Update to Limits to Growth: Comparing the World3 Model With Empirical Data

The Harvard community has made this article openly available. Please share how this access benefits you. Your story matters

Citation	Branderhorst, Gaya. 2020. Update to Limits to Growth: Comparing the World3 Model With Empirical Data. Master's thesis, Harvard Extension School.
Citable link	https://nrs.harvard.edu/URN-3:HUL.INSTREPOS:37364868
Terms of Use	This article was downloaded from Harvard University's DASH repository, and is made available under the terms and conditions applicable to Other Posted Material, as set forth at http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA

Update to Limits to Growth: Comparing the World3 Model with Empirical Data

Gaya Branderhorst

A Thesis in the Field of Sustainability

for the Degree of Master of Liberal Arts in Extension Studies

Harvard University

March 2020

Abstract

For more than three decades, the authors of the bestseller *Limits to Growth* (LtG) warned that a pursuit of continuous growth would result in a sharp decline (i.e., collapse) of global human welfare levels within the 21st century. The authors published three LtG books between 1972 and 2004, in each of which they studied interactions between global variables of a model called World3. With World3, which was updated for each book, the authors generated different scenarios for global developments by varying assumptions about technological development, amounts of natural resources, and societal priorities. Their "business as usual" (BAU) scenario contained no assumptions on top of historical averages. BAU showed a halt in the increase of global welfare levels around 2020, and a collapse starting around 2030. Not all scenarios led to collapse; the LtG team identified a set of assumptions that produced a "stabilized world" (SW) scenario in which decline was avoided and welfare remained high. But independent empirical data comparisons since then, most recently from 2014, indicated that the world was still following BAU.

The objective of my research was to examine whether this still was the case based on data available in 2019, and whether there was opportunity left for society to align with the SW scenario. My research objectives were to i) conduct a data comparison between the current global state and scenarios made with the latest version of World3, and ii) determine how close each scenario compared with observed data. I hypothesized that BAU would align more with the data than other scenarios, and do so closely for most or all variables. I collected data for real-world indicators of the World3 variables population,

fertility, mortality, pollution, industrial output, food, services, non-renewable natural resources, human welfare, and ecological footprint. This data came from academia, (non-)government agencies, United Nations entities, and the World Bank. I used four LtG scenarios with underlying assumptions that span a range of technological, social, and resource conditions: BAU, SW, "comprehensive technology" (CT), and "business as usual 2" (BAU2). CT represents the technologist's belief in humanity's ability to innovate out of environmental constraints. BAU2 assumes double the resources as in BAU and depicts a pollution collapse, including from CO_2 (i.e., climate change). Both scenarios indicate a halt in growth within the next few decades, but BAU2 shows a sharp decline while CT shows a moderate one. To measure alignment of empirical data with scenarios I used: value difference, rate of change difference, and normalized root mean square error.

My research revealed an overall close alignment of empirical data with each of the four scenarios, which is a testament to the accuracy of World3. SW was followed least closely, then BAU, and both BAU2 and CT aligned closest. My hypothesis was rejected, but this could change with an update of the comparison because for several variables the scenarios only diverge significantly after 2020. This is especially so for BAU2 and CT, which is why it was not possible to differentiate between them. It's thus unclear whether a future decline can be expected to be moderate or sharp, but both scenarios indicate society will run into limits in the medium term. The close alignment of scenarios and their lack of divergence means that the identification of BAU2 and CT as closest fits could be nullified or even reversed with a few years' extra data points. It also means that it is not too late to change course. Although SW tracks least closely, a deliberate trajectory change is still possible. That window of opportunity is closing fast.

Dedication

To Donella Meadows, whose wonderfully written insights sparked my research and to my mother, who sparked everything.

Acknowledgements

I'm grateful to Graham Turner for his support, insights, and engagement throughout this process. I could not have wished for a better Thesis Director. It was a pleasure and honor to work with him.

I'd like to thank Esther G. Naikal and Giovanni Ruta from the World Bank for providing me with the underlying data on natural capital calculations, John Sterman for meeting with me on a short notice at MIT during his sabbatical, and of course Mark Leighton for his guidance from start to finish.

Table of Contents

List of Tables

List of Figures

Definitions of Terms

BAU scenario	Business as usual scenario
BAU2 scenario	Business as usual 2 scenario
BP	British Petroleum
CT scenario	Comprehensive technology scenario
EF	Ecological footprint
EI	Education index
FAO	Food and Agriculture Organization
GDP	Gross domestic product
GFCF	Gross fixed capital formation
GFN	Global Footprint Network
GP	Geochemical Perspective
HDI	Human Development Index
IIP	Index of industrial production
IMF	International Monetary Fund
LtG	Limits to Growth
MIT	Massachusetts Institute of Technology
NOAA	National Oceanic & Atmospheric Administration
NRMSD	Normalized root mean square deviation
OECD	Organisation for Economic Co-operation and Development
p.c.	per capita

RMSD	Root mean square deviation
ROC	Rate of change
SW scenario	Stabilized world scenario
USGS	US Geological Survey
UN DESA	UN Department of Economic & Social Affairs
UN DESA PD	UN DESA Population Division
UN DESA SD	UN DESA Statistical Division
UN DP	UN Development Programme
UN EP	UN Environment Programme
UNIDO	UN Industrial Development Organization
WB	World Bank
WHO	World Health Organization

Chapter I

Introduction

In this thesis I describe my research on the principle and model of the Club of Rome's *The Limits to Growth* (LtG). I conducted a comparison between empirical world data and scenarios described in the LtG books, analyzed deviations and corroborations, and drew conclusions on what these might imply for future global developments. Part of this work I plan to submit to a journal, and to that end one chapter in this document was written as a full article that can be read on its own.

This thesis' structure is as follows. The rest of this chapter, Chapter I, provides a background on LtG, updates to LtG from other researchers, and my research objectives, question, and hypothesis. Chapter II consists of my article, which means it follows its own organizational structure conforming with the journal submission guidelines. Chapter III, the last chapter, contains further discussion of my research results, followed by the final conclusions.

Background

The essence of the LtG message is that a continued pursuit of growth on a finite planet will inevitably lead to an "overshoot and collapse" pattern (Meadows, Meadows, & Randers, 2004). The term overshoot and collapse originates from ecology and describes a three-phase pattern. In the first phase a population is growing until it reaches the number that can be sustained by its environment, i.e., its "carrying capacity" (e.g.,

Schmitz, 2007). The population can grow beyond its carrying capacity, but it can only remain there temporarily. Because there aren't enough resources to sustain that population size, population growth slows down and subsequently ends altogether as the mortality rate rises. This is the second phase, at which the population is said to be in overshoot. In the third phase, the mortality rate has surpassed the birth rate and the population starts to decline, at a higher speed than it was growing in the first phase. This third phase is called a collapse because of the steepness that typically marks the decline.

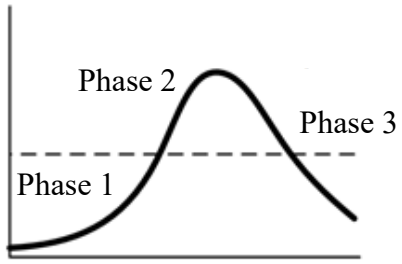

Figure 1. Stylized version of an overshoot and collapse pattern (Thwink.org, n.d.).

The principle that an expansive growth will be brought to a halt by some limiting factor, followed by a collapse or not, can be generalized beyond population to any real-world growth process (Chichakly, 2009). Any adult is, most often tacitly, familiar with limits to growth. For example, we have learned that coffee works at first to increase our focus, but that in the long run it stops working and can become a limiting factor if it keeps us from getting the sleep we need (Meadows, 2012). In system thinking, this dynamic of changing and often delayed diminishing forces that counteract an expansive force is known as the Limits to Growth principle (Senge, 1994). Another example of this dynamic is that of continuous use of natural resources in pursuit of economic growth. If

these natural resources are finite and non-renewable, continuous use will render them scarce over time, however abundant they might have been historically. At some point the resources will become so scarce that they stop to function as the contributing factor to economic growth that they had been, and instead become a limiting factor in standards of living (or: welfare levels, the two terms are used interchangeably throughout this document). Figure 2 shows the systems depiction of the Limits to Growth principle as it pertains to this last example.

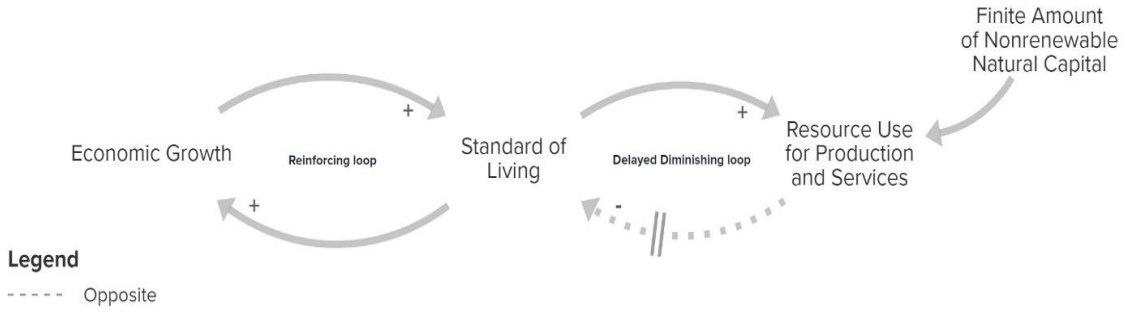

Figure 2. Systems depiction of the Limits to Growth principle (by author).

Sustained economic growth has been a recent achievement from a historical perspective (Maddison, 2006; Piketty, 2014), although one would not be able to tell from the dominance of the growth imperative in modern day debates, amongst economists, business leaders, and politicians alike. There are those that have felt it necessary to warn about the dangers in society's striving for continuous growth, amongst them a team of scientists from the Massachusetts Institute of Technology (MIT). Over the past four decades, these MIT scientists published three LtG books: in 1972 (Meadows, Meadows, Randers, & Behrens), 1992 (Meadows, Meadows, & Randers), and 2004 (Meadows et

al.). Each book described the LtG message illustrated with scenario runs of the system dynamics model World3, which was updated for each book. World3 is based on the work of former MIT professor Forrester (1971; 1975), generally considered the founder of system dynamics modelling. The basis of system dynamics modelling is the recognition that to understand a system's behavior one cannot just study the behavior of its individual parts in isolation; the structure of the system, the total of relationships between its parts, is often just as important.

The World3 Model

The World3 model consists of many interacting stocks, flows, and rates. Examples are industrial capital (a stock), industrial output (a flow), and industrial capital depreciation (a rate). Other examples are the total surface of arable land (stock), deaths per year (flow), and the service capital investment rate. The key characteristics of World3, as in any dynamic systems model, are the causal links between the variables. These enable one to analyze global society as a system, i.e., as a world where the influence of policies and major environmental, financial, social, technological, and other trends are not always linearly proportional in impact, nor always felt and responded to immediately, and do not neatly stay within industry, sector, or country boundaries.

The global societal system is analyzed by using the World3 model to run scenarios. By varying World3's parameters, for example a pollution impact factor or available resources at the start of the run, one can begin to understand how variables could interact over time to form the general behavior of the global system. The general behavior that World3 runs revealed was a halt in industrial capital growth at some point

in the 21st century, followed by a sharp decline (i.e., collapse). The most discussed scenario was the "business as usual" (BAU) scenario, which ran on historic averages without any additional assumption. This BAU scenario ended in collapse. There were scenarios in which collapse was avoided, but assumptions in those runs were markedly different from prevailing real-world priorities at the time.

There are five subsystems in World3: population, industrial output, agricultural production, non-renewable natural resources, and pollution. Figure 3 shows a stylized rendering, i.e., a causal loop diagram, of some of the interactions in World3.

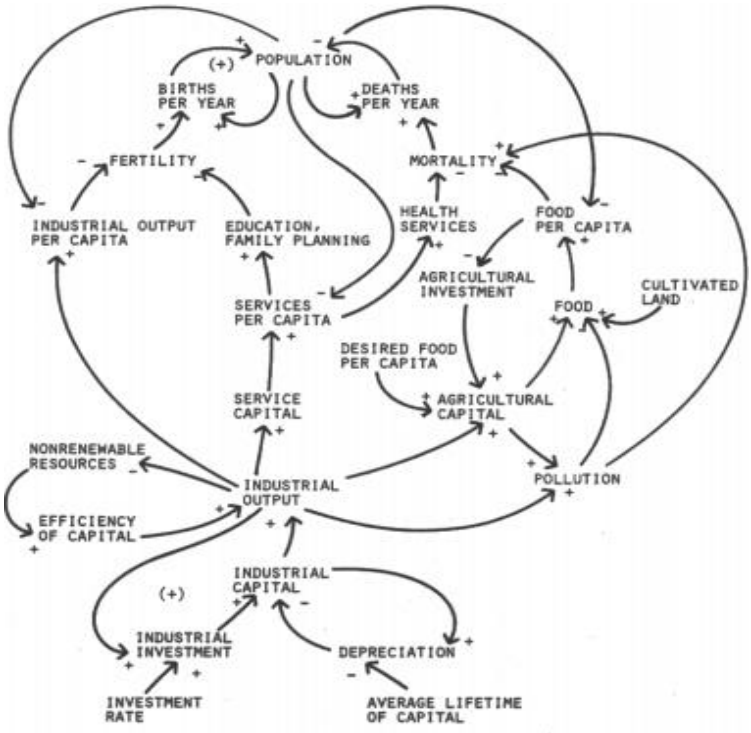

Figure 3. Causal loop diagram of World3 (Sverdrup, Koca, & Ragnarsdóttir, 2015).

Note that Figure 3 does not depict the actual dynamic systems model, which is more complex and contains many more variables. See Appendix 1 for an overview of all the variables and their interactions as modelled in World3 from the original book. A more

detailed and technical analysis of how the model behaves was published shortly after the first LtG book (Meadows, 1974).

World3 Variables

Many descriptions of World3 still mention the subsystems— population, industrial output, agricultural production, resources, and pollution—as the five LtG variables. However, the graphs of the 1972 LtG book depicted eight variables in one graph: population, fertility, mortality, industrial output per capita (p.c.), food p.c., services p.c., fraction of non-renewable resources remaining, and persistent pollution (e.g., Figure 7 in Chapter II).

In their 2004 update, the LtG team showed three graphs instead of one and changed some of the variables depicted. The five macro variables are in the first "State of the World" graph: population, industrial output, agricultural production, non-renewable resources, and pollution (Figure 4).

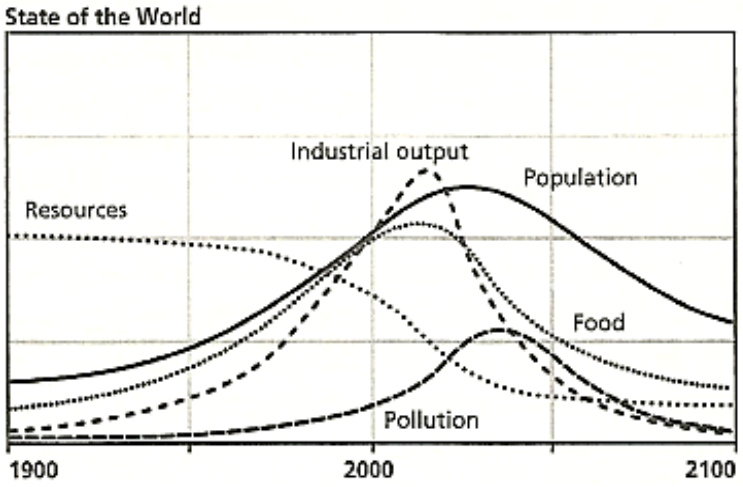

Figure 4. First graph of scenario 1 or BAU scenario, State of the World (Meadows et al., 2004).

The second graph in the update, “Material Standards of Living” (Figure 5), showed four more variables: life expectancy (replacing fertility and mortality rates), food p.c., services p.c., and consumer goods p.c.. This last variable is calculated as a constant consumption fraction times industrial output p.c. (i.e., industrial output divided by the population).

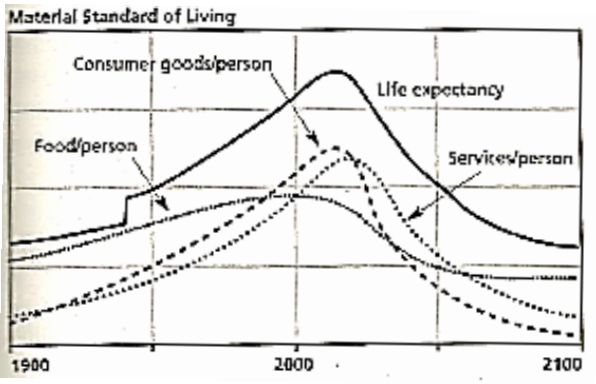

Figure 5. Second graph of scenario 1 or BAU scenario, Material Standard of Living (Meadows et al., 2004).

The third “Human Welfare and Footprint” graph showed two new variables: human welfare levels and ecological footprint (Figure 6).

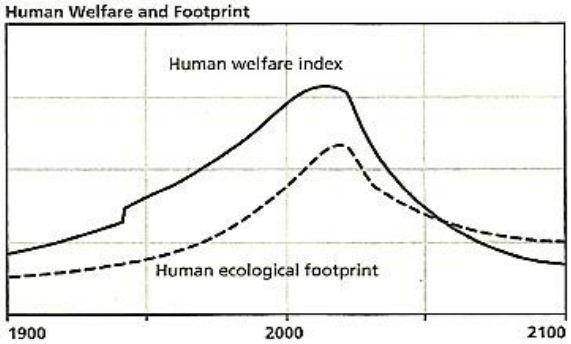

Figure 6. Third graph scenario 1 or BAU scenario, Human Welfare and Footprint (Meadows et al., 2004).

Thus, in the last LtG book there are eleven variables to compare with real-world data. It should be noted however, that only two of the added variables were not directly derived from or linked to other 1972 variables: human welfare levels and ecological footprint (EF), the variables of the third graph (Figure 6). As mentioned, life expectancy replaced fertility and mortality rates to convey the same concept of longevity. And the two variables, global agricultural production and industrial output, do not add a whole new dimension to a set of variables already containing food p.c., industrial output p.c., and population. Table 1 contains an overview of depicted variables in both books.

Table 1. Variables depicted in scenario runs of first and last LtG books.

	First book (1972)	**Last book (2004)**
Depicted variables	population non-renewable resources pollution industrial output per capita food per capita services per capita fertility mortality	population non-renewable resources pollution industrial output per capita food per capita services per capita life expectancy industrial output agricultural production human welfare levels (*new*) ecological footprint (*new*)

Technical Modelling Criticisms of World3

There were many critics of the LtG. I discuss the criticisms on the LtG message and the economic and technological assumptions underlying the World3 model in the article in Chapter II (see also Bardi (2011) for another account of criticism and counterarguments). Here I discuss the technical criticism of World3. Some critics focused on the working of World3 specifically, others critiqued the new modeling technique (system dynamics) itself as non-rigorous or even non-scientific.

The World3 model can be sensitive; relatively small parameter changes will in some cases significantly alter a scenario's trajectory (Castro, 2012; de Jongh, 1978; Vermeulen & de Jongh, 1976). This is a valid critique, however it seems insufficient to refute the general validity of World3's outcomes. Sensitivity is problematic in predictive models because it reduces the confidence one can have in a prediction. The LtG authors did not intend World3 to be a predictive model, but a tool to understand world dynamics. The accuracy of general dynamics that occur once global limits are approached and breached, is not necessarily nullified by the fact that the timing of such events cannot be robustly predicted within a few years' precision (Lyneis, 2000; Sterman, 1994). Indeed, recreation of runs with the same parameter changes as in these critical studies confirmed that World3 can be sensitive to parameter changes, but also showed that these changes did not avoid an overshoot and collapse pattern (Turner, 2013).

