-renewable resources data

In short, the approach taken here used upper and lower bounds to the observed data. These bounds were based on high and low

estimates of the ultimate fossil-fuel resources; mineral resources are broadly considered here to be unlimited. This approach aligns with what might be considered the position of the critics of LtG and therefore presents a demanding test of the comparison between the observed data and the World3 output.

To account for substitutability between resources, a simple and robust approach has been adopted. First, it is assumed here that metals and minerals will not substitute for bulk energy resources such as fossil fuels.[4] A brief survey of the literature (including that of some decades ago (Khan et al., 1976; Interfutures, 1979; Meadows et al., 1972, 1974, 1992)) on reserves and resource base for non-fuel materials illustrates that many of the common metals are available in substantial abundance, e.g., iron and aluminium. Typically the ratio of reserves to production rates (or "static reserve index") is some hundreds of years. For some other metals, e.g., nickel and lead, more recent examination of the trend in reserve estimates indicates that the situation may be more constrained (Andersson, 2001), but there remain possibilities for substituting other metals and materials for at least some of the more constrained metals (Khan et al., 1976). On the basis of these general evaluations, the analysis here assumes that non-fuel materials will not create resource constraints.

Therefore, the upper and lower bounds for the observed data on non-renewable resources presented in this paper are a direct result of high and low estimates of the ultimate resource obtained from differing opinions of ultimate fossil-fuel resources, as described below.

Compared with metals and minerals, the situation for energy resources is arguably more constrained. Estimates of the ultimate energy resource depend on opinions about the degree to which non-conventional and potentially politically sensitive resources are included in the estimates. Broad figures are presented below that provide reasonable upper and lower bounds, although it is beyond the scope and requirements of the analysis in this paper to undertake a comprehensive literature review on energy resources—given the purpose of the LtG study and corresponding level of modeling precision, it is appropriate to provide estimates specified to one significant figure (and even simply to orders of magnitude). This is also consistent with the high degree of uncertainty surrounding energy resource estimates.

A lower bound for energy resources can be constructed that includes conventional oil and gas, development of non-conventional oil and gas, high-quality coal (assumed equivalent to oil in energy units), and non-breeder nuclear fission, but omits extensive coal resources and speculative sources such as methane hydrates and nuclear fusion. This lower bound assumes that further substantial exploitation of coal or adoption of breeder technology for nuclear fission is limited by global political sensitivity, and that technological advances are made in the extraction of the currently dominant energy sources (oil and gas) but not in other speculative sources (or means of eliminating pollution, such as carbon sequestration). It is on this basis that full coal resources have been omitted in the lower bound estimate, consistent with this large resource being undeveloped due to environmental concerns. It is reasonable to include the non-conventional resources in the lower bound since the LtG simulation incorporates the requirement for significant extraction efforts that might be associated with these resources.

With each of the energy resources included in the lower bound contributing roughly 10,000 EJ (approximately equivalent to 2000 Gboe (giga barrels of oil equivalent); see Table 1), the lower bound for the energy resource base sums to about 60,000 EJ (±30%). To put this in perspective, the cumulative consumption of energy to date amounts to roughly 10–20,000 EJ (Grübler, 1998, Fig. 6.18).

Table 1
Collated estimates of ultimate resources of primary energy

Fuel	Ultimate resource estimate	Estimate in Joules	Reference
Conventional			
Oil	2000 G barrels	10×10^{21}	Bentley (2002)
	300 Gtoe		Rogner (1997)
	2–2.5 G barrels		McCabe (1998)
Gas	420 Gtoe	20×10^{21}	Rogner (1997), Grubler (1998)
	2000 Gboe	10×10^{21}	Bentley (2002)
		10×10^{21}	Khan et al. (1976)
Coal	2400 Gtoe	$100–200 \times 10^{21}$	Rogner (1997), Grubler (1998)
	6750 Gtoe	300×10^{21}	Interfutures (1979)
Non-conventional			
Oil	7000 G barrels	40×10^{21}	Bentley (2002)
	30–2000 Quad	20×10^{21}	Khan et al. (1976)
	520 Gtoe	10×10^{21}	Rogner (1997), Grubler (1998)
Gas	450 Gtoe	20×10^{21}	Grubler (1998)
	1450 Gboe		Bentley (2002)
Coal	Not applicable	–	
Nuclear fission, non-breeder	100 Gtoe	5×10^{21}	Interfutures (1979)
	300 TW-yr	9.5×10^{21}	Hoffert et al. (2002)

An upper bound to the energy resource base is suggested in this paper that is essentially founded on the ultimate coal resource, being in the range of 100,000–200,000 EJ. The uncertainty range in this figure (i.e., 100,000 EJ) is sufficient to include the assumption that conventional oil and gas also continue to be part of the future energy mix and are therefore included in the upper bound estimate for the energy resource base.