Other technical modelling criticism, from acclaimed academics in their field, seemed to be based on a lack of understanding of the essence of system dynamics modelling. A 1973 critique contained a technical review of World3 and the conclusion that it was inadequate from the perspective of linear modeling (Cole, Freeman, Jahoda, &

Pavitt, 1973), which is not the right criterion for a system dynamics model (Sterman, 2000). Yale economist Nordhaus (1973; 1992), who was awarded a Nobel Prize in Economics in 2018, focused on isolated equations of World3 in a response to the first and second LtG books, thereby neglecting feedbacks between system variables in his analysis (Forrester, Low, & Mass, 1974; Turner, 2012). Nordhaus (1973) also stated that "not a single relationship or variable is drawn from actual data or empirical studies" (p. 1157). This is incorrect; although historical data is not fitted to a model using econometrics, it is used for setting numerical values for the assumptions underlying World3 (Forrester et al., 1974).

No Critical Data Comparisons

None of the LtG critics mentioned above or in Chapter II have gone on to publish a study in which World3 scenarios are compared against recent data, even though that seems an obvious and convincing way to make claims about the model's inadequacy. The only empirical test along that line of thinking was a famous bet between ecologist Ehrlich and economist Simon about the price of a basket of five commodities (Sabin, 2013; Worstall, 2013). Ehrlich bet that the price would rise between 1980 and 1990 as a result from increased scarcity; he lost. Many have pointed out that Ehrlich would have won the bet had it been for a different ten-year period (Sabin, 2013; Worstall, 2013). More importantly, none of the LtG team members made this bet and the World3 model does not run scenarios for specific commodities. In fact, some scenarios assumed perfect substitutability of resources and even an endless supply of non-renewable natural resources (this does not avoid collapse, but merely changes its cause from resource

depletion to a pollution crisis). Still, Erlich losing the bet was interpreted by many as proof that LtG has been wrong.

Qualitative and Partial Empirical Updates of LtG

There have been some qualitative updates on LtG. A report to a United Kingdom Interparliamentary group concluded that there was "unsettling evidence that society is still following" the BAU run of the first LtG book (Jackson & Weber, 2016, p.3). A report to the Club of Rome by Bardi (2014) that focused on non-renewable natural resources concluded the same. Bardi, based on his own research and contributions from senior scientists across relevant disciplines, concluded that industrial civilization is likely to deplete its low-cost (i.e., high quality and in sizeable and concentrated quantity available) mineral, metal, and fossil resources with debilitating impacts for the global economy and key infrastructures within the coming decade. This message was repeated in a *Geochemical Perspective* article that same year (Sverdrup & Ragnarsdóttir, 2014). Less likely ally Simmons (2000), an investment banker, former energy adviser to United States (US) President Bush, and member of the National Petroleum Council, stated: "The most amazing aspect of the book is how accurate many of the basic trend extrapolation[s] […] still are, some 30 years later" (p. 15).

There have been many studies on variations on the World3 model (e.g., Saeed, 2014), and/or partial validation such as those into peak oil (e.g., Hall & Day, 2009) and peak supply of other non-renewable resources like minerals and metals (e.g., Sverdrup & Ragnarsdóttir, 2014). Although they cannot serve as a validation of the complete World3 model, the conclusions of these studies align with the LtG message.

Turner's Quantitative Empirical Updates of LtG

The only quantitative comparisons of real-world data with the original output of World3 have been published by Turner (2008, 2012, 2014). Turner compared empirical data with three of the twelve scenarios from the first LtG book:

1. BAU, the "no assumptions" scenario based on historical values from between 1900-1970 (Meadows et al., 1972, p. 129).
2. "Comprehensive technology" (CT), which assumes a broad range of technological solutions (Meadows et al., 1972, p. 147).
3. "Stabilized world" (SW), the scenario that assumes both technological solutions and social changes (Meadows et al., 1972, p. 147).

Turner chose these scenarios because they "effectively span the extremes of technological and social responses as investigated in the LtG" (Turner, 2008, p. 400). These 1972 LtG scenarios are described in more detail in Chapter II.

Based on quantitative comparisons for all variables, Turner concluded that overall, world data compared favorably to key features of the BAU, and much more so than for the other two scenarios.

Research Objectives, Question, and Hypothesis

Given the outcomes so far of LtG updates, most notably those from Turner, I thought it useful to perform a quantitative update of the LtG comparison. My research objectives were to:

- conduct an empirical update with the latest data available in 2019, i.e., a data comparison between the current global state and World3 scenarios, including the BAU one.
- determine how close each World3 scenario compares with empirical data, and draw conclusions about what these results means for potential future developments of global trends.

I used the variables and scenarios of the 2004 book. One exception on the variables was for life expectancy; I used fertility and mortality rates because the World3 version that I used for running the LtG scenarios did not provide life expectancy as an output. I focused on four scenarios: the 2004 versions of the scenarios that Turner used in his work, plus "business as usual 2" (BAU2), where the effect of increased non-renewable resources is explored. BAU2 and the other three scenarios are described in Chapter II and in Appendix 2.

Given that Turner found a close track to BAU (of 1972) and that society hadn't made revolutionary global changes in policies and priorities since 2014, I expected to find that observed data would indicate global society following the 2004 BAU scenario most closely. This then translated into the following research question and hypothesis:

- Research question: To what extent do real-world indicators of population, fertility, mortality, pollution, industrial output p.c., food p.c., services p.c., non-renewable natural resources, global human welfare, and ecological footprint over the past four decades track their respective variables in the BAU, BAU2, SW, and CT scenarios of the latest World3 version?

- Hypothesis: Of the four scenarios, the BAU scenario approximates the most recent empirical data the best, and does so relatively closely for most or all variables.

Chapter II

Update to Limits to Growth: Comparing the Word3 Model with Empirical Data

This chapter is written as an article that can stand on its own. Its organizational structure follows the guidelines of the journal targeted for submission, which is as follows: Introduction, Background, Results, Discussion, Conclusions, and a separate Methods section. Because the article is co-authored with Turner, it's written in first person plural, instead of first person singular like the rest of the thesis.

Abstract

We conducted a data comparison between scenarios from the 2004 Limits to Growth (LtG) book and empirical data. The scenarios ran on the latest version of the system dynamics model World3-03, which had not before been evaluated in this way. Our research benefitted from improved data availability, and included a scenario and two variables that had not been part of previous quantitative LtG analysis. Sourcing data from various organizations, including the World Bank and the United Nations, we plotted observed data along with four LtG scenarios spanning a range of assumptions on technological developments, the amount of natural resources, and societal priorities. From these graphs and two quantitative accuracy measures we constructed, we found that the four World3-03 scenarios align closely with observed global data. The two scenarios that showed the closest alignment indicate a decline in food productivity, industrial capital, and human welfare levels within three decades. Our results are inconclusive as to

whether this decline would necessarily constitute a collapse, because such a pattern is present in only one of the two scenarios. Because the scenarios diverge significantly after 2020, an update of this comparison in another few years might be able to identify one specific closest fit to empirical data. Without major changes in societal priorities, this is unlikely to be the scenario showing a sustainable path; the one scenario in which any decline in human welfare within this century is avoided, aligned with the data the least.

Introduction

In the bestseller *Limits to Growth* (LtG) (Meadows et al., 1972), the authors concluded that if humanity kept pursuing economic growth without regard for environmental and social costs, global society would experience a sharp decline (i.e., collapse) in economic, social, and environmental conditions within this century. They used a model called World3 to study key interactions between variables for global population, birth rate, mortality, industrial output, food production, health and education services, non-renewable natural resources, and pollution. The LtG team generated different World3 scenarios by varying assumptions about technological development, amounts of non-renewable resources, and societal priorities. The few comparisons of empirical data with the scenarios since then, most recently from 2014, indicated that the world was still following the "business as usual" (BAU) scenario. BAU showed a halt in the hitherto continuous increase in welfare indicators around present day, and a sharp decline starting around 2030.

Given the unappealing prospect of collapse, we considered whether humanity was still following BAU or had changed course and aligned more with another LtG scenario,

perhaps one in which collapse was avoided. This article describes our research to answer that question. We quantitatively compared World3 scenarios with empirical data. Our research thus constitutes a 2019 update to previous comparisons, but it also adds to them in several ways. Earlier data comparisons used scenarios from the 1972 LtG book. We used the latest, revised and recalibrated, World3 version. Our comparison also included a scenario and two variables that had not before been part of such research, and benefitted from better empirical proxies thanks to improved data availability.

Background

The LtG message was that continuous growth cannot be sustained indefinitely (Meadows et al, 1972). Effectively, humanity can either choose its own limit or at some point reach an imposed limit, at which time a decline in human welfare will have become unavoidable. An often missed, but key point in the LtG message is the plural of "limits" (Meadows et al., 2004; Meadows & Meadows, 2007). In an interconnected system like our global society, a solution to one limit inevitably causes interactions with other parts of the system, giving rise to a new limit which now becomes the binding constraint to growth (Meadows & Meadows, 2007). To illustrate this point, the LtG authors had created various scenarios with World3. World3 was based on the work of Forrester (1971; 1975), the founder of system dynamics: a modeling approach for interactions between objects in a system, often characterized by non-linear behavior like delays, feedback loops, and exponential growth or decline. The LtG scenarios were thus not meant to produce point predictions, but rather to help us understand the behavior of systems in the world over time.

LtG Publications

The first book (Meadows et al., 1972) was commissioned by the Club of Rome and introduced World3 together with twelve scenarios. The most widely discussed scenario has been the BAU. It maintained parameters at historic levels from the latter part of the 20th century, without imposing any additional assumptions. In BAU, standards of living would at some point stop rising along with industrial growth once the accompanying depletion of non-renewable resources had started to render these a limiting factor in industrial and agricultural production. Continuation of standard economic operation without adapting to the constraint of growing resource scarcity would then require increasingly more industrial capital to be diverted towards extracting non-renewable resources. This would leave less for food production, citizen services and industrial re-investment, causing declines in these factors and, subsequently, in population (Meadows et al., 1972).

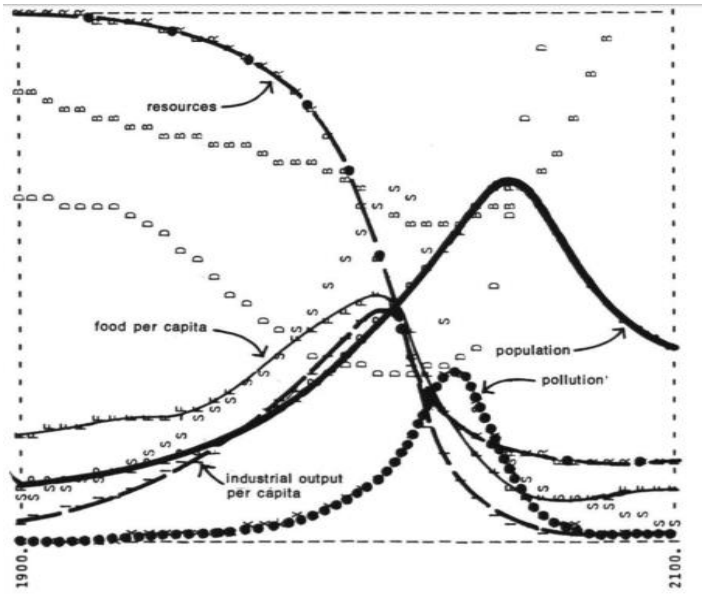

Figure 7. The BAU scenario from the first LtG book (Meadows et al., 1972).

There were eleven other scenarios in the first book, including "comprehensive technology" (CT) and "stabilized world" (SW). CT assumes a range of technological solutions, including reductions in pollution generation, increases in agricultural land yields, and resource efficiency improvements that are significantly above historic averages (Meadows et al., 1972, p. 147). The SW scenario assumes that in addition to the technological solutions, global societal priorities changed from a certain year onwards (Meadows et al, 1972). A change in values and policies translate into, amongst other things, low desired family size, perfect birth control availability, and a deliberate choice to limit industrial output and prioritize health and education services. SW was the only scenario in which declines were avoided.

The second book, *Beyond the Limits*, was published in 1992 (Meadows et al.). The LtG team had recalibrated World3 to two decades of additional data. The authors concluded that while humankind had had the opportunity to act during the twenty years after the first LtG book, humanity had now reached overshoot (i.e., transgression above earth's carrying capacity).

The third and last book, *Limits to Growth: The 30-Year Update*, dates from 2004 (Meadows et al.). It described ten new scenarios which were similar to those from the first two books in assumptions, but made with a revised World3 model: World3-03. The model revisions included incorporation of two new variables: the human ecological footprint and human welfare. The assumptions regarding technological progress were also intensified, going above historic rates even further, making the CT scenario more optimistic compared to its 1972 version.

Criticism

The LtG books and World3 received much criticism (e.g., Norgard, Peet, & Ragnarsdóttir, 2010), most of which was unsubstantiated (Bardi, 2011). Some critics misinterpreted the scenarios and key message of the books, others critiqued World3's modeling assumptions.

Despite obviously being false, some misconceptions have proven persistent and influential in the public debate. An example is the claim that the first book predicted resource depletion by 1990 (Passell, Robert, & Ross, 1972). This misconception promulgated to the point of being repeated even by organizations like the United Nations Environment Programme (UN EP, 2002). It was actively revived by analysts (Bailey, 1989; Lomborg & Olivier, 2009; "Plenty of Gloom", 1997), who subsequently dismissed LtG because depletion and collapse had not taken place. However, what the authors had claimed was that without major change in the global system, growth will halt before 2100. It is clear from the scenario graphs that reversal points lie beyond 2000.

Modelling criticism focused mostly on the assumptions concerning technological progress and market correction. Some argued that World3 did not give enough credence to humanity's ability to invent technological solutions to environmental challenges (Cole et al., 1973; Kaysen, 1972). These critics ignored that the LtG book contained several scenarios with very optimistic assumptions about technological innovation and adoption, given historic averages. Even the very optimistic assumptions on humankind's ingenuity and willingness to share solutions (also with those that cannot pay for it) did not prevent declines in a scenario, unless it was paired with societal value and policy changes. Others regarded the absence of a corrective price mechanism as a fatal flaw, contending that

increased prices would spur substitutions between resources and other technological solutions (Kaysen, 1972; Solow, 1973). For example, Nobel prize winning economist Solow (1973) argued that price pressures would increase public demand in the future for higher taxes on scarce resources. This has not occurred. Research by the International Monetary Fund (IMF, 2014) and the Organisation for Economic Co-operation and Development (2017; 2018), amongst others, suggests that the social costs of pollution and non-renewable resource depletion are currently nowhere fully reflected in taxes. Fossil fuels alone still carry large government subsidies (Coady, Parry, Sears, & Shang, 2017), totaling 6.5% of global gross domestic product (GDP).

Updates to LtG

Several qualitative reviews of the LtG publications have described how dynamics in World3 could be observed in the real world (Bardi, 2014; Jackson & Weber, 2016; Simmons, 2000). One such review was from LtG author Randers (2000). Randers did admit that non-renewable resources, particularly fossil fuels, had turned out to be more plentiful than assumed in the 1972 BAU scenario. He therefore postulated that not resource scarcity but pollution, especially from greenhouse gases, would cause the halt in growth. This aligns with the second scenario in the LtG books. This scenario has the same assumptions as the BAU, except that it assumes double the non-renewable resources. We refer to this scenario as BAU2. More resources do not avoid collapse in World3; the cause changes from resource depletion to a pollution crisis.

BAU2 was quantitively assessed in a 2015 recalibration study of World3-03 (Pasqualino, Jones, Monasterolo, & Phillips). Results indicated that society had invested

more to abate pollution, increase food productivity, and invest in services compared to BAU2. However, the authors did not compare their calibration with SW, nor did they use their recalibrated version of World3 to run the scenario beyond the present to see if collapse was avoided.

Quantitative comparisons between LtG scenarios and empirical data were conducted by Turner (2008; 2012; 2014). He compared global observed data for the LtG variables with three of the twelve scenarios from the first book: BAU, CT, and SW. Turner concluded that world data compares favorably to key features of BAU, and much more so than for the other two scenarios.

We examined whether a comparison for data available in 2019 with the recalibrated World3-03 produced the same outcomes as Turner had found. Because he used the 1972 variables, Turner did not include the two that were added in 2004, human welfare and ecological footprint (EF). Another open question therefore was to what extent these variables aligned with their real-world counterparts. Lastly, given the attention that BAU2 had gotten and that its pollution crisis can be interpreted as depicting climate change (i.e., collapse from greenhouse gas pollution), this scenario ought to be included in a comparison.

Research

Our goal was to determine to what extent empirical data aligned with scenarios of World3-03 (henceforth called "World3"). We compiled data from various databases, including the United Nations and World Bank. These data were indicators for what the following ten variables represented: population, fertility (birth rate), mortality (death

rate), industrial output per capita (p.c.), food p.c., services p.c., non-renewable resources, persistent pollution, human welfare, and EF. We plotted this data along with four World3 scenarios: BAU, BAU2, CT, and SW. These were the 2004 LtG book equivalents of the three scenarios in Turner's earlier work, plus BAU2.

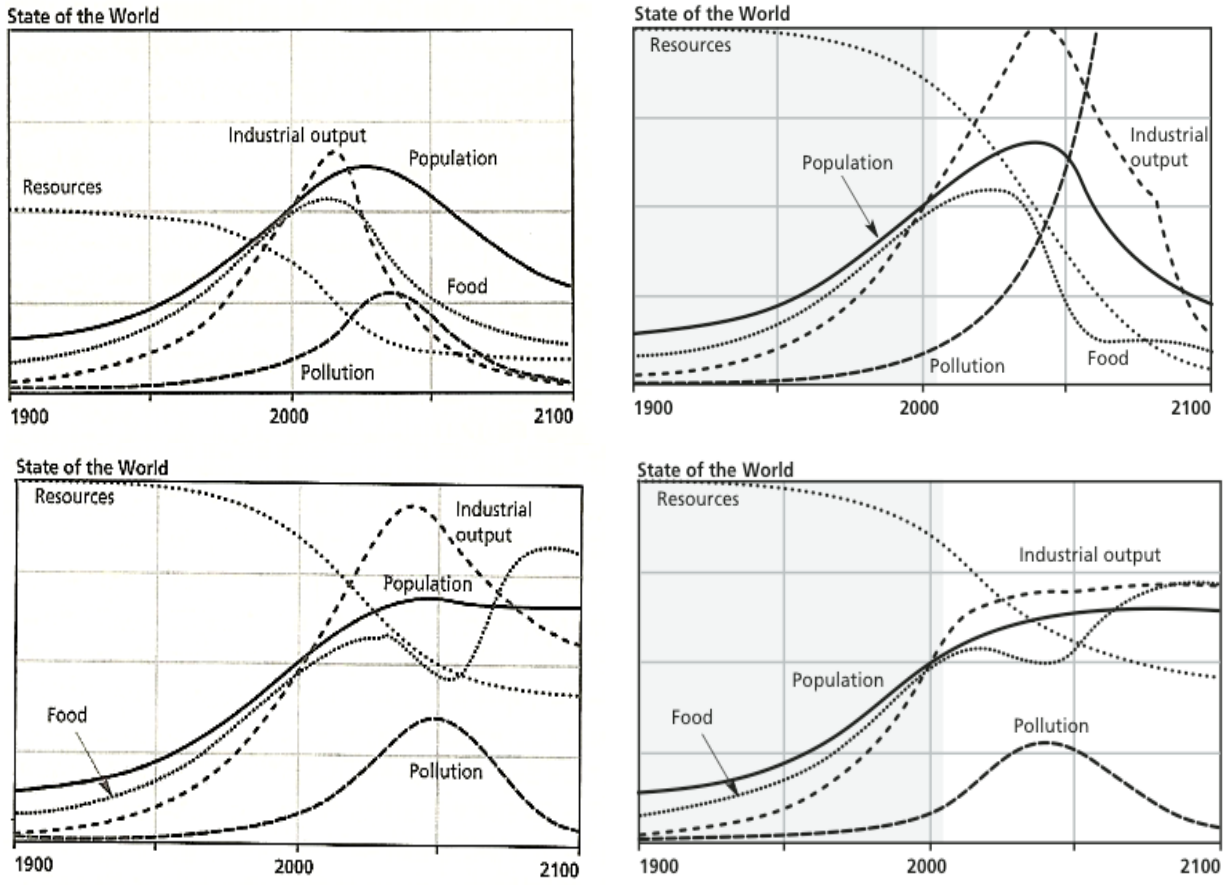

Figure 8. BAU (upper left), BAU2 (upper right), CT (lower left), and SW (lower right) scenarios (Meadows et al., 2004; n.d.).