If it is assumed that energy sources are made available through technological advances on energy sources such as breeder-style nuclear fission, nuclear fusion, or methane hydrates, then for all intents and purposes the non-renewable resource base becomes unlimited. Similarly, if it is assumed that renewable energy sources such as solar energy are developed to replace non-renewable sources, then this is broadly equivalent in the LtG model to an unlimited non-renewable resource base.[5] The LtG scenarios that incorporate unlimited resources show that limits are consequently reached in other sectors of the world system.

Assuming that energy resources are not completely unlimited, the analysis presented here uses an upper and a lower limit for the original resource base of 150,000 and 60,000 EJ, respectively.[6] Having these bounds, the fraction of non-renewable resources remaining is determined by subtracting the cumulative production of resources from the original resource base. Production data have been obtained from the WorldWatch Institute's "Vital Signs" (Brown et al., 2002), which has compiled the data from several sources: "UN, BP, DOE, IEA and press reports". There is negligible difference (roughly 10% variation on year 2000 cumulative production) with data from other sources, e.g., IIASA (see Grübler's (1998) Figs. 6.18 and 6.19, data available from the

[4] The chemical potential implicit in fuel cells can be used to generate energy; however, the potential of most minerals is low as they are often oxidized. Hydrogen fuel cells are currently being proposed as a potential supply of bulk energy from fuel cells, and apart from the use of renewable energy the most likely means of production of the hydrogen fuel is from fossil fuels or nuclear energy.

[5] This simple assumption ignores issues that essentially depend on the efficiency and rate of energy delivery to the economic system, and analysis indicates that these aspects may be significantly limiting to the operation of a modern economy on renewable energy.

[6] The upper limit is an average of the range in ultimate resources of coal.

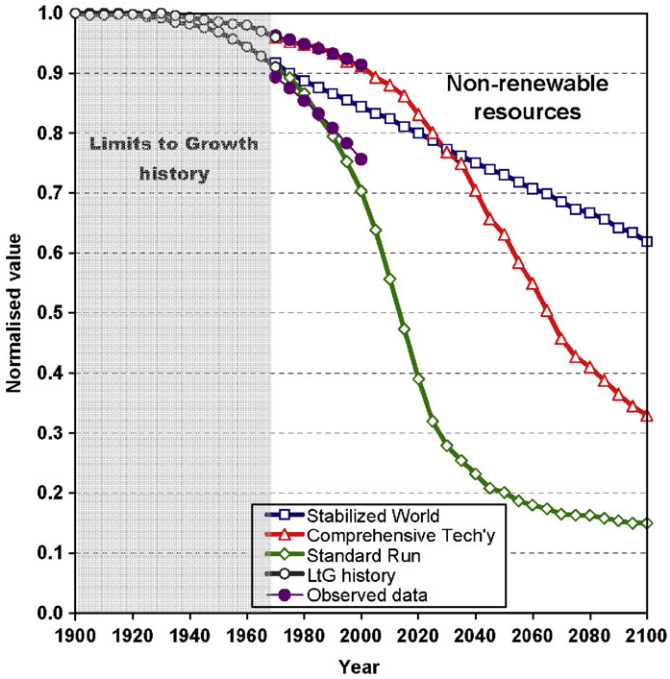

Fig. 9. Comparison of observed data (solid circles ●) for non-renewable resources remaining with the LtG model output for each scenario ("standard run" with open diamonds ◇, "comprehensive technology" with open triangles △, and "stabilized world" with open squares □). The calibrated model output over 1900–1970 is shown with open cirlces ○.

Internet) and World Resource Institute Earthwatch database (WRI, 2002).

3.12. Non-renewable resources comparison

As shown in Fig. 9, the observed data on the fraction of non-renewable resources remaining vary between the upper and lower estimates of 96% and 87% in 1970, decreasing to 91% and 76%, respectively, in the year 2000. These values are sufficiently high that the extraction effort assumed in the LtG remains relatively minor, and therefore capital is not significantly diverted from the agricultural and industrial sectors. The range in the observed data bounds all of the World3 scenario outputs. A noticeable increase in the capital required would appear in about 2030 using a simple extrapolation of the lower bound of observed data on non-renewable resources and applying the LtG assumptions for capital requirements.