The assumptions underlying each scenario differ in technological, social, or resource conditions. The cause of decline, varying from a temporary dip to societal collapse, also differs for each scenario (Table 2)

Table 2. Description and cause of halt in growth and/or decline per scenario.

Scenario	**Description**	**Cause**
BAU	No assumptions added to historic averages.	Collapse due to natural resource depletion.
BAU2	Double the natural resources of BAU.	Collapse due to pollution (climate change equivalent).
CT	BAU2 + exceptionally high technological development and adoption rates.	Rising costs for technology eventually cause declines, but no collapse.
SW	CT + changes in societal values and priorities.	Population stabilizes in the 21st century, as does human welfare on a high level.

To quantify how closely the LtG scenarios compare with observed data, we used the same measures as in Turner (2008):

1) the combination of

- the value difference (between the model output and empirical data), and
- the difference (between the model output and empirical data) in rate of change (ROC)

—both applied at the time point of most recent empirical data,

2) the normalized root mean square difference (NRMSD).

It was necessary to establish suitable uncertainty ranges for each of these measures, given World3's low precision and the error margins we can expect in the empirical data. We chose uncertainty ranges of 20%, 50% and 20% for the value difference, ROC and NRMSD, respectively. This recognizes that global data is unlikely

to have higher than 10% accuracy due to measurement difficulties, and many variables are combinations of factors. At the same time the uncertainty ranges are still narrow enough to be a meaningful indication of agreement between observed and simulated data. We do not suggest interpreting the 20% and 50% as strictly as say, one would use α as a cut-off point in statistical analysis. The accuracy measures complement a visual inspection of the graphs by quantifying the alignment error.

See Methods for data sources, formulas of the accuracy measures, and other specifics.

Results

Below we show graphs of the LtG scenarios and empirical data plotted for the ten variables, and discuss to what extent they aligned. An overview of the outcomes per variable for each of the two accuracy measures are provided subsequently.

The graphs are in 5-year intervals, which means that in some cases the most recent data point is not depicted. All the accuracy measures are calculated using the most recently available data. For example, for variables where the data series extended to 2017, the accuracy measures were calculated with the 2017 figures, but 2015 is the last empirical data point plotted in the graph.

Population

The SW scenario was the farthest off, BAU2 and CT were the closest. The BAU also still fell within the ranges we had set for the accuracy measures.

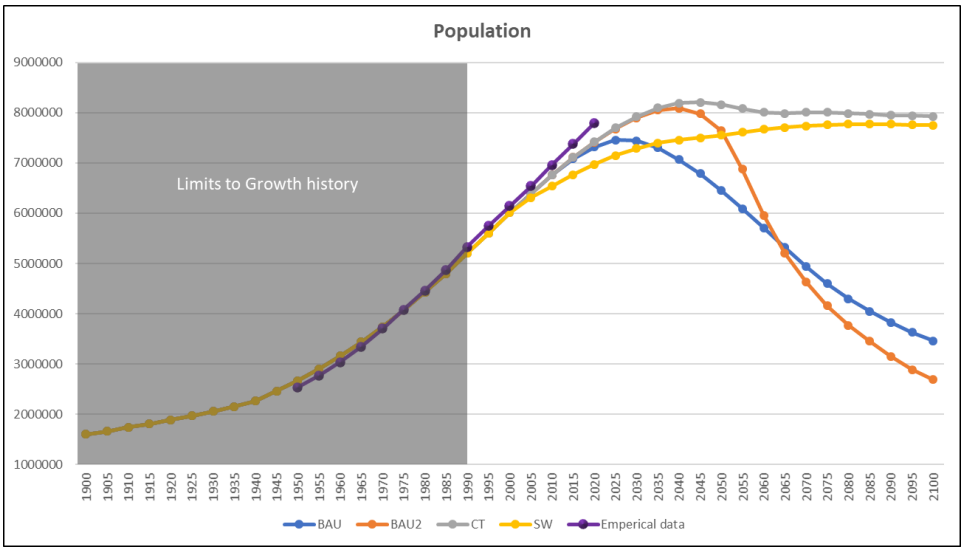

Figure 9. Scenarios and empirical data for population (in thousands of people).

Fertility

The birth rate was higher than in any scenario. The SW scenario fell outside of the uncertainty ranges for all measures. BAU was closer in value but fell outside the 50% range for the ROC. Both BAU2 and CT were in range for all accuracy measures.

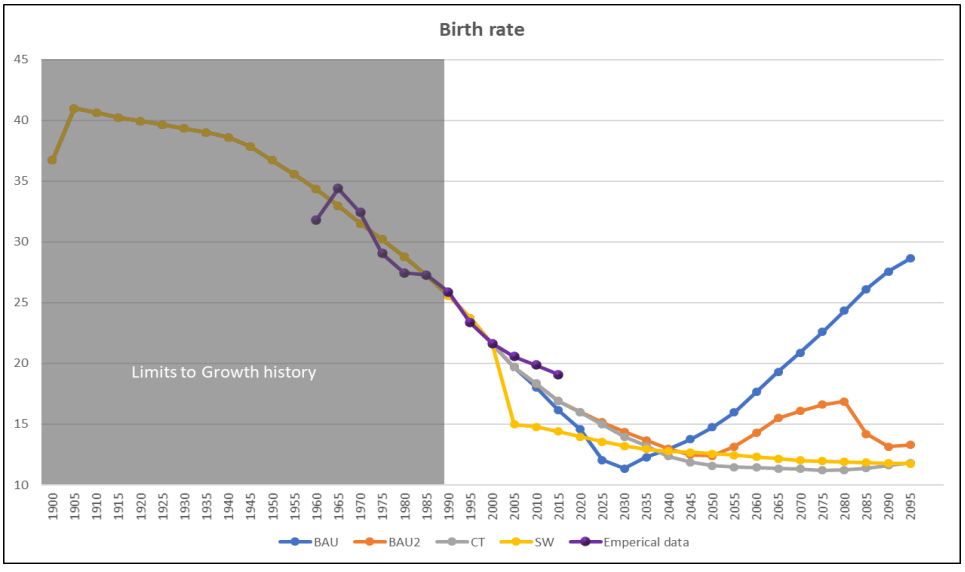

Figure 10. Scenarios and empirical data for fertility (births per thousand people).

Mortality

All scenarios aligned closely with the crude death rate in value and NRMSD. Each scenario was well out of the uncertainty range for the ROC, because contrary to the scenarios the empirical data shows no increase in mortality at this point.

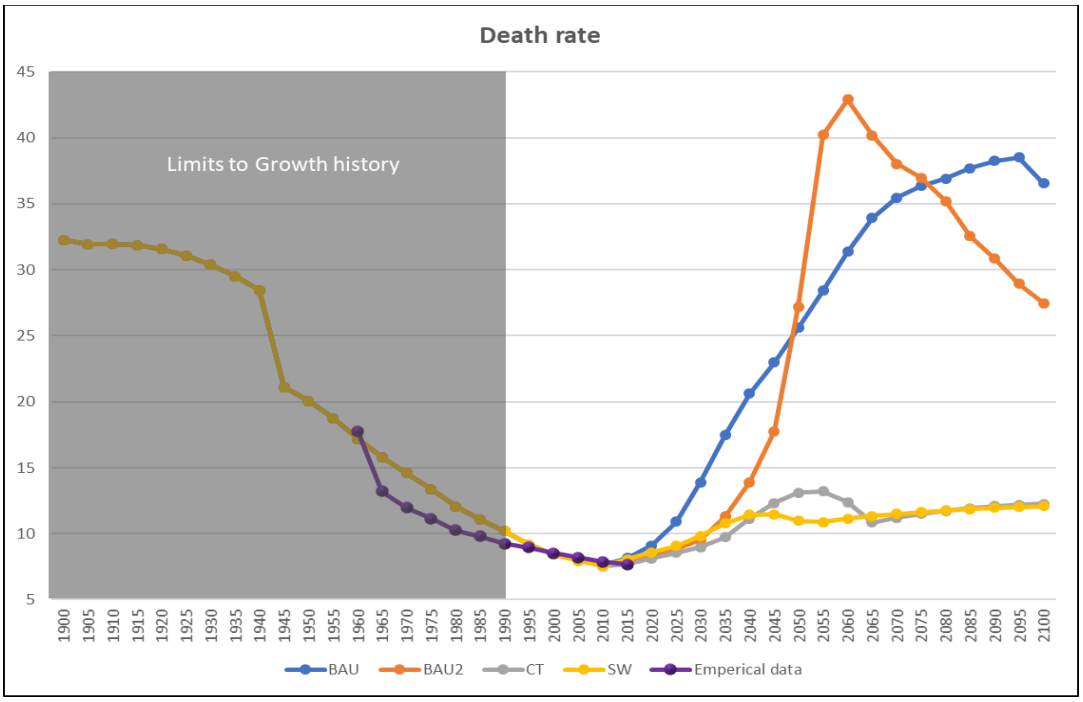

Figure 11. Scenarios and empirical data for mortality (deaths per thousand people).

Food Per Capita

Food p. c. was higher than in any scenario. All scenarios compared favorably in value and NRMSD, with SW being the closest. However, all scenarios were well outside of the 50% range when it came to ROC.

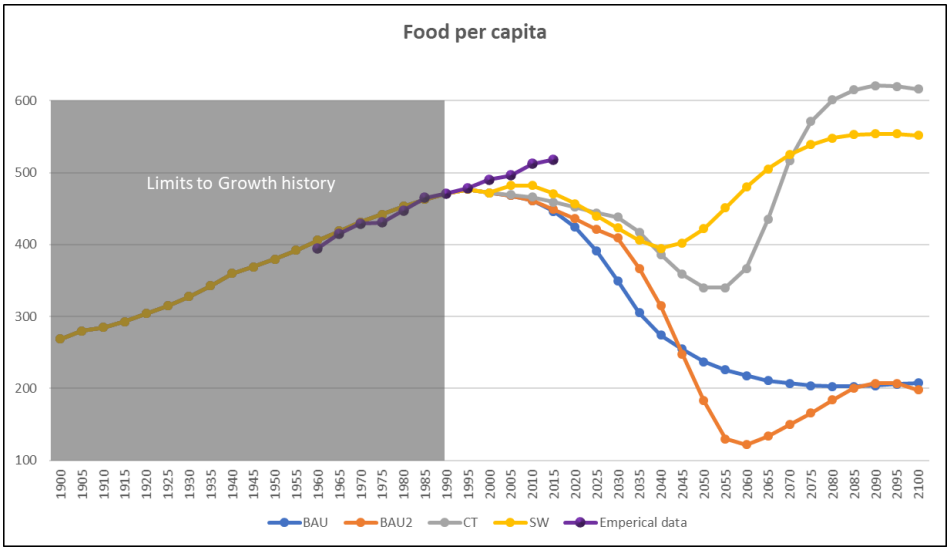

Figure 12. Scenarios and empirical data for food per person (in kilocalories per day).

Pollution

We used two proxies, CO_2 and plastics. Scenarios have not started to diverge yet, so all show the same comparison. Both accuracy measures were outside the uncertainty ranges for the CO_2 series. For the plastics proxy, measure 1 was within range for each scenario, measure 2 was right on the uncertainty range and therefore inconclusive.

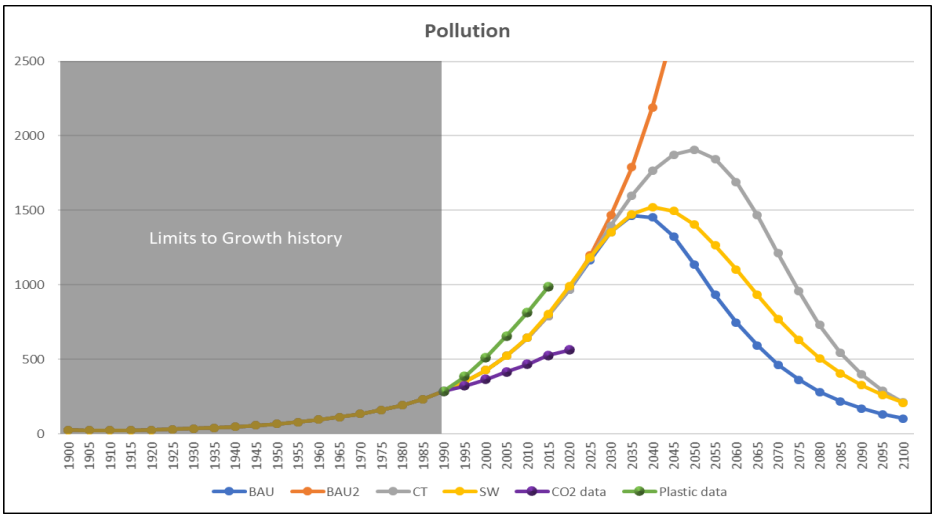

Figure 13. Scenarios and empirical data for pollution (plastic and CO_2).

Services Per Capita

Three proxies were used for this variable: health expenditure, education expenditure, and the education index (EI). Health expenditure showed a close agreement in value and NRMSD for all scenarios, but none were below 50% with regards to the ROC. Education expenditure showed a close agreement for both measures for all scenarios, with BAU clearly showing the closest alignment. The EI gave the same results: accuracy measures were within range for each scenario, with the BAU closest.

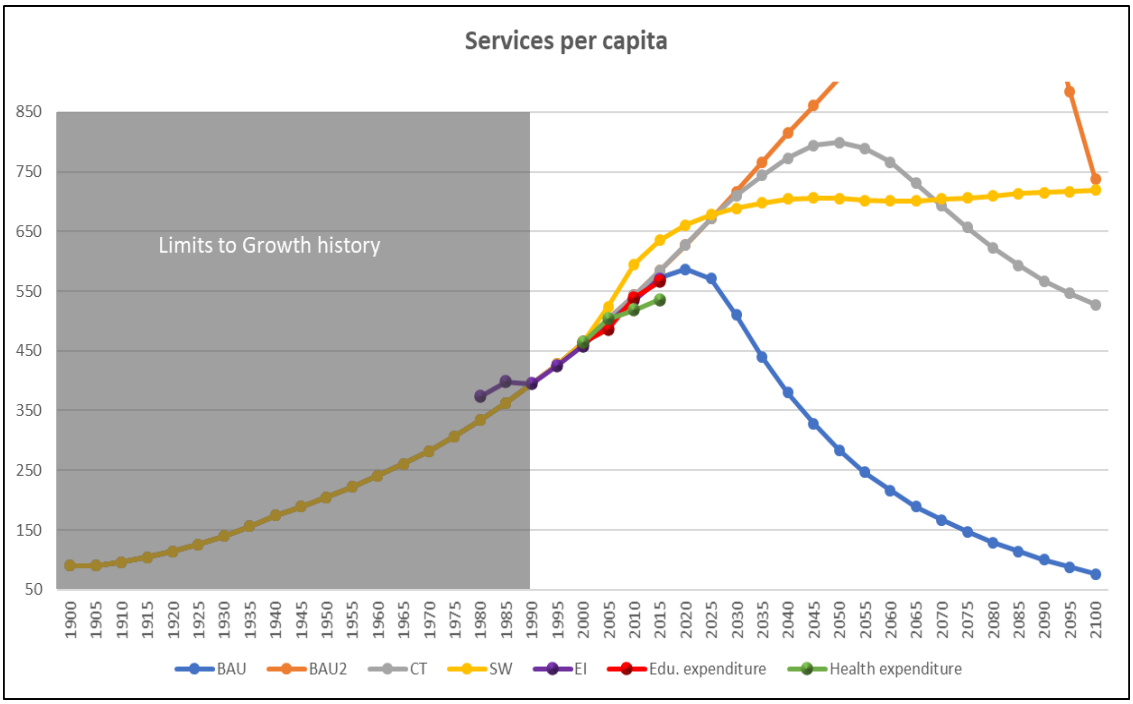

Figure 14. Scenarios and empirical data for services (health or education expenditure and education index).

Industrial Output Per Capita

We used two proxies for this variable, the index of industrial production (IIP) and gross fixed capital formation (GFCF). The GFCF series compared closely in value and

NRMSD for all scenarios, but only BAU2 and CT also showed a close enough comparison to the ROC. The IIP proxy also compared closely in value and NRMSD, but none of the scenarios were below 50% for the ROC.

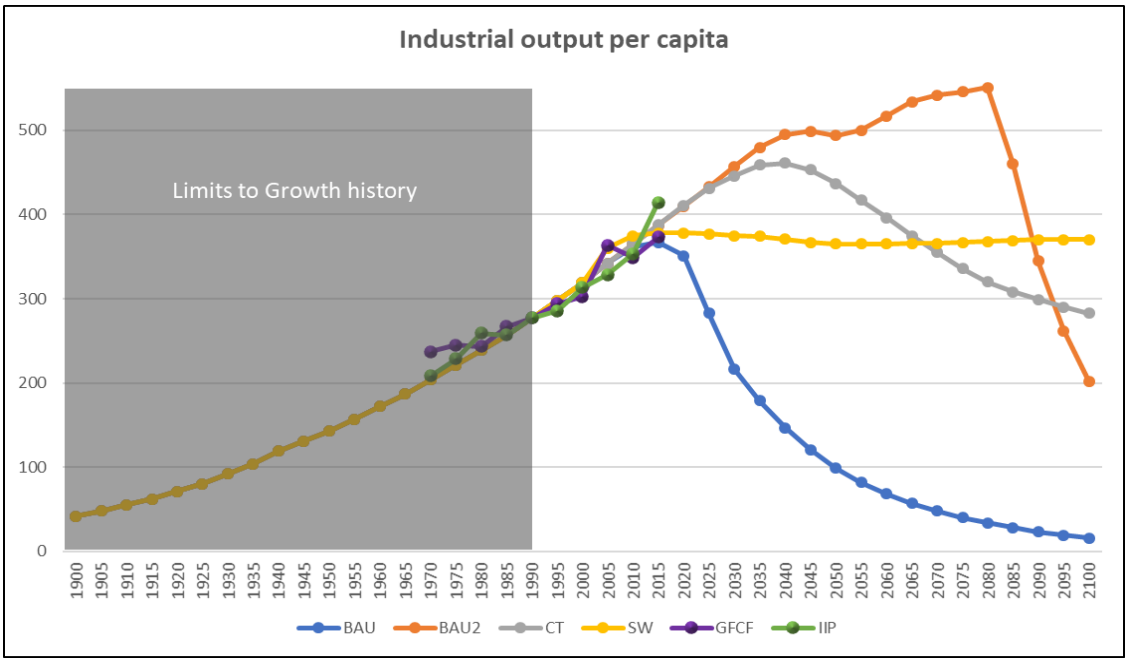

Figure 15. Scenarios and empirical data for industrial output (gross fixed capital formation and index of industrial production).

Non-renewable Natural Resources Per Capita

We used three proxies: two for fossil energy and one for metals. We also used upper and lower bounds for each fossil energy proxy, based on various expert estimates of ultimately recoverable resources. Because the scenarios have not diverged yet, all exhibited similar comparisons. Accuracy measures of the metals proxy were in range for all scenarios. Both fossil energy proxies showed all alignment errors below 20% with regards to value and NRMSD. The proxies' lower bounds for the most part were also

relatively close for the ROC. However, the two upper bounds of both fossil energy proxies fell outside of range for the ROC.