In the case of the "standard run" scenario, the lower bound at the year 2000 level is about 5% above the modeled level, and the rate of decrease for observed resources remaining is not as rapid as that of the World3 output. There is very good agreement between the time-series of the upper estimate of observed resources remaining and the World3 output for the "comprehensive technology" scenario. The "stabilized world" scenario shows almost linearly decreasing resources, at a level between the upper and lower estimates of observed data.

3.13. Persistent pollution data

In keeping with the LtG properties for persistent pollution, the most reliable and relevant quantity appears to be atmospheric greenhouse gases, in particular CO_2 levels. These data were obtained from the WorldWatch Institute's "Vital Signs" (Brown et al., 2002), which has compiled the data from several sources: "UN, BP, DOE, IEA and press reports". It compares well with other sources, such as Fig. 133 of Lomborg (2001).

Ideally, the observed data would be the sum of all persistent pollutants, each weighted by an appropriate factor for the longevity and ultimate ecological impact of the pollutant. Other potential components of persistent pollution include heavy metals, radioactive wastes, persistent organic pollutants (such as PCBs), NO_x, SO_x, and ozone-depleting substances. Generally, these suffer from: a lack of suitably long time-series data, globally aggregated figures, or are not expressed as a relative or absolute amount of the pollutant. In the case of ozone-depleting substances, typically data are presented either as concentrations of separate CFC gases (e.g., WRI EarthTrends database) or as annual emissions (e.g., Lomborg's (2001) Fig. 143 or Grübler's (1998) Fig. 6.7), which requires knowledge of atmospheric dynamics such as residence times to be able to infer the cumulative atmospheric concentration.

Given the difficulty of obtaining suitable data on other pollutants, the approach taken was to use atmospheric CO_2 levels relative to 1900 levels as a measure of persistent pollution. The 1900 level of about 300 ppm was subtracted from the reported total CO_2 concentration because the LtG simulation assumes zero global pollution in 1900. These offset data (i.e., CO_2 concentration less 300 ppm) were normalized to the LtG value at 1970. The offset CO_2 levels grow in a slowly compounding fashion (1–1.5% pa) from 1970 to year 2000, increasing by a factor of 2.7 times the 1970 value.

3.14. Persistent pollution comparison

In the "standard run" scenario, pollution has increased from 1970 by more than a factor of three by year 2000. Since these increases are from relatively low levels, the difference between observed and modeled levels of persistent pollution at year 2000 is about 15% in the "standard run" scenario, Fig. 10 (and any scenario that does not employ enhanced pollution control or stabilizing policies). Due to pollution control technology and resource efficiencies, both the "comprehensive technology" scenario and "stabilized world" scenario produce pollution levels lower than half the observed levels of atmospheric CO_2.

4. Discussion

The good general comparison of the observed data with the LtG "standard run" scenario is summarized in Table 2 and Fig. 11. This table shows the difference at year 2000 of both the value and the rate of change of the scenario variable relative to the value and rate of change of the observed data. The use of these two measures is suited to the smoothly varying time-series, which generally are either concave up or down (i.e., approximately second-degree polynomials) over the time period of the comparison. Entries in the table greater than 20% for the value at 2000, and 50% for the rate of change highlight discrepancies between data and model output. Differences below these levels are judged to be within typical uncertainty bounds of the data and model outputs.

A more general comparison of data and model output over the time-series is given in Fig. 11 by the normalized RMSD for each variable, for each scenario. The deviation is the difference between the observed data and the model output at each 5-year time-step. To remove scale effects the RMSD has been normalized to the mean of the observed data for each variable (i.e., it is a "co-efficient of variation"). The "standard run" scenario is in substantially better agreement with the observed data than either alternative scenario as shown by the generally smaller normalized

RMSD values for the "standard run" (where all normalized RMSD values, expect death rate, are below 20%).

Generally, the "stabilized world" and "comprehensive technology" scenarios over-estimate food, services, and material goods for the population. Population is under-estimated by the "stabilized world" scenario. All scenarios match the remaining non-renewable resources to varying extents. Global persistent pollution is under-estimated by both the "stabilized world" and "comprehensive technology" scenarios.

While the comparison between observed pollution level and the different scenarios is instructive, it is worthwhile to consider the ultimate impact of pollution. At two or three times the 1970 levels of global pollution—i.e., observed data and "standard run" scenario output at 2000—the impacts on health and agriculture are assumed in World3 to be very low, only becoming substantial at significantly higher levels. For example, at 40 times the 1970 levels of pollution, in the World3 model assumes a 10% reduction in average life expectancy, and this accelerates non-linearly as pollution increases (Meadows et al., 1974).