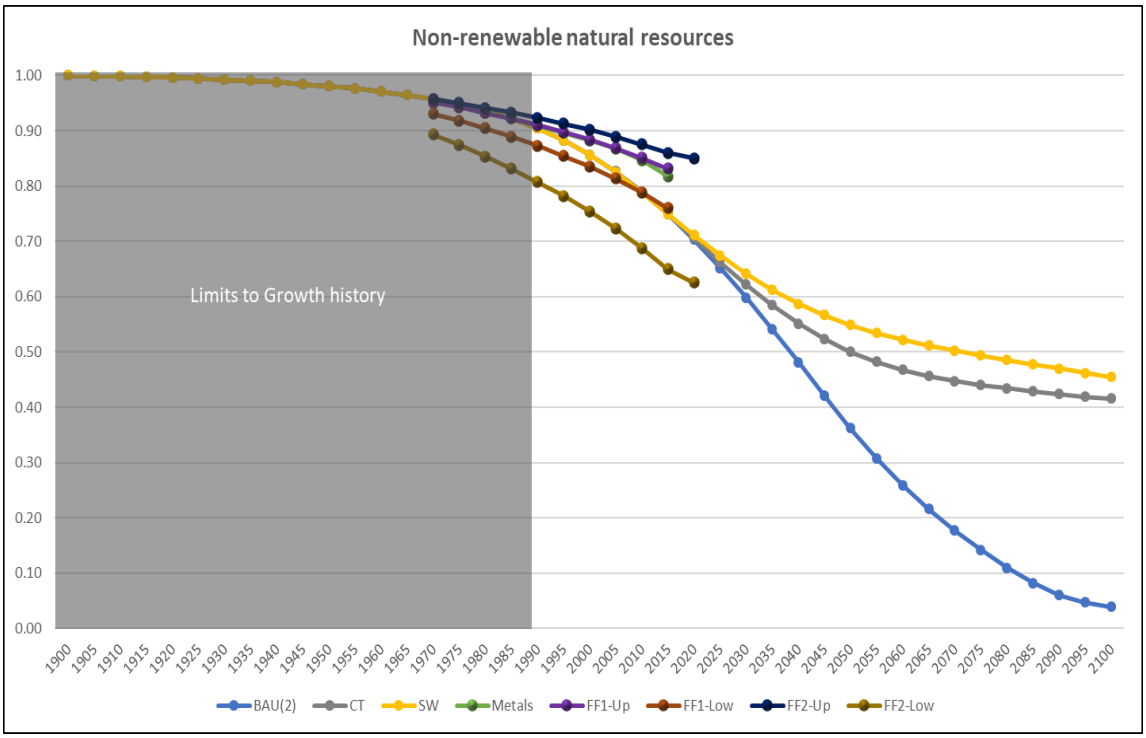

Figure 16. Scenarios and empirical data for non-renewable resources (metals and two fossil fuel expert estimates, both with high and low estimates).

Human Welfare

The LtG team (Meadows et al., 2004) created this variable to represent the UN Human Development Index (HDI). The HDI showed a close agreement in value and NRMSD for all scenarios. The CT scenario was the only one within range for the ROC.

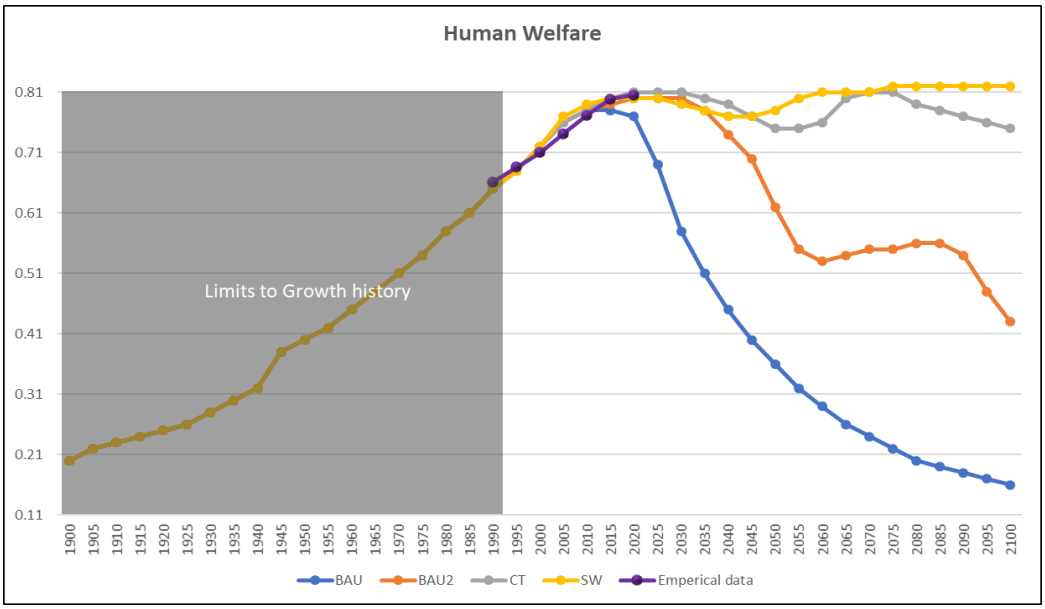

Figure 17. Scenarios and empirical data for welfare (UN Human Development Index).

Ecological Footprint (EF)

This variable represents Wackernagels' ecological footprint (Meadows et al., 2004). The EF was below 20% for all scenarios for value and NRMSD. However, each scenario was significantly outside the 50% range for the ROC.

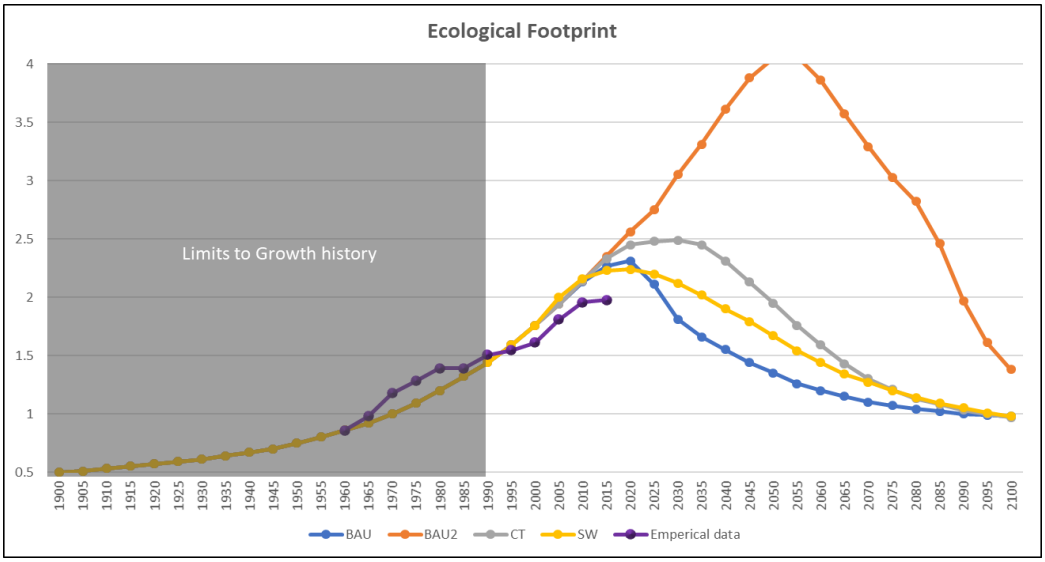

Figure 18. Scenarios and empirical data for the human ecological footprint.

Accuracy Measures

The below table and graph provide an overview of the two accuracy measures for each variable and scenario. Table 3 shows the results for accuracy measure 1, the graph in Figure 19 shows accuracy measure 2. Some variables had more than one data series for comparison with the scenario (i.e., more than one proxy). These data are listed in one cell per variable in the table and displayed separately in the graph.

The numbers in Table 3 that were within the uncertainty ranges (20% for the value difference and 50% for the ROC) are printed in green, the ones outside the range in red. The uncertainty boundaries were left in black. The 20% line is easily identified in Figure 19.

Table 3. Accuracy measure 1: value difference and rate of change difference (in %) for World3-03.

Scenario		Popula-tion	Fertility	Mortality	Food p.c.	Services p.c.	Industrial output p.c.	Pollution	Natural cap.p.c.	Welfare	EF
BAU	Δ value	-6	-18	12	-13	1; 1; 7	-1; -11	-20; 59	-15; -11; -8; -2; 15	-3	15
	ΔROC	-42	118	-109	-230	1; 12; 76	-123; -90	-14; 169	12; 43; 55; 121; 179	-125	593
BAU2	Δ value	-5	-12	5	-12	3; 4; 9	-7; 9	-20; 59	-15; -11; -8; -2; 15	-1	19
	ΔROC	-28	41	-105	-213	53; 70; 140	-64; 240	-14; 173	12; 43; 55; 121; 179	-66	940
CT	Δ value	-5	-12	3	-11	3; 5; 9	-6; 9	-20; 59	-15; -11; -8; -2; 16	0	18
	ΔROC	-25	43	-104	-162	53; 71; 140	-62; 250	-14; 170	7; 41; 50; 113; 166	-42	841
SW	Δ value	-11	-24	9	-8	12; 13; 19	-9; -2	-19; 62	-15; -11; -8; -2; 16	0	13
	ΔROC	-52	-50	-107	-173	33; 49; 134	-127; -95	-8; 190	-3; 36; 39; 97; 143	-70	247

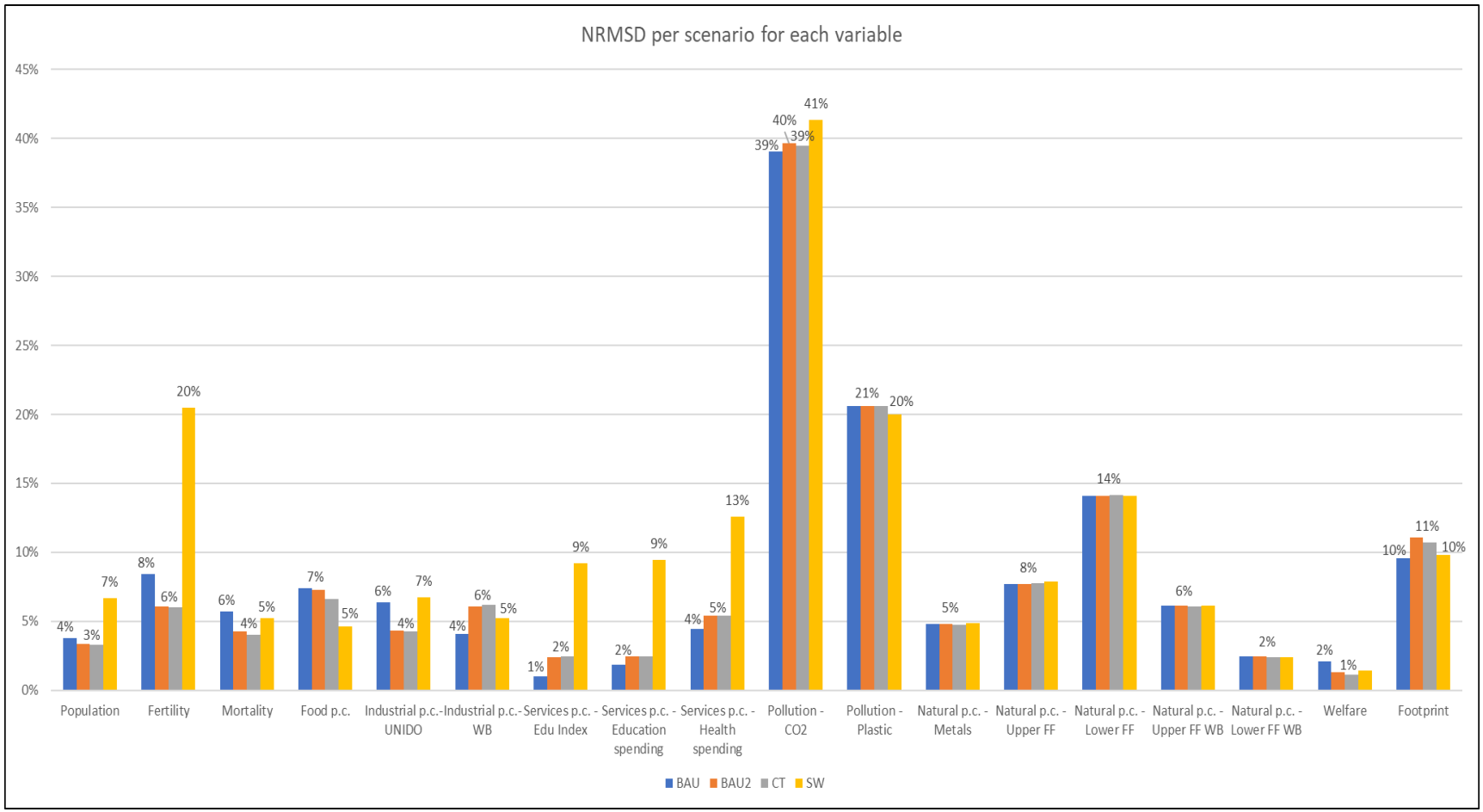

Figure 19. Accuracy measure 2: NRMSD. Plotted for each World3-03 scenario and variable.

Discussion

The LtG scenarios overall aligned closely with empirical data in value. Measure 2 (the NRMSD) was not greater than 20% for all variables (Figure 19), except for pollution. Table 3 shows that most differences in value were also within the 20% range, except for pollution and for fertility in SW. The ROC showed more and larger deviations between scenarios and empirical data.

Table 4 contains a count per scenario for each time it was the closest fit. A scenario was counted as a closest fit when it aligned more closely than other scenarios and at least one proxy was within the uncertainty bounds for both accuracy measures. This last criterium is a stringent, we could also have used the requirement of only one accuracy measure being within uncertainty bounds. (As is clear from Figure 19, accuracy measure 2 is within bounds for at least one proxy for every variable.) We chose both measures instead of either one, because scenarios show a reversal around present time for several LtG variables. Therefore, alignment in ROC is an important part of the accuracy assessment. As a second derivative, however, ROC is also the most sensitive part of the measure. In one case, industrial output p.c., we decided to balance the ROCs sensitivity with its importance by counting the scenario that showed close alignment in value (both difference and NRMSD) and the ROC slightly over the 50% bound (i.e., 62% and 64%). When all scenarios were outside of uncertainty bounds for at least one measure, they were counted as inconclusive (the last column in Table 4). For the cases where two or more scenarios aligned to the same extent, they were all counted. This is why Table 4 shows 22 counts total over ten variables. The use of more than one proxy for some variables did not lead to double counting. Although different proxies for the same

variable sometimes had different numerical results, they often led to the same outcomes in terms of alignment (or not) to a certain scenario.

Table 4. Count per scenario of closest agreement with empirical data.

Scenario	BAU	BAU2	CT	SW	None
Count of closest alignment with data	4	6	7	3	2

Unlike previous comparisons, this research did not reveal one particular scenario aligning with empirical data more closely than the others. This is because scenarios start to deviate later in World3-03 than was the case in the 1972 version of World3. Even when scenarios showed close alignment, in some cases choosing a closest fit scenario was not possible because they all aligned to a similar extent. This was the case with the non-renewable resources, for example, and with the plastics proxy for the pollution variable. Especially the BAU2 and the CT scenarios don't deviate significantly before 2020, resulting in both being closest fits for several variables. Because scenarios often aligned closely in value, a decisive factor in determining the closest fit was the difference in ROC. This means that even in cases where one scenario could be picked as a closest fit, this outcome could change in future updates because additional datapoints can change a ROC significantly. For example, the accuracy measures for the welfare variable indicated CT as the closest fit, but this is only because its ROC difference was below the 50% uncertainty range. The other scenarios agree closely in value too, and mathematically speaking it's entirely possible that even next year's datapoint will cause their rates of change (now 66% and 70%) to dip below 50%. This should be kept in mind with Table 4.

The lowest count for closest fit is for SW, the scenario that would indicate a sustainable path. When it was possible to distinguish between scenarios, the CT and BAU2 aligned closest most often. One cannot simply "take the midway" between two scenarios produced by a complex, nonlinear model like World3. However, both BAU2 and CT indicate that continuing business as usual, even when paired with unprecedented technological development and adoption, is not possible. Trying to do so would inevitably lead to declines in industrial capital, agricultural output, and welfare levels within this century. Our results are inconclusive as to whether such declines could be labeled collapse, because the two scenarios show a distinctly different decline pattern. Although the steepness of a scenario's collapse pattern cannot be used for predictive purposes (Meadows et al., 2004), the fact that CT has the highest count in close alignments might suggest the possibility of future declines being relatively soft landings, at least for humanity in general. This would align with the global forecast that Randers made in 2012 with a different model than World3. Randers' forecast described a high-tech world of changing weather patterns, a shrinking population, and a natural environment diminished in size and biodiversity. It included consumption and GDP stagnation around the middle of the century, but the subsequent decline was not forecasted as an overshoot and collapse pattern.

Conclusion

We compared empirical data with the most recent version of the LtG model, World3-03. The scenarios overall align closely with global data, indicating that World3's dynamics can still be observed in the real world. The four LtG scenarios in this

comparison, BAU, BAU2, CT, and SW, diverge significantly after 2020. For this reason, it was often not possible yet to distinguish between scenarios, and an update of this comparison in another few years will likely yield more pronounced outcomes. It also means that our results should be interpreted as preliminary, because the closeness of scenarios as well as the uncertainty within the empirical data theoretically allows for any scenario to still become a closest fit even in the short term. At this point, our results indicate that humanity is not following a sustainable path as laid out by SW. When divergence between scenarios allowed to make such distinctions, observed data aligned most closely with BAU2 and CT. Although this result does not necessarily indicate an impending collapse, both scenarios display a halt in growth and subsequent decline in industrial capital, agricultural output, and welfare within three decades. This suggests that humanity is on a path to having limits imposed on itself, rather than consciously choosing its own.

Methods

BAU, BAU2, CT, and SW, correspond to scenarios 1, 2, 6, and 9 in the 2004 LtG book. This means that for the SW scenario, we assumed policy changes starting in 2002.

To create the scenarios, we used the original CD-ROM that came with the 2004 book. (We obtained a mint condition with CD-ROM still attached.) The CD-ROM contains simulations of the scenarios, numerical output of the variables, and the code to run simulations in STELLA, a dynamic systems modelling program (ISEE Systems, 2019). A zip file of World3-03 is also available from MetaSD (2019) and it can be run on free software from Vensim (2019).

The CD-ROM provides World3 output in 5-year intervals, this is also what we used in our plots and calculation of accuracy measures.

Data Sources

Below we list for each variable the source of empirical data that we used for the comparison, and briefly discuss reliability. Some variables required proxies because the variable in World3-03 (henceforth called "World3") is not directly observable or quantifiable in the real world. We often used the same data sources as Turner in his earlier work, however, in several cases we were able to improve on those thanks to new or recently enhanced indices and databases. When empirical data was expressed in different units than the LtG scenarios, we normalized them to the 1990 scenario value, because that is the year that World3 was recalibrated to last (Meadows et al., 1992).

Population. We used figures from the Population Division of the United Nations Department of Economic & Social Affairs (UN DESA PD, 2019). Their population series includes estimates for 2020, which we used to compare against the LtG 2020 values. Annual population figures can also be found on the World Bank Open Data website (WB, 2019a). Both sites mention national agencies and international organizations as their sources, such as Eurostat, the US Census Bureau, and census publications from national statistical offices.

Global population will likely be one of the more accurate data used in this research. Although censuses in some countries will be less frequent and/or of lower quality than in others (WB, 2019a), variances in the data should be within the precision

that we worked with. Estimates for next year can be made with enough accuracy for our purpose too. The WB population data differs slightly from the UN figures, but the errors are around 0.5%, which is negligible compared to the precision level of World3.