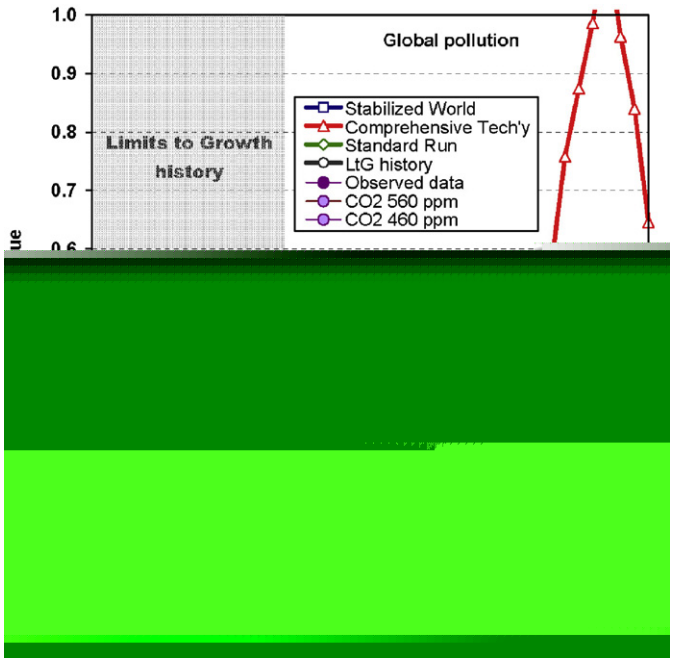

Fig. 10. Comparison of observed data (solid circles ●) for global persistent pollution with the LtG model output for each scenario ("standard run" with open diamonds ◇, "comprehensive technology" with open triangles △, and "stabilized world" with open squares □). The calibrated model output over 1900–1970 is shown with open cirlces ○. Separate points at 2050 show IPCC estimates of possible upper and lower CO_2 levels at 2050 (from A1F1 and B2 scenarios), corresponding to 560 and 460 ppm, respectively.

Such an impact response function qualitatively reflects concerns raised by some climate scientists that dangerous anthropogenic interference may occur at global temperature increases as little as 1 °C above current global temperature (Hansen, 2003), though Hansen (and others) (Schneider and Lane, 2006) notes that other scientists estimate the critical threshold level may be 2 °C or more. Continuation of recent growth rates of CO_2 of about 1–1.5% pa may result in an approximate doubling of CO_2 concentration by 2050, which may cause an increase in global temperature of 2 °C, and therefore possible dangerous climate change.

To compare the LtG scenarios with those of the IPCC, a range of possible CO_2 levels at 2050 are indicated by the vertical bar on the pollution graph (Fig. 10): 460 ppm (lower end of the bar) is estimated to result from low annual emissions scenarios (such as the IPCC B2 scenario), while 560 ppm (upper end) is possible under high growth scenarios (such as IS92a and A1F1 scenarios) (Solomon et al., 2007). The levels of pollution calculated in the LtG scenarios near mid-century are broadly in keeping with respective scenarios of the IPCC and associated environmental impacts, though the LtG pollution levels are 1–2 decades in advance of the respective IPCC scenarios. More recent research suggests that annual greenhouse gas emissions are rising more quickly than the IPCC scenarios (Raupach et al., 2007), and could double by 2030 (Garnaut et al., 2008, draft). This would bring the potential future CO_2 levels into close agreement with the relevant LtG scenarios (560 ppm and "standard run", and 460 ppm and "comprehensive technology").

At current pollution levels, the LtG appears to over-estimate the impact (e.g., 0.2% reduction in life expectancy). This may be one reason for the higher level of the modeled crude death rate compared with observed data in the "standard run" (see Fig. 4), though drawing a firm conclusion requires a detailed understanding of other responses, such as the improvement in health from services and food per capita, and complicated interactions among the factors in the system dynamics of the World3 model.

To undertake such an examination at this time may not be justified, since data on such impacts are extremely limited. Additionally, the World3 model was designed for highlighting potential dynamics of the global system—the aggregate nature of the model was not intended for making precise predictions, but for understanding the degree to which technological and behavioural changes can influence global dynamics.