Fertility & mortality. We used the data series from the WB Open Data site (2019b; 2019c). The WB mentions as its sources the same organizations and publications as for its population series.

These two series' reliability should be similarly high as for population. Uncertainties around data on deaths and births can be higher in some developing countries (2019c). However, the WB notes that its data "are generally considered reliable measures of fertility in the recent past" (2019b), and for the precision level we were working with we can assume the same for mortality.

Food per capita. We used total energy available per person per day to approximate this variable. The daily caloric value per capita can be found in the Food Balance Sheets on FAOSTAT (2019a), the database of the Food and Agriculture Organization (FAO).

The FAO states that "there is a substantial amount of estimated or imputed data points", leading it to conclude that "the accuracy for certain products, countries and regions is not that good" (FAOSTAT, 2019b). Because the FAO does not quantify the inaccuracy, we cannot say to what extent it impacted our research outcomes. An additional source of error was the fact the series has not been updated in several years; it extends to 2013. Because we worked with 5-year periods, we used the 2013 observed value to compare with the 2015 LtG scenario values. This is unlikely to have

significantly impacted the accuracy measures based on value, because global values will not change that much in absolute terms over two years. However, it is possible that it made a significant difference in the calculated rate of change.

Industrial output per capita. We divided both proxy series, index of industrial production (IIP) and gross fixed capital formation (GFCF), by population to arrive at per capita numbers. The industrial output p.c. variable represented citizens' material and technological standard of living, and was a factor in the World3 society's ability to grow food and deliver services (Meadows et al., 2004).

IIP is a standardized macroeconomic indicator of an economy's real output in manufacturing, mining, and energy (e.g., Moles & Terry, 1997). Unlike gross domestic product (GDP), IIP excludes retail and professional services, making it an obvious proxy for industrial output. The IIP series can be retrieved as "INSTAT2" on the data portal of the UN Industrial Development Organization (UNIDO, 2019a). UNIDO does not provide a global IIP, so we created one with a weighted average of country IIPs. As weights we chose national manufacturing value added, also sourced from UNIDO (2019b).

The WB (2019d) provides a global GFCF series. GFCF includes land improvements (e.g., fences and drains), infrastructure (e.g., roads), building construction plants (e.g., schools, offices, hospitals, and industrial buildings), machinery, and equipment purchases. This aligns closely with the definition of the industrial output variable in World3, especially as it relates to a society's ability to deliver services and grow food.

Reliability of both proxies should be adequate for our purpose. Given the mandates of UNIDO (2019c) and the WB (2019e), we can assume they source from industry associations and government agencies. These are credible institutions, who in turn collect the data through regular censuses and firm surveys (Moles & Terry, 1997). Although data quality on fixed capital formation can be weak in some cases (WB, 2019f), the series should be accurate enough because we normalized the data for this variable. Rather than comparing absolute numbers, in this case we were comparing the trend in industrial capital growth. Therefore, consistency in the underlying data collection is more important than precision, especially at the level of aggregation that we worked with. The GFCF series is based on the System of National Accounts 1993 standards (WB, 2019d), which ensures some standardization in reporting across national accounts (UN DESA Statistical Division, 2019). The INDSTAT2 series is the only one that provides "data by a single classification standard for more than 40 years, which makes it particularly valuable for long-term structural analysis" (UNIDO, 2019d).

Services per capita. In World3, services p.c. represents education and health services (Meadows et al., 2004). We used the Education Index (EI), spending on health, and spending on education as proxies.

The EI is constructed by the UN Development Programme (UN DP, 2019a). It's calculated using mean years of schooling and expected years of schooling (UN DP, 2019b). These two figures can be quite different especially in developing countries, and combined thus provide a good indication of currently available education services (UN

DP, 2019c). UN DP does not provide a global EI, so we created one by weighing each country's EI by its population fraction.

The reliability of the EI proxy should be adequate for our purpose. The EI consists of census/survey information compiled by various official government agencies, which are widely considered reliable (Barro & Lee, 2019; UN DP, 2019b). The EI had some missing data points, and we filled in the gaps with the value from the first year that data became available (again). For six small countries the EI was unavailable completely, so we left those countries out of the proxy. Because these missing data points or series were only for a handful of countries with a relatively small population, these adjustments will not have affected the aggregate significantly, especially not because we normalized the data series.

The WB provides global figures for both government spending on education (2019g) and health expenditure (2019h). The two series are expressed as a percentage of GDP. The LtG authors described many collapse patterns as resources being diverted away from services to industrial capital in order to keep extracting natural resources, abate pollution, and/or produce food. Faction of GDP is an indication of how resources are allocated towards something on a macro level, as expressed by the WB's statement that a "high percentage to GDP suggests a high priority for education" (2019g). Therefore, tracking the fraction of global GDP spent on education or health can help reveal whether the mechanism described by LtG is indeed observable.

Both GDP and government expenditure on education and health are widely and frequently recorded figures. The health spending series is sourced from the World Health Organization (WHO) and consist of "all health spending in a given country (…)

regardless of the entity or institution that financed and managed that spending" (WB, 2019h). The WHO (2019) collets data from "government budgets and health accounts studies", which, given that our research does not require high-precision data, should be sufficiently reliable. This is underlined by the WB comment that the series "generates consistent and comprehensive data on health spending (…), which in turn can contribute to evidence-based policy-making" (2019h).

Pollution. World3 assumes pollution to be globally distributed, persistent, and damaging to human health and agricultural production. We used CO_2 concentrations and plastic production as proxies.

Atmospheric CO_2 data (Tans & Keeling, 2019) were obtained from the National Oceanic & Atmospheric Administration (NOAA). We subtracted the 1900 CO_2 level of 297 parts per million (Etheridge et al., 1996), because the LtG scenarios put pollution at 0 in 1900. Although CO_2 it not the only persistent pollutant —NO_x, SO_x, heavy metals, and ozone-depleting substances are other examples— it is a good proxy because of the global impacts that climate change brings for human health, the environment, and our ability to grow food, and because there is accurate time series data.

CO_2 data from credible organizations like NOAA are widely considered reliable. NOAA (2019) uses air samples taken from remote sea level locations, which it claims, "results in a low-noise representation of the global trend". The NOAA CO_2 series differs little from global CO_2 averages published by other organizations that use different methods (NOAA, 2019).

Global plastic production data was sourced from Geyer, Jambeck, & Law (2017). We adjusted the data downwards by the share of plastic that gets discarded, which reportedly went from 100% in 1980 to 55% in 2015 (Geyer et al., 2017). Not all plastic is considered pollution, however, we felt it an appropriate proxy given that plastic is persistent and ubiquitous in today's society. Various kinds of plastics can be found throughout the entire consumer product and food supply chain, from oceans and marine wildlife (van Sebille et al, 2015; Smillie, 2017) to tap water (Kosuth, Wattenberg, Mason, Tyree, & Morrison, 2017), from agricultural land (Nizzetto, Langaas, & Futterto, 2016) to dietary components and the air we breathe (Wright & Kelly, 2017a), prompting a growing body of scientific literature on a wide range of possible negative human health effects (Halden, 2010; Wright & Kelly, 2017b).

The models used to create the plastics data series contained multiple assumptions and simplifications, introducing considerable uncertainty for the estimates (Geyer et al., 2017). For this reason, the authors rounded cumulative results to the nearest 100 metric ton and conducted sensitivity analyses around mean product lifetimes and waste management rates. In these analyses, plastic estimates changed by between 4% to 8%. This is well below the 20% uncertainty range we used, so we can assume the plastics data accurate enough for our research.

Non-renewable resources. We used two fossil fuel proxies and one metal proxy. We assumed full substitution between energy or metal resources, which is conservative given the current state of technology (Brathwaite, Horst, & Iacobucci, 2010; Driessen, Henckens, van Ierland, & Worrell, 2016; Graedel, Harper, Nassar, & Reck, 2015). The

proxy data series that we created were not normalized to 1990 values because they represent fractions (i.e., they run on a scale from 1 to 0) and so scaling them would distort the comparison. Because BAU and BAU2 differed only in amount of resources and these were set to 1 at 1900, the two scenarios show the same curve.

Both fossil energy proxies consisted of estimates of remaining coal, natural gas, and oil. The first fossil fuel proxy was the same as in Turner's earlier work. His 2008 paper lists all the sources he used to determine high and low expert estimates for fossil energy resources in 1900. Annual production of each resource was sourced from the World Watch Institute, which in turn had compiled the data from organizations including the UN, British Petroleum (BP), and the US Energy Information Administration. We updated Turner's series with production data from BP's *Statistical Review of World Energy* (2019), and summed over the three fossil resources to arrive at the total annual production series. These production data were cumulatively subtracted from the total high and low resource estimates, resulting in an upper and lower bound for the fraction of non-renewable resources remaining over time. The second fossil energy proxy was constructed using the same method, but with resource estimates from a *Geochemical Perspective* (GP) publication (Sverdrup & Ragnarsdóttir, 2014), and production data from the WB (2019i).

Although both proxies are based on data from credible organizations, non-renewable natural resources data are amongst the more uncertain compared to other variables in this research. Consequently, we worked with upper and lower bounds of expert estimates, which should mitigate the inherent uncertainty in fossil resource data sufficiently for a meaningful comparison. Turner (2008) deliberately created bounds for

the fossil energy proxy that lay on extreme ends of the spectrum. High and low expert estimates from the GP publication for the second fossil energy proxy were closer together. We took some assurance from the fact that the second fossil fuel proxy falls in between the upper and lower bounds of the first one.

The metals proxy consisted of resource estimates of 21 metals: Aluminum, Antimony, Bismuth, Chromium, Cobalt, Copper, Gold, Indium, Iron, Lead, Lithium, Manganese, Nickel, Niobium, Palladium, Platinum, Silver, Tantalum, Tin, Vanadium, and Zinc. Resources estimates of the metals available in 1900 were based on the GP publication also used for the second fossil energy proxy (Sverdrup & Ragnarsdóttir, 2014). Production of each metal was obtained from the US Geological Survey (USGS, 2019). GP provided remaining recoverable amounts for each metal as of 2010, so we summed USGS production over 1900 to 2009 and added this sum to the metal resource GP estimate to arrive at the 1900 resource figure. Production and resource data were subsequently summed over the 21 metals, and the total annual production was subtracted from the 1900 total resource over time.

The USGS production series were comprehensive overall. There were some missing data points, but sensitivity analysis showed that neither the most conservative nor extreme choice for the missing data points significantly impacted research outcomes. (We interpolated with the mean of the last and next known year when possible, and otherwise conservatively assumed zero production.) We took assurance from the fact that the metals proxy too falls in between the upper and lower bounds of Turner's fossil energy proxy.

Human welfare. The HDI data series can be found on the website of UN DP (2019a). The HDI has undergone methodological changes over the years (UN DP, 2019d), which have led to significant retroactive adjustment to the series. The 2004 LtG book (Meadows et al.) tells that the World3 welfare variable was very close to the UN DP value of 1999, but this was no longer the case for the latest version of the HDI data series. The UN DP (2019d) states: "The difference between HDI values (…) published in HD Reports for different years represents a combined effect of data revision, change in methodology, and the real change in achievements in indicators". UN DP (2019d) therefore advises not to source HDI numbers from Reports, but to use the "data series available in the on-line database". Therefore, we scaled the current HDI data with a factor 1.106 to line up with the World3 scenarios value of 2000.

The extent to which revisions to the HDI may have impacted our comparison beyond a scaling issue is unknown. The HDI series also had two missing data points, which we filled through linear interpolation. The inaccuracy that this introduced is unlikely to be significant, given firstly our research's level of precision and secondly that with the scaling of the series the most important aspect becomes the rate of change.

Human ecological footprint. The Global Footprint Network (GFN, 2019a) publishes the ecological footprint (EF) on its website. We scaled the EF series to scenario values between 1990 and 2000 (with a factor 1.17), because the LtG team would have calibrated World3 to line up with EF figures at the time. The reason that today's EF data did not exactly line up is most likely the several revisions to the EF calculation over the past two decades (GFN, 2019b), similarly to the HDI.

The GFN states that the "Ecological Footprint accounts provide a robust, aggregate estimate of human demand on the biosphere as compared to the biosphere's productive capacity" (2019b). Revisions to the calculation may have impacted our comparison beyond what can be solved with scaling, but to what extent is not known.

Determination of Accuracy

We used the same statistical measures as in Turner (2008) to determine relative closeness between a scenario variable and observed data:

1) the combination of the value difference and the rate of change difference,
2) the normalized root mean square deviation (NRMSD).

The calculations of the two measures are done for 5-year intervals ending in the final year of the data series. In the below equations, we assume that ending year to be 2015 to make the formulas easier to interpret. It is straightforward to adjust the equations for data series ending in another year.

Measure 1*: value change and rate of change*

$$\Delta Value = \frac{Variable_{2015} - ObservedData_{2015}}{ObservedData_{2015}}$$

$$\Delta RateOfChange = \frac{(Variable_{2015} - Variable_{2010}) - (ObservedData_{2015} - ObservedData_{2010})}{ObservedData_{2015} - ObservedData_{2010}}$$

Measure 2: NRMSD

In the formula below we assume the start of the sum to be 1990. This is what we used for each variable where this was possible, however, some series did not go back as far, in which case below equation would have to be adapted accordingly.

$$NRMSD_{2015} = \frac{\sqrt{\frac{\sum_{t=0}^{5}(Variable_{1990+5t} - ObservedData_{1990+5t})^2}{6}}}{\left(\frac{\sum_{t=0}^{5} ObservedData_{1990+5t}}{6}\right)}$$

These two measures of accuracy do not provide the level of precision of some statistical tests. As discussed in the article, the accuracy measures are appropriate when combined with visual inspection given World3's global scope and aggregation. Precision does not always correspond to accuracy. The precision of linear regression and other econometric methods are based on assumptions of constancy like linearity, homoscedasticity, or normality, which cannot be assumed outside controlled experiments or other unusually stable environments (Branderhorst, 2018; Sterman, 1994). As such, they are inadequate for analyzing the dynamics of a system like our society (Forrester, 1971; Meadows, 2012). The accuracy measures are useful to determine World3' merit, not for point predictions, but as an analysis tool for general global dynamics.

Chapter III

Further Discussion and Final Conclusion

In this final chapter I elaborate on my research results, including a data comparison for the 1972 version of World3, and interpret what the deviations between observed data and LtG scenarios might indicate about the model's assumptions and validity. As mentioned in Chapter II, overall alignment with empirical data was close for all scenarios. Data series typically extended to 2016, 2017, or 2018, and in one case to 2013 (food per capita). New data points could change which scenario(s) align(s) closest in a future update of this research, especially because by then scenarios will have diverged more. With that caveat, I close this chapter and thesis with what my results could mean for world trend developments in the upcoming few decades.

Comparison with the 1972 World3 Version

Because Turner's comparisons were more conclusive than my research, I repeated the exercise for the 1972 World3 version. Thus, I also conducted an update to Turner's work. I used the same scenarios and variables as he did, thereby leaving the BAU2 scenario and the EF and welfare variables out. Although the BAU compared favorably with empirical data more often than in the comparison with the World3-03 scenarios, in the update reported here it no longer showed a conclusively closer alignment over other scenarios (Table 5). In Turner's last paper (2014), the count of the BAU was twice that of the second closest fit, the CT scenario. This is no longer the case.

Table 5. Count per scenario of closest alignment for 1972 version of World3 from this research and from the last comparison by Turner (2014).

Scenario	BAU	CT	SW	None
Count of closest alignment with data in 2019	3	4	1	2
Count of closest alignment with data in Turner (2014)	6	3	1	2

Appendix 3 contains the results of the 1972 World3 comparison. These show that overall, empirical data followed the three 1972 scenarios less closely than the scenarios created with World3-03. Deviations were higher in frequency and size than in the results in Chapter II. Although the BAU was the closest fit for more variables in the 1972 comparison, empirical data aligned more closely with the World3-03 version of the BAU scenario. The reason that BAU was less often counted a closest fit in this research was not because of less alignment with empirical data, but because the CT and BAU2 aligned even closer (Table 3 and Figure 19). The overall closer alignment with observed data available in 2019 of the World3-03 scenarios makes sense given that they were based on the most recent version of the model, while the 1972 version was calibrated on historical data that is by now almost half a century old. It does seem then, that any future LtG data comparisons should be conducted with the World3-03 scenarios, although there certainly are still lessons to be learned from comparative studies between the World3 scenario versions and their underlying assumptions.

What a Global Model Will Miss: Distribution

It's an interesting contrast that on one hand empirical data for the food p.c. variable did not show signs of the decline in food production that the scenarios indicate

(Figure 12), while on the other hand according to the UN Food and Agriculture Organization (FAO) the number of undernourished people in the world has been on the rise again since 2015 (FAO, 2019a). (I should note that the food p.c. data series only goes to 2013, see the Methods section of Chapter II). At the same time of growing undernourishment, a third of the food produced in the world for human consumption still gets lost or wasted every year (FAO, 2019b). This points at a distribution issue. Likewise, economic and other inequalities have been increasing in the world since the 70s, certainly so in advanced economies and to more varied extents in developing and emerging countries (Piketty, 2014; Dabla-Norris, Kochhar, Suphaphiphat, Ricka, & Tsounta, 2015; World Inequality Database, 2018). As the IMF put it (Dabla-Norris et al., 2015): "Widening income inequality is the defining challenge of our time".

Perhaps the lack of a distributional factor in the World3 model could be one possible explanation that not one specific scenario was followed anymore based on data available in 2019 (Table 4). In this light, it is also worth noting that the one variable for which the BAU was still most closely followed, including in terms of ROC, was services p.c (Figure 14). Although industrial capital and welfare aligned closest to CT (Figure 15 and Figure 17), this was not paired by quality education and health services to the point, and especially not at the rate of increase, that one would expect based on those scenarios. This would suggest that resources are not divided as evenly as is modelled in World3, and rather are diverted to other priorities such as resource extraction and/or are used to service a smaller fraction of the population only. This too would be in line with Randers (2012), which included forecasts of increased inequalities between countries and regions.

SW Followed Least

For those variables where the scenarios had started to diverge at the end point of the data series, SW was followed the least closely (Table 3 and Figure 19). This indicates that the world is not on a sustainable path. The reason for the relatively larger deviations is simply that the assumptions in SW, especially regarding societal priorities, are not and have never been fully present in the real world.

Population and birth rate were both higher than in SW because this scenario assumes low desired family size and perfect birth control availability, which had not been the situation globally so far (UN Population Fund, 2018). The SW scenario also assumes deliberate efforts to redirect resources away from industrial capital accumulation towards education and health services. This results in stagnation in industrial capital p.c. around present time (without a subsequent decline) and a short growth spurt around 2010 in services p.c. (Figure 14 and Figure 15). The empirical data of the respective proxies, however, did not show either of these movements. This could also be derived from accuracy measure 1 (Table 3). For services p.c., there was a positive ROC difference between SW and empirical data, indicating that the increase in the variable in the real world was not as high as in the scenario. The SW also showed the largest positive value difference amongst the four scenarios, because the absence of the growth spurt in the real world resulted in a lower value than the scenario one. For industrial output p.c. on the other hand, accuracy measure 1 showed a negative ROC difference out of the uncertainty bound, because industrial growth was higher in the real world than in SW (and in the other scenarios).

BAU Not Followed Closest

My hypothesis was rejected, as the BAU was not a best fit scenario in this comparison (Table 4). This does not mean that the BAU scenario is eliminated; new data points could change the outcomes in a future comparison. The population variable, for example, was within uncertainty bounds for both accuracy measures for BAU (Table 3 and Figure 19). It was not the closest alignment because BAU2 and CT were significantly closer in ROC in this comparison, but a slowdown in population growth over the next few years could change that outcome.

Another example is the industrial output p.c. variable. Both proxies aligned closely in value with BAU but were out of bounds for the ROC at -90% and -123% (Table 3 and Figure 19). As mentioned in the section above, historical industrial output growth has been higher than in the scenarios, however, a future slowdown in observed industrial output growth is not just a theoretical possibility. As the head of the IMF, Kristalina Georgieva, recently mentioned, the global economy is experiencing a "synchronized slowdown" (Lawder, 2019). The most recent empirical data has been heavily influenced by China's performance, but with the country hitting a 30-year low in GDP growth this year (Crossley & Yao, 2019) it might not be able to keep holding the industrial production figures up at these levels (Qui & Yao, 2019; "China's Economy Slows on Weak Investment", 2019).

The Meaning of BAU2 and CT as Closest Fits

Based on data available in 2019, both the CT and BAU2 scenarios were the closest fits. The two scenarios can't effectively be distinguished because they hadn't

diverged sufficiently yet. However, these scenarios do show significantly different developments in about five years from now (Figure 8 and Figure 20).

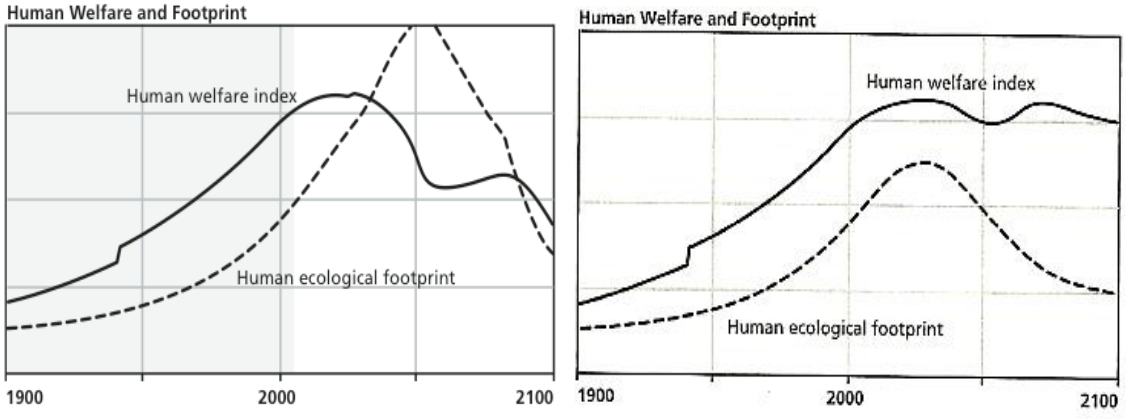

Figure 20. Welfare and EF developments for BAU2 (left) and CT (right) (Meadows et al., 2004).

The BAU2 depicts a scenario where pollution will cause societal collapse, while the CT shows only a moderate decline in welfare levels. So, what do we make of these two scenarios both being the best fit? The short answer is that at the moment we do not know whether we are following either scenario or a mix of both. Available data is inconclusive, and no one knows the future with certainty.

The question of whether we are following CT or BAU2 seems to come down to whether we believe society could be facing impending collapse, as depicted in BAU2, or whether technological innovation can stretch earth's carrying capacity to a point where collapse is largely avoided, as CT seems to indicate. It's important to note however that even if we followed CT, this would not necessarily mean declines can be assumed to be as moderate as in Figure 8 and Figure 20. The LtG authors were careful to point out that the behavior of World3 after collapse is not informational (Meadows et al., 2004). This is partly because of the modelling limitations. As with any model, World3 is a simplified

version of the real world. As mentioned, lack of distribution is one major simplification. The rich and the poor are not represented separately in World3. Many pervasive social issues, such as discrimination, oppression, violence, and corruption, are not explicitly modelled. World3 does not distinguish between geographic parts of the world. Local natural disasters, e.g., floods or earthquakes, are absent. There is no military capital in the model. As the LtG authors stated (Meadows, Meadows, & Randers, n.d.), these limitations probably make World3 "highly optimistic". For example, it is hard to imagine how domestic and international resource conflicts would not have significant impact on the course of a decline once set in. The implication is that one must be extremely careful with drawing detailed, quantitative conclusions from a collapse pattern. My results indicate that global society can expect a halt in growth in the medium term, because this is what happens in both scenarios. We can expect declines in CT to not constitute a collapse and thus to be less dramatic than under BAU2, but we cannot be more precise than that. If I assumed the world is following CT, I could not use the scenario patterns to quantify the declines. For example, one cannot look at Figure 20 and draw the assuring conclusion that the decline in our standard of living will be less than a non-threatening 10% on a global level.

The fact that both the BAU2 and CT were the best fits could also suggest a mix of the two scenarios; humanity has carried on business as usual while putting its faith in innovating itself out of any environmental crisis it would encounter along the way, as many LtG critics promised we could. This would be in line with findings of Pasqualino et al. (2015) that humanity had invested more to abate pollution and increase food productivity compared to BAU2. Society may successfully innovative itself out of some

constraints. Indeed, one reason that natural capital turned out to be more abundant that most experts expected in the 70s is that technological developments made it possible to extract from deeper and more dispersed resources (e.g., Helm, 2011; Faucon, 2013; The University of Texas at Austin, 2019). But a new limit emerged once the constraint from non-renewable natural resources was relaxed, just as the Limits to Growth principle predicts. Pollution, notably but not only in the form of CO_2, became the new constraint on carrying on business as usual (e.g., Woody, 2013; Jakob & Hilaire, 2015). This illustrates one of the major reasons that humanity cannot be expected to technologically innovate itself out of an environmental crisis: as long as the goal of the economic system is perpetual growth, technological developments will mostly serve to sustain growth, not life (Meadows, 2012). And as long as growth continues, new limits will be met.

BAU2 forecasts that the new limit will come from pollution, including from greenhouse gasses. The pollution variable did not show a close fit with empirical CO_2 data, but the impact factor in World3 (both versions) is too low given the myriad and complex ways that climate change impacts life. In BAU2, pollution levels have to literally get off the scale of the graph for it to cause collapse (Figure 8). But it is well established that increases in CO_2 levels much smaller than those depicted in the BAU2 graph would cause a crisis in the next few decades (e.g., Intergovernmental Panel on Climate Change, 2018). At the current impact factor in World3, other forms of pollution may be a better approximation. Many localized chemical pollution, e.g., water, land, and air contamination, by now has a persistent occurrence in locations around the globe. However, there is no global data repository of any kind for these contaminations. Plastics

are another example of a localized pollution with global occurrence, and that proxy did show a close fit with LtG scenarios.

My Future Scenario

Based on my results, I would indeed synthesize a future scenario that is a mix of CT and BAU2. In this scenario, society will stay on the current path that conflates progress with expansion, albeit with the best intentions behind the concept of "green growth". Natural non-renewable resources will be depleted further, and pollution in all its manifestations of contamination, toxicity, and climate change will become an increasing problem. Pressing problems present opportunities to those who are able to capitalize on them (which are not necessarily the ones most affected). Therefore, we will see unprecedented innovation in fields like renewable energy, pollution abatement, resource efficiency, agricultural practices, and disaster resiliency, although not as much as in the assumptions underlying CT. These technologies will come at major costs. It is these costs that cause declines in CT, but because World3 lacks a distributional factor, in the scenario they are borne equally by every person. I do not think this will happen in the real world. Amidst major income and wealth inequality, a mix of CT and BAU2 will mean that negative impacts from pollution on water and food supply, human health, and weather patterns, will be largely spared from those that can afford the technological solutions, and borne mostly by those that cannot. Basically, when I say that I expect a mix of the two scenarios I mean that some of us will experience a CT future while others will experience the BAU2 one.

What If We Are Following CT?

Some might postulate that there is no mix between the BAU2 and the CT at all, and argue that we are following the CT, which will become apparent in the upcoming years when new data shows the closest alignment to CT instead of BAU2. They might look at Figure 20 and say: "We will all be fine with only a temporary dip in welfare levels around 2050." I could point out that the assumptions underlying the CT scenario are highly optimistic given historic figures. For example, CT assumes technological progress rates of 4% a year which, amongst other things, should lead to reductions in pollution emissions of 10% from their 2000 values by 2020 and 48% by 2040 (Meadows et al., 2004). Compared to our performance record of reducing global CO_2 emissions, the CT assumptions seem unrealistic to me. However, the technologist might argue that technological developments are ever accelerating, and the solar technology boom or nuclear fusion breakthrough are around the corner to completely change our trajectory. We could keep going back and forth for a long time with our arguments, none of which would change the fact that ultimately the future is uncertain.

Much more important, whether we are following the CT is not the right discussion to have. Is the only thing that can motivate society an impending collapse? I would argue not, in fact, I would argue the opposite. One just needs to look at the climate change debate and realize: if impending doom was enough motivation for humanity to make the necessary changes, we would have made them by now. The overwhelming threats of climate change and other sustainability challenges seem to not scare people into action so much as they scare them into the arms of economists, technology gurus, and spiritual leaders who promise that some force, be it the invisible hand, human ingenuity, or

surrender to a higher power will solve our systemic problems for us (Vargish, 1980). I intentionally avoided delving into all the details of why I think the CT is unrealistic, because it would obscure the question we really should be asking: do we want to be following the CT scenario in the first place? Why would we use our innovative powers to invent robot pollinators to replace the bees, if we also have the choice to invent agricultural practices that do not have the side effect of insecticide? Why use drones to plant new trees, when we could also restructure our economic priorities so that existing rainforest is not cut and burned down? Now that humanity has attained truly global reach, now that we have an unprecedented power to shape our own destiny, limits to growth force upon us the question: who do we want to be and what world do we want to live in?

Conclusion

I compared empirical world data available in 2019 against scenarios from both the first and last LtG books, which were created by an earlier and recalibrated version of the World3 model. The data comparison with the latest World3 version included four scenarios: BAU, BAU2, CT, and SW. Empirical data showed a relatively close fit for most of the variables. This was true to some extent for all scenarios, because in several cases the scenarios don't significantly diverge until 2020. The overall close track with empirical data of the latest World3 version is a testament to the accomplishment of the LtG team, when they created and recalibrated a model which has been able to generate global interacting trends accurately three decades into the future.

When scenarios had started to diverge, the ones that showed a closest fit with empirical data most often were BAU2 and CT. I thus rejected my hypothesis that society

was still following BAU, which had been the conclusions of comparisons that used the earlier World3 version. The BAU not being the closest fit scenario does not imply that societal collapse can be ruled out. The scenario that depicts the smallest declines, SW, is also the one that aligned least closely with empirical data. Furthermore, one of the best fit scenarios, BAU2, shows a collapse pattern. The other best fit scenario however, CT, shows only a moderate decline. At this point, therefore, results indicate a halt in growth within the next three decades, but leaves open whether the subsequent decline will constitute a collapse.

This outcome does not mean that human suffering will likely or even possibly be avoided. In fact, my results show services p.c., a variable directly related to wellbeing, following the scenario that puts a collapse nearest in the future (BAU). This suggests that, contrary to what is assumed in World3, resources are not distributed equally amongst people. It may be worth researching whether incorporation of a distribution effect improves the model. Given the major income and wealth inequality in the world, I have interpreted both CT and BAU2 being the closest fits, as that both scenarios will play out in the upcoming few decades; the high-tech solutions and moderate welfare decline of CT will befall on the rich, while the effects of the pollution crisis and collapse in living standards of the BAU2 will be borne mostly by the poor.

Lastly, the close alignment to empirical data and the fact that the scenarios had not diverged yet, together form a call to action. Hidden behind a seemingly ambiguous outcome of two best fit scenarios that marginally aligned closer than the other two, hails the message that it’s not yet too late for humankind to change course and alter the

trajectory of future data points. Global society does not have to settle for CT as a best-case scenario. We have another choice.

This thesis has mostly focused on the hard data analysis, but there is a value aspect around LtG and it would be a shortcoming to ignore this other, non-quantifiable dimension. As the LtG books and many other experts have stated: humanity needs a change in values and priorities in order to reach a global equilibrium. But changing our societal priorities does not need to be a capitulation to grim necessity. A world in which human activity is regenerative instead of rapacious is not just one in which collapse is avoided, it is a world where our natural surroundings are full of life. The LtG graphs show how society would be more stable in the SW scenario, but not how much more its citizens would be thriving. World3's equations do not capture human's innate love for nature in all its abundance and diversity, and how we hurt when we lose parts of it forever. By the time the next data comparison may be able to show one best fit, more will be lost and a course change will be more difficult or even impossible. Now is the time to deliberately choose global equilibrium with nature in all its forms, including fellow humans. Not because we cannot survive without parts of nature, although we very well may not, but because we love life more than growth.

Appendix 1

Dynamic Systems Depiction of World3

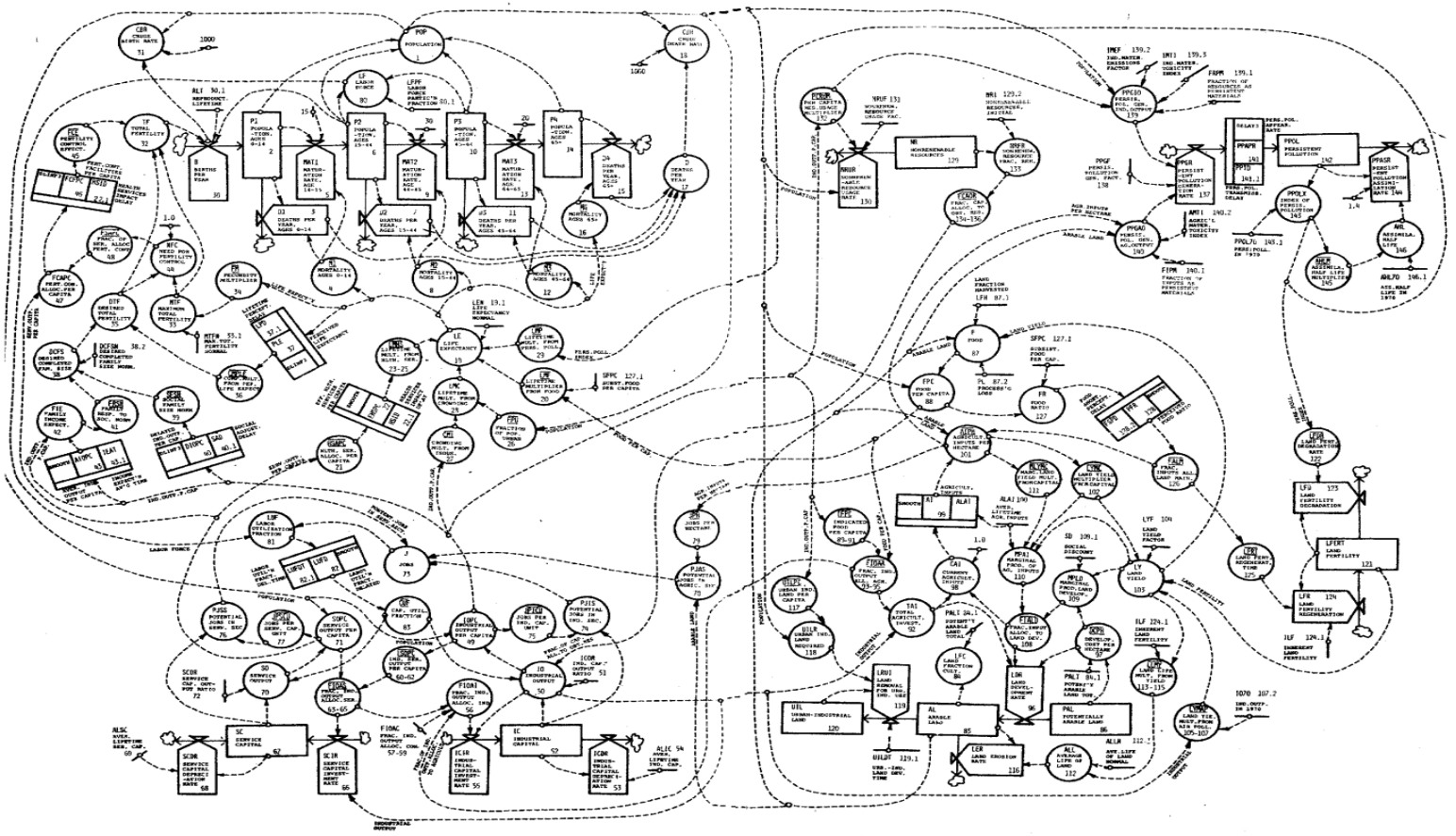

Figure 21. Depiction of the interactions in the World3 model (Pasqualino, et al., 2015).

Appendix 2

The Four LtG Scenarios Used in the Research

Scenario 1 (BAU).

Scenario 1 represents a global society that proceeds as long as possible without major structural policy changes. Meadows et al. (n.d.) describe this scenario as follows:

> As natural resources become harder to obtain, capital is diverted to extracting more of them. This leaves less capital for investment in industrial output. The result is industrial decline, which forces declines in the service and agricultural sectors. About the year 2030, population peaks and begins to decrease as the death rate is driven upward by lack of food and health services.

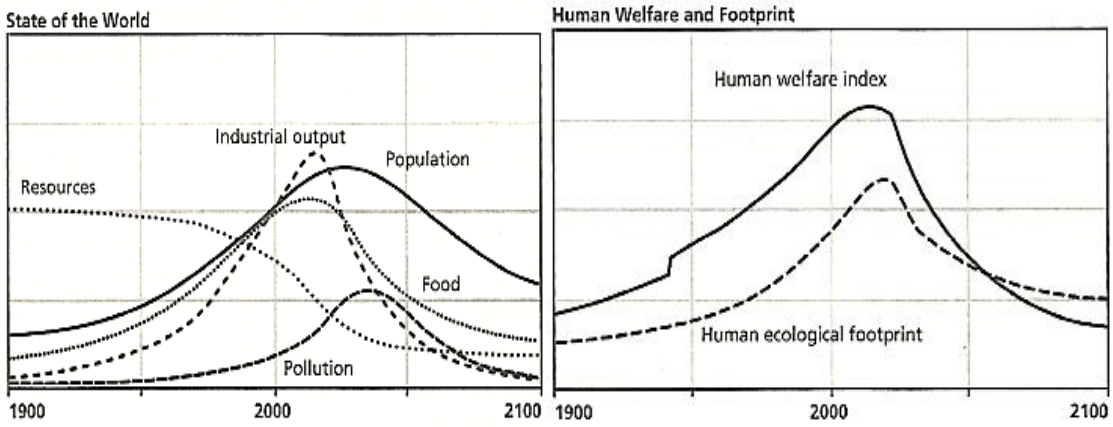

Figure 22. Scenario 1, or the BAU scenario (Meadows et al., 2004).

Scenario 2 (BAU2)

Scenario 2 assumes that the world's non-renewable natural resources double, and further assumes that resource extraction technologies will postpone the onset of increasing extraction costs. Meadows et al. describe scenario 2 as follows (n.d.):

> Under this scenario industry can grow 20 years longer. But pollution levels soar, depressing land yields and requiring huge investments in agricultural recovery. The population finally declines because of food shortages and negative health effects from pollution.