In keeping with this purpose, we draw broad conclusions below about the likely trajectory of the global system. More generally, even though the comparison of scenario outputs with historical data cannot be construed as providing absolute confirmation of the model, if there were fundamental flaws in

Table 2
Values and rates of change of scenario variables compared with the data at year 2000 for three scenarios

Scenario	% Difference at 2000 relative to observed data	Population	Crude birth rate	Crude death rate	Non-renewable resources	Services per capita	Food per capita	Industrial output per capita	Persistent pollution
Standard run	Value	0	15	40	−25 to −5	−5 to 30	−5	5	15
	Rate of change	25	−15	70	80 to 415	25 to 470	−30	10	80
Comprehensive technology	Value	0	5	−10	0 to 30	35 to 80	100	35	−55
	Rate of change	10	0	250	−15 to −75	360 to 1970	170	65	−155
Stabilized world	Value	−25	−30	0	−10 to 20	45 to 90	25	10	−55
	Rate of change	−70	−75	130	15 to −65	20 to 450	−70	−125	−155

Percent differences are with respect to the observed data, and positive when the scenario values (or rate of change) are greater than the observed data. Entries of more than 20% in value, or greater than 50% for rates of change generally highlight discrepancies between data and model output.

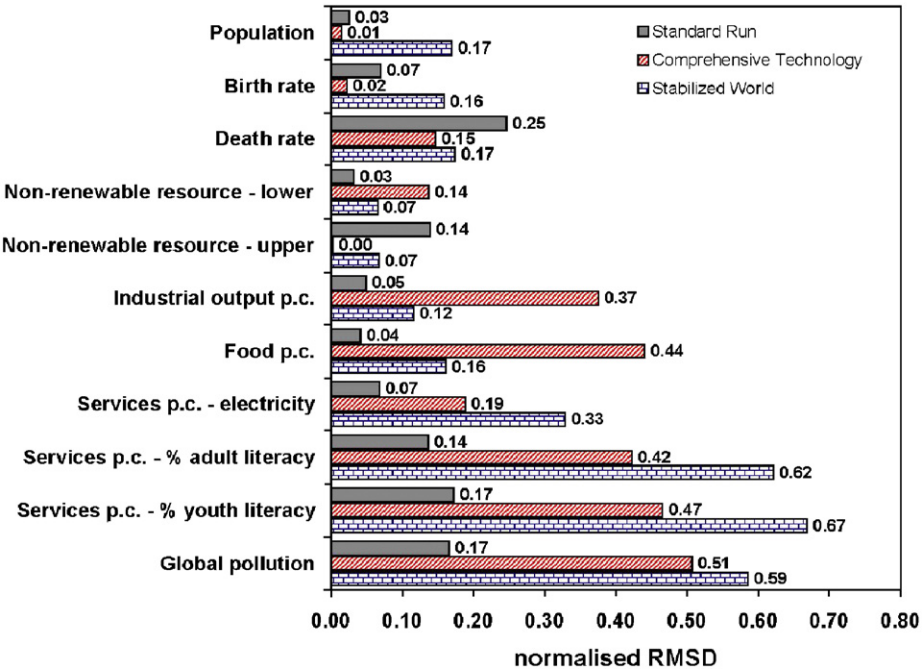

Fig. 11. Normalized root mean square deviation for each LtG output compared with the observed data, for each scenario. Closer agreement between data and model output is indicated by smaller RMSD.

the World3 model then scenario outputs from the model would be unlikely to match the long time-series data as well as they do. This follows from the multiple interactions in the model between the demographic, industrial, agricultural, services, resources and environmental components. These interactions are likely to cause any significant flaw in one part of the model to be propagated into other outputs, resulting in multiple discrepancies with the historical data. Consequently, the good comparison of scenario outputs with historical data provides a degree of validation of the World3 model, and emphasizes the likelihood of the global system reproducing the underlying dynamics of the "standard run" scenario. Full confirmation that these dynamics lead to "overshoot and collapse" requires either that this event occurs (which is clearly undesirable), or that details of thresholds and impact response functions in the LtG model are judged in advance to be sufficiently accurate. The parallels described above between pollution in the LtG "standard run" and dangerous climate change impacts from further greenhouse emissions, as well as the extensive agreement of observed data with the "standard run" scenario output, provide considerable but not complete confirmation of the "overshoot and collapse" dynamics.

The comparison presented here also emphasizes that the LtG did not predict collapse of the global system by 2000, contrary to pervasive but incorrect claims. In fact, all LtG scenarios show the global economic system growing at the year 2000.

Furthermore, the general trends and interactions involved in the "standard run" scenario resonate with contemporary environmental and economic pressures, notably "peak oil", climate change, and constrained food production. As further growth occurs in the "standard run" scenario under business-as-usual settings, the attempts of the World3 model to alleviate pressures in one sector of the global system by technological means generally results in increasing pressures in other sectors, often resulting in a vicious cycle or positive feedback. Stressful signs of this may be apparent now, as the following examples illustrate. Reduced crop production has been blamed on newly introduced bio-fuels displacing crops, extreme weather conditions possibly associated with early climate change impacts, and growing demand for meat-based diets (Ki-Moon, 2008). The overall system-wide effect of some bio-fuels in reducing greenhouse gases is also in contention, when factors such as fertilizer, new infrastructure, land-clearing (Searchinger et al., 2008; Fargione et al., 2008), and transport requirements are included. Bio-fuels may also increase pressures on water resources, deplete soil nutrients, and increase destruction of native forests (UN-Energy, 2007). Efforts to provide water security such as recycling water or desalination require greater energy use than more conventional means, further increasing the demand for resources and production of greenhouse gases.

Nor have efficiency gains generally resulted in overall decrease of pressures, but instead are likely to have contributed to increased pressure due to the rebound effect or Jevons paradox, as efficiency contributes to economic growth (see e.g., Jevons, 1865; Polimeni and Polimeni, 2006; Huesemann, 2003; Herring, 2006; Grossman and Helpman, 1991; Wackernagel and Rees, 1997; Homer-Dixon, 2006)). A most notable example is the overall reduction of carbon intensity of the economy almost continuously for well over a century, while the rate of carbon emissions has not decreased but instead grown exponentially (Grübler, 1998). This general feature of undue reliance on technological solutions was explored in more complex dynamic scenarios using the World3 model (Meadows et al., 1974).

The LtG scenarios also provide some indication of the change in consumption (as well as technological progress) that may be required to achieve a sustainable global system. The "stabilized world" scenario presents a sustainable *global average* per capita level of material wealth as approximately equal to contemporary levels (see Fig. 8). Currently most of this wealth is enjoyed by roughly one-quarter or less of the global population. Assuming that this total level of material wealth was distributed evenly across a large fraction of the future global population (say 9 billion people) compared with less than 1.5 billion people in developed countries requires an average per capita material wealth about 1/6th of current levels in developed countries. Note that the "stabilized world" scenario also incorporates higher *average* per capita services and food than the contemporary average, though

equitable global distribution would also involve some reduction in these levels for people in developed countries.

5. Conclusion

Appropriate and publicly available global data covering 1970–2000 have been collected on the five main sub-systems simulated by the Limits to Growth World3 model: population, food production, industrial production, pollution, and consumption of non-renewable resources. In the style of predictive validation, these data have been compared with three key scenarios from the original LtG publication (Meadows et al., 1972). This comparison provides a relatively rare opportunity to evaluate the output of a global model against observed and independent data. Given the high profile of the LtG and the implications of their findings, it is surprising that such a comparison has not been made previously. This may be due to the effectiveness of the many false criticisms attempting to discredit the LtG.

As shown, the observed historical data for 1970–2000 most closely match the simulated results of the LtG "standard run" scenario for almost all the outputs reported; this scenario results in global collapse before the middle of this century. The comparison is well within uncertainty bounds of nearly all the data in terms of both magnitude and the trends over time. Given the complexity of numerous feedbacks between sectors incorporated in the LtG World3 model, it is instructive that the historical data compare so favorably with the model output.

By comparison, the "comprehensive technology" scenario is overly optimistic in growth rates of factors such as food, industrial output and services per capita, and global persistent pollution. Similarly, significant departures in the trajectory of key factors such as population, food and services per capita, and global persistent pollution are evident between the data and the "stabilized world" scenario.

Global pollution has an important role in the LtG modeling, the scenario outcomes, and in this data comparison. Fortunately, uncertainty about the relationship between the level of pollution and ultimate impacts on ecological systems and human health is diminishing, particularly regarding greenhouse gases and climate change impacts.

In addition to the data-based corroboration presented here, contemporary issues such as peak oil, climate change, and food and water security resonate strongly with the feedback dynamics of "overshoot and collapse" displayed in the LtG "standard run" scenario (and similar scenarios). Unless the LtG is invalidated by other scientific research, the data comparison presented here lends support to the conclusion from the LtG that the global system is on an unsustainable trajectory unless there is substantial and rapid reduction in consumptive behaviour, in combination with technological progress.

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