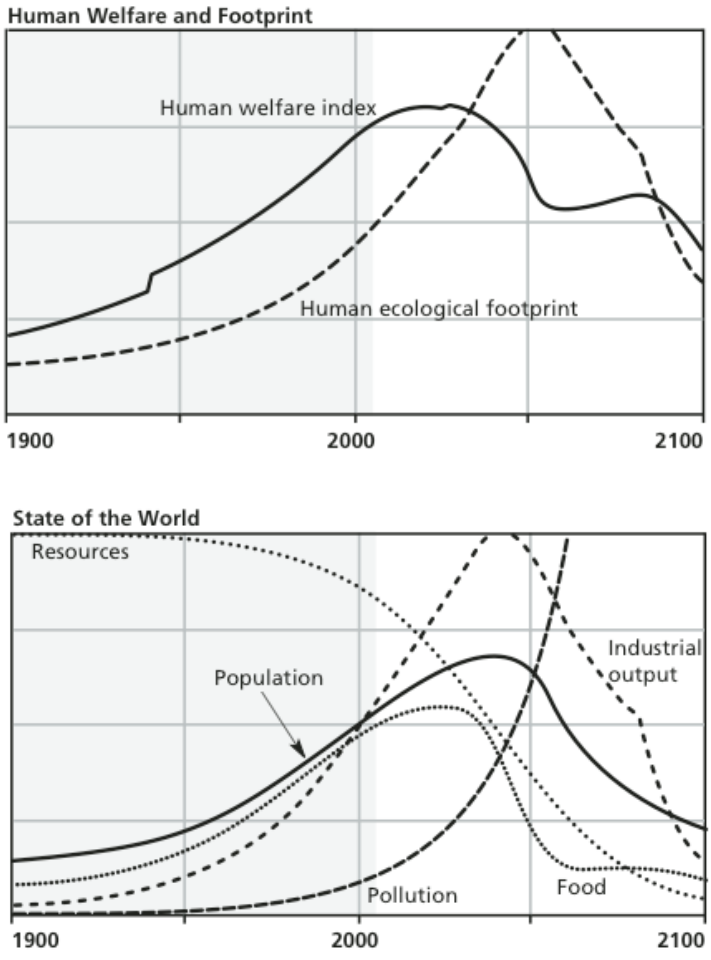

Figure 23. Scenario 2, or the BAU2 scenario (Meadows et al., n.d.).

Scenario 6 (CT)

This simulated world focusses on technological advancements to solve natural resources scarcity and pollution problems. Powerful technologies that abate pollution, increase land yields, counter land erosion, and boost resource conservation are assumed to take place. The technological innovation and implementation is assumed to involve financial costs, and the delay between discovery and full implementation of innovations is assumed to be 20 years. Technology does in fact seem to avoid a decline as steep as in some other scenarios in CT, however, standards of living still show a moderate decline around 2030 as a result from the costs that the high rate of technological innovation requires.

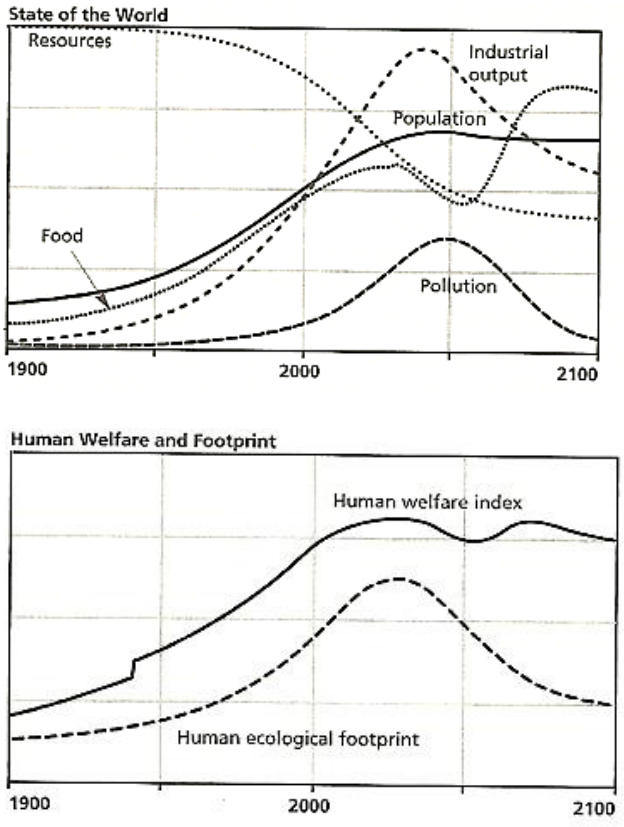

Figure 24. Scenario 6, or the CT scenario (Meadows, et al., 2004).

Scenario 9 (SW)

In this scenario, global society deliberately seeks stable population by perfect birth control availability and average desired family size of two children per family. It also caps industrial output per person, and prioritizes investments in pollution control, resource conservation, and agricultural technologies. The effectiveness in avoiding collapse depend on when these changes are assumed to take place. In the below graph, this was 2002.

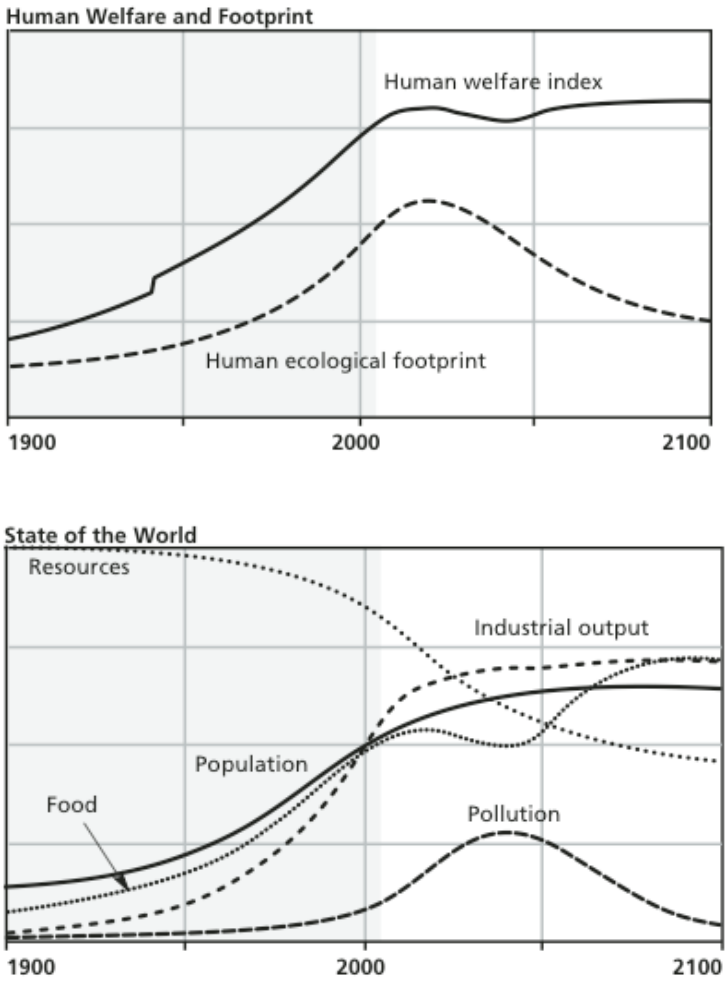

Figure 25. Scenario 9, or the SW scenario (Meadows, et al., n.d.).

Appendix 3

Results From the 1972 World3 Data Comparison

Table 6. Accuracy measure 1: value difference and rate of change difference (in %) for 1972 World3 version.

Scenario		Population	Fertility	Mortality	Food p.c.	Services p.c.	Industrial output p.c.	Pollution	Natural cap.p.c.
BAU	Δ value	-7	1	27	-9	-18 ; -13 ; 8	-12 ; 10	-21 ; 78	-45 ; -42 ; -43 ; -38 ; -27
	ΔROC	-41	180	128	-86	-49; -49 ; -21	-94 ; -87	-36 ; 432	115 ; 189 ; 198 ; 323 ; 436
CT	Δ value	-1	-3	-21	67	60 ; 69 ; 111	66 ; 107	-70 ; -44	0 ; 4 ; 5 ; 13 ; 33
	ΔROC	26	-55	-13	337	647 ; 654 ; 1072	16 ; 138	-77 ; -73	-53 ; -37 ; -35 ;-8 ; 16
SW	Δ value	-36	-33	9	16	0 ; 6 ; 33	-24 ; -5	-87 ; -74	-6 ; -2 ; -1 ; 7 ; 25
	ΔROC	-81	-72	-100	-176	-166 ;-143 ;-142	-142 ; -120	-77 ; -102	-66 ; -55 ; -53 ; -34 ;-16

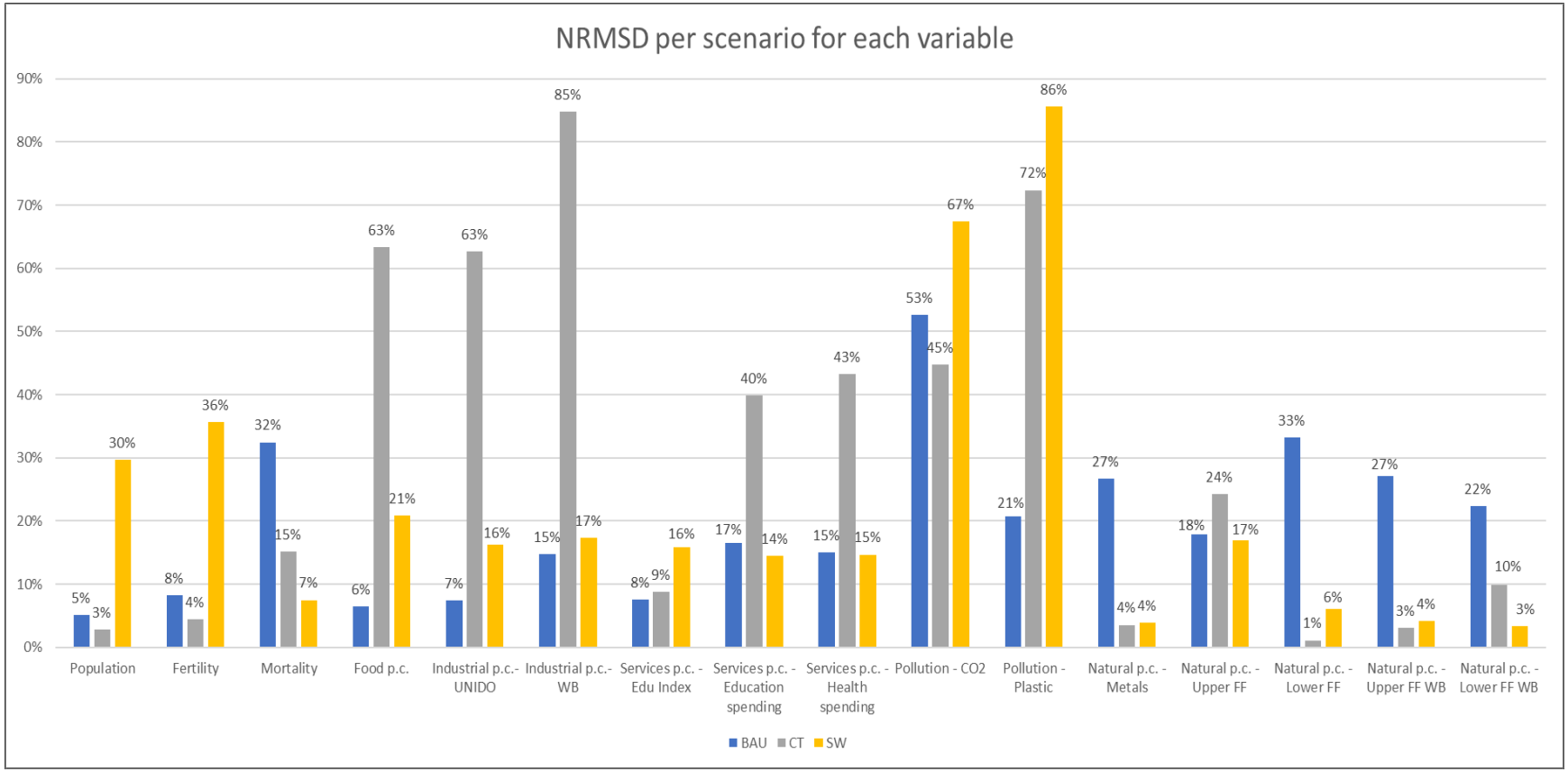

Figure 26. Accuracy measure 2: NRMSD. Plotted for each 1972 World3 scenario and variable.

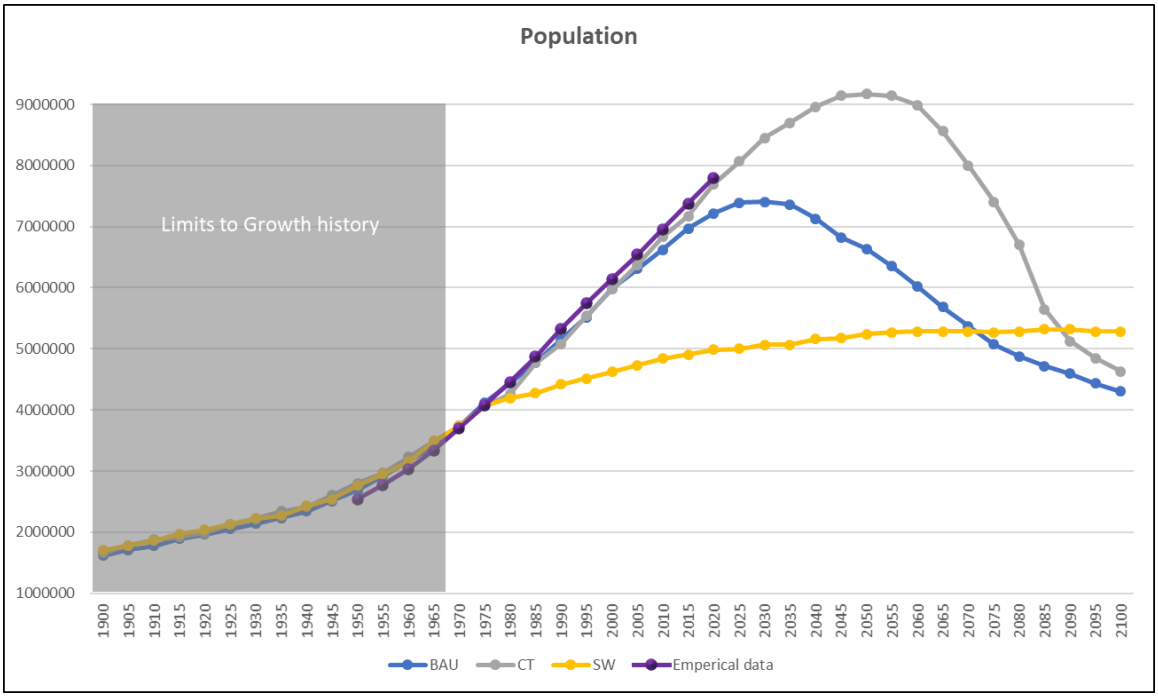

Figure 27. 1972 World3 scenarios and empirical data for population (in thousands of people).

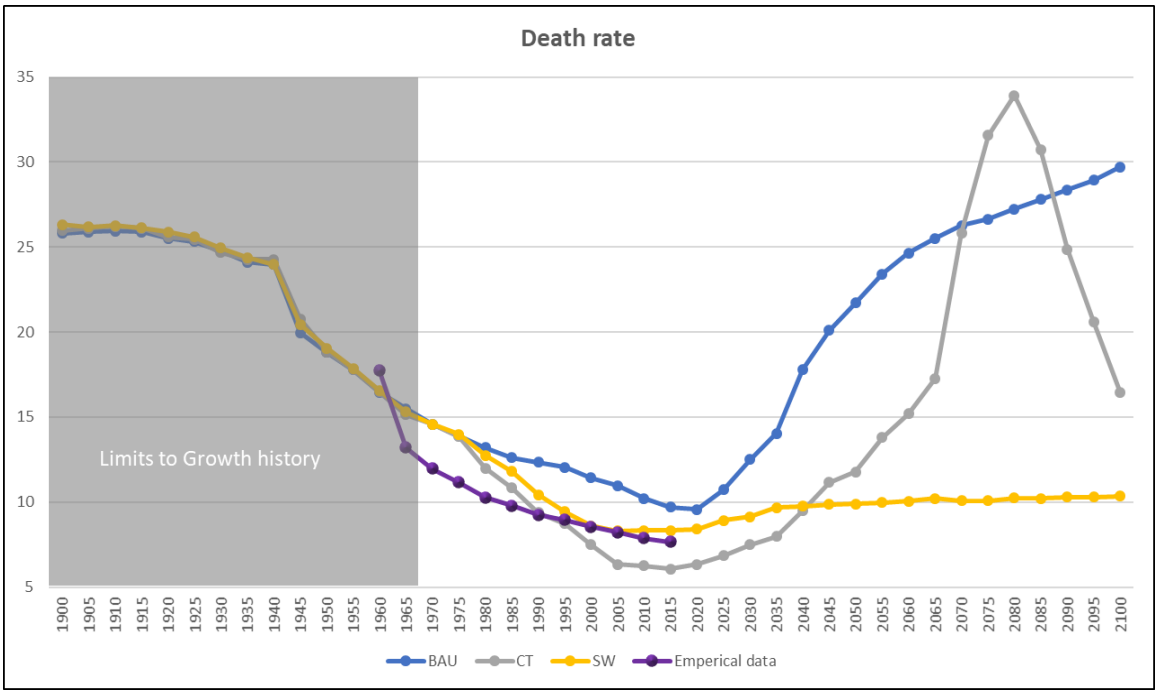

Figure 28. 1972 World3 scenarios and empirical data for mortality (deaths per thousand people).

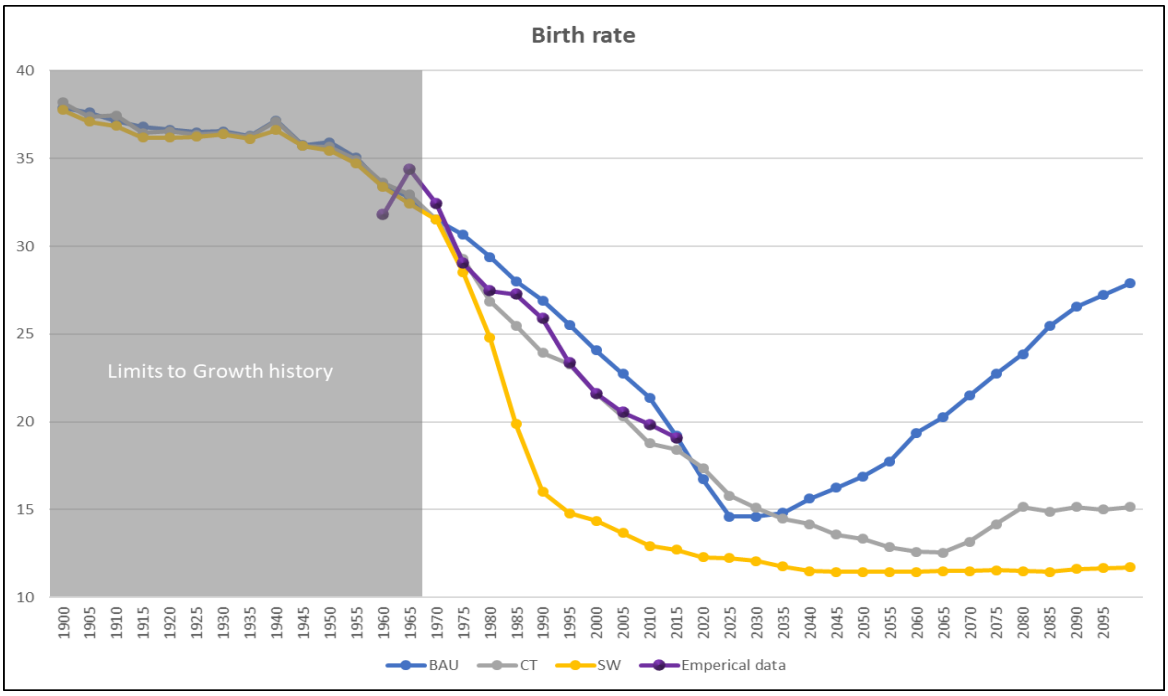

Figure 29. 1972 World3 scenarios and empirical data for fertility (births per thousand people).

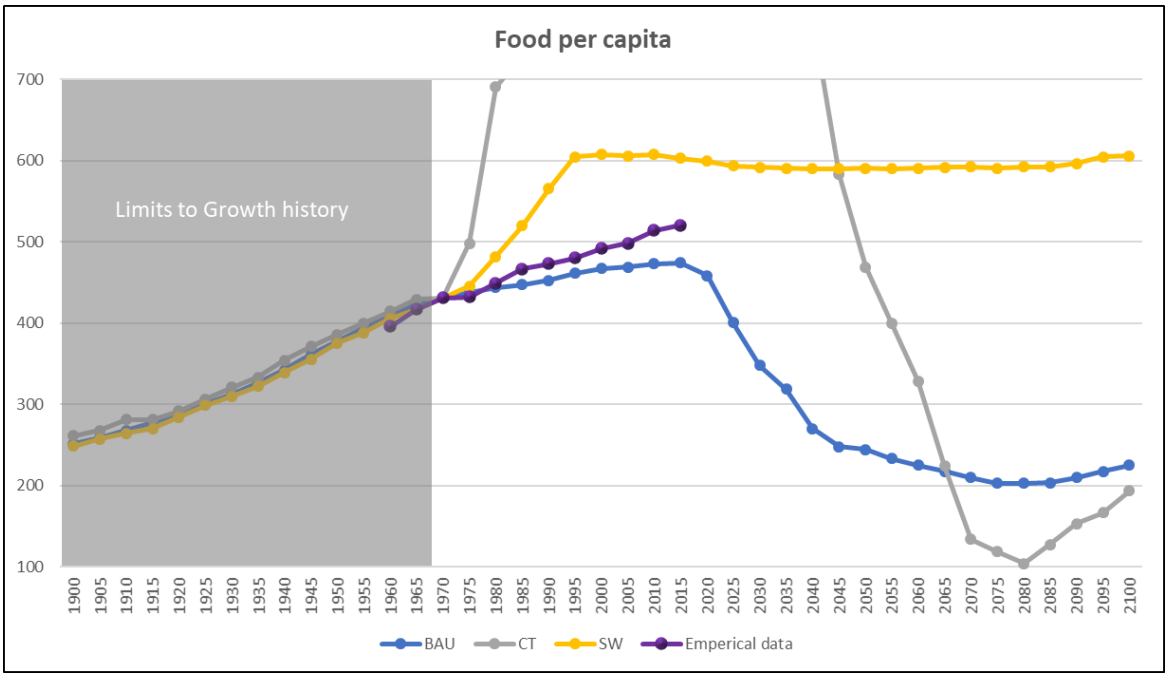

Figure 30. 1972 World3 scenarios and empirical data for food per capita (in kilocalories per day).

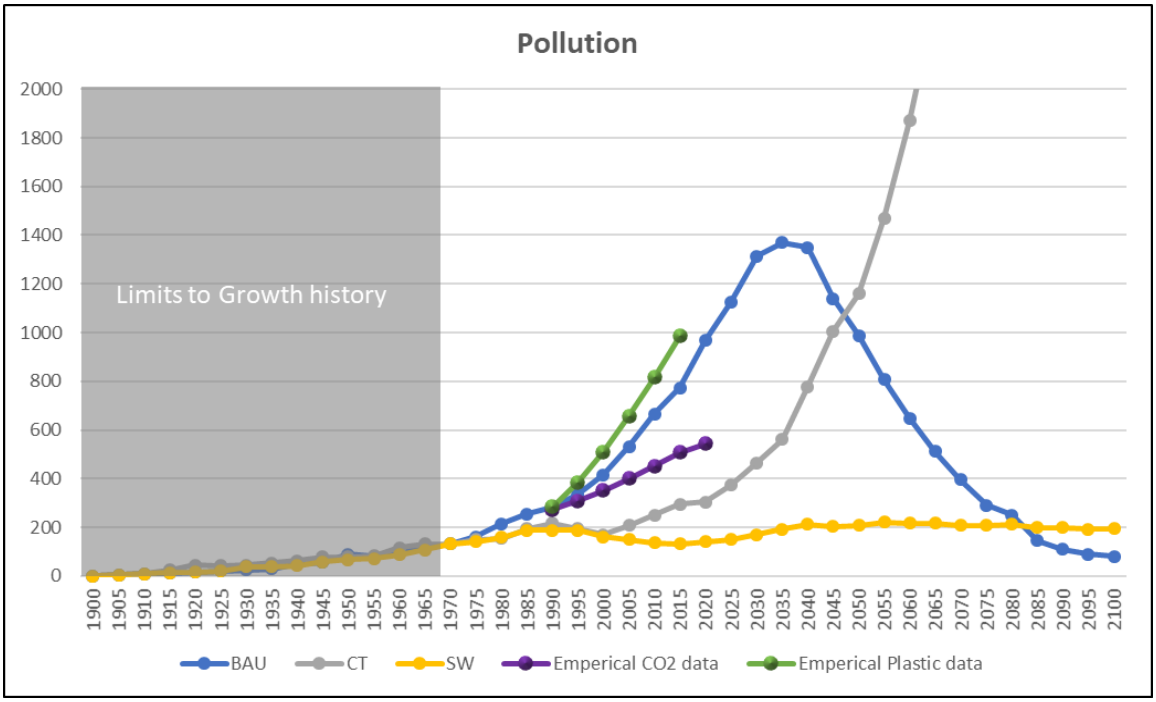

Figure 31. 1972 World3 scenarios and empirical data for pollution (plastic and CO_2).

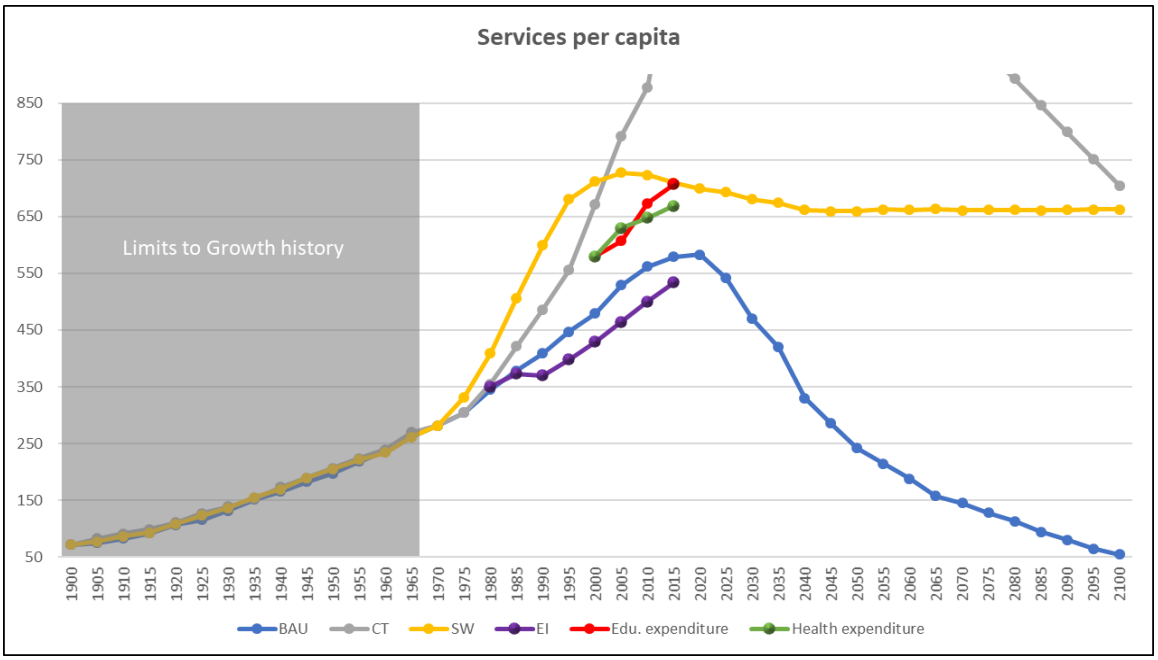

Figure 32. 1972 World3 scenarios and empirical data for services (health or education expenditure and education index). In this case the EI is probably the best proxy, because expenditure data does not go back beyond 2000 and the LtG scenarios have diverged already by then. We chose to scale expenditure data to somewhere in between the scenarios.

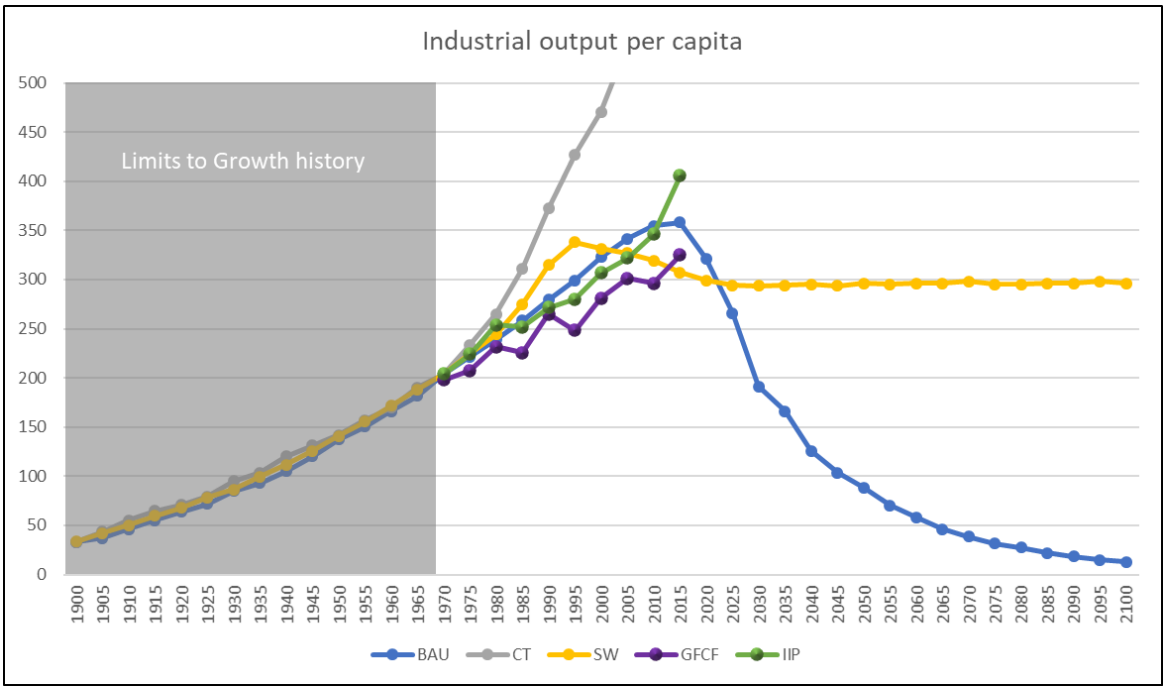

Figure 33. 1972 World3 scenarios and empirical data for industrial output per capita (gross fixed capital formation and index of industrial production).

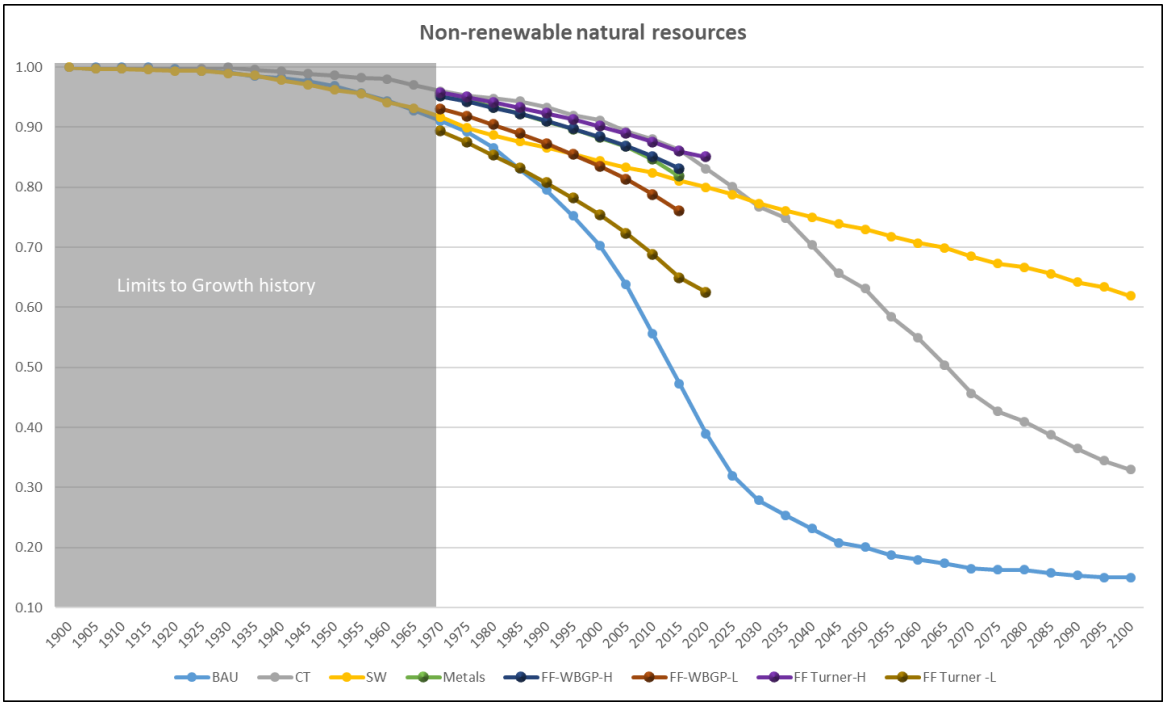

Figure 34. 1972 World3 scenarios and empirical data for non-renewable natural resources (metals and two fossil fuel expert estimates, both with high and low estimates).

References

Bailey, R. (1989). Dr. Doom. *Forbes, 144*, 44.

Bardi, U. (2011). Cassandra's curse: How "the Limits to Growth" was demonized. Retrieved from https://www.resilience.org/stories/2011-09-15/cassandras-curse-how-limits-growth-was-demonized/

Bardi, U. (2014). *Extracted: How the quest for mineral wealth is plundering the planet*. White River Junction VT: Chelsea Green Publishing Co.

Barro, R., & Lee, J-W. (2019). (2019). Barro-Lee: Data sources. Retrieved from http://www.barrolee.com/aboutset/sources.htm

Branderhorst, G. (2018). *Mapping the mess: Planning for the unprecedented in a complex, dynamic, and interconnected world*. Retrieved from http://workspace.unpan.org/sites/Internet/Documents/UNPAN98846.pdf

Brathwaite, J., Horst, S., & Iacobucci. J. (2010). Maximizing efficiency in the transition to a coal-based economy. *Energy Policy, 38*(10), 6084-6091.

British Petroleum (BP). (2019). *Statistical review of world energy*. Retrieved from https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

Castro, R. (2012). Arguments on the imminence of global collapse are premature when based on simulation models. *GAIA, 21*, 271–273.

Chichakly, K. (2009). Limits to growth. Retrieved from https://blog.iseesystems.com/stella-ithink/limits-to-growth/

China's economy slows on weak investment, testing global growth. (2019, October 17). Retrieved from https://www.bloomberg.com/news/articles/2019-10-18/china-economic-growth-unexpectedly-slows-to-6-in-third-quarter

Coady, D., Parry, I., Sears, L., & Shang, B. (2017). How large are global fossil fuel subsidies? *World Development, 91*, 11-27. doi: 10.1016/j.worlddev.2016.10.004

Cole, H. S. D., Freeman, C., Jahoda, M., Pavitt, K. L. R. (1973). *Models of doom: A critique of the Limits to Growth.* Bloomington, IN: Universe Publishing.

Crossley, G., & Yao, K. (2019). China's GDP growth grinds to near 30-year low as tariffs hit production. *Reuters.* Retrieved from https://www.reuters.com/article/us-china-economy-gdp-idUSKBN1WX05A

de Jongh, D. C. (1978). Structural parameter sensitivity of the Limits to Growth world model. *Applied Mathematical Modelling, 2*, 77-80.

Dabla-Norris, E., Kochhar, K., Suphaphiphat, N., Ricka, F., & Tsounta, E. (2015, June). *Causes and consequences of income inequality: A global perspective*. Retrieved from https://www.imf.org/external/pubs/ft/sdn/2015/sdn1513.pdf

Driessen, P. P. J., Henckens, M. L. C. M., van Ierland, E. C., & Worrell, E. (2016). Mineral resources: Geological scarcity, market price trends, and future generations. *Resources Policy, 49*, 102-111. doi: 10.1016/j.resourpol.2016.04.012

Etheridge, D.M., Steele, L.P., Langenfelds, R.L., Francey, R.J., Barnola J.-M., & Morgan, V.I. (1996). Natural and anthropogenic changes in atmospheric CO2 over the last 1000 years from air in Antarctic ice and firn. *Journal of Geophysical Research, 101*.

Food and Agriculture Organization of the United Nations (FAO). (2019a). The state of food security and nutrition in the world. Retrieved from http://www.fao.org/state-of-food-security-nutrition/en/

Food and Agriculture Organization of the United Nations (FAO). (2019b). Key facts on food loss and waste you should know! Retrieved from http://www.fao.org/save-food/resources/keyfindings/en/

FAOSTAT. (2019a). Food Balance Sheets. Retrieved from http://www.fao.org/faostat/en/#data/FBS

FAOSTAT. (2019b). Food Balance Sheets - Metadata. Retrieved from http://www.fao.org/faostat/en/#data/FBS/metadata

Faucon, B. (2013, November). Energy: Oil Companies Go Deep --- Despite predictions of retrenchment, offshore drilling has taken off. *The Wall Street Journal Asia*, p. 10.

Forrester, J. W. (1971). *World dynamics*. Cambridge, MA: Wright-Allen Press.

Forrester, J. W. (1975). *Collected papers*. Waltham, MA: Pegasus Communications.

Forrester, J., Low, G., & Mass, N. (1974). The debate on "World Dynamics": A response to Nordhaus. *Policy Sciences, 5*, 169-190.

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances, 3*(7).

Global Footprint Network (GFN). (2019a). Country Trends. Retrieved from http://data.footprintnetwork.org/#/countryTrends?cn=5001&type=earth

Global Footprint Network (GFN). (2019b). FAQs. Retrieved from https://www.footprintnetwork.org/faq/

Graedel, T. E., Harper, E. M., Nassar, N. T., Reck, B. K. (2015). On the materials basis of modern society. *Proceedings of the National Academy of Sciences, 112*, 6295. doi: 10.1073/pnas.1312752110

Halden, R. U. (2010). Plastics and Health Risks. *Annual Review of Public Health, 31*(7).

Hall, C., & Day, J. (2009). Revisiting the Limits to Growth after peak oil. *American Scientist, 97*, 230-237.

Helm, D. (2011). Peak oil and energy policy—a critique. *Oxford Review of Economic Policy, 27*(1), 68-91.

Intergovernmental Panel on Climate Change. (2018). *Special report: Global warming of 1.5 ºC*. Retrieved from https://www.ipcc.ch/sr15/

ISEE Systems. (2019). Products. Retrieved from https://www.iseesystems.com/store/products/

Jackson, T., & Weber, R. (2016). *Limits revisited: A review of the Limits to Growth debate*.
Retrieved from http://limits2growth.org.uk/revisited

Jakob, M., & Hilaire, J. (2015). Unburnable fossil-fuel reserves. *Nature, 517*(7533), 150-152.

Kaysen, C. (1972). The computer that printed out W*O*L*F*. *Foreign Affairs, 50*, 660–668. doi:10.2307/20037939. JSTOR 20037939.

Kosuth, M., Wattenberg, E. V., Mason, S. A., Tyree, C., Morrison, D. (2017) Synthetic polymer contamination in global drinking water. *Orb Media*. Retrieved from https://orbmedia.org/stories/Invisibles_final_report/multimedia

Lawder, D. (2019). New IMF chief Georgieva warns of "synchronized slowdown" in global growth. *Nasdaq*. Retrieved from https://www.nasdaq.com/articles/new-imf-chief-georgieva-warns-of-synchronized-slowdown-in-global-growth-2019-10-08

Lomborg, B., Olivier, R. (2009). The dustbin of history: Limits to Growth. *Foreign Policy, 103*, 34-48. Retrieved from http://foreignpolicy.com/2009/11/09/the-dustbin-of-history-limits-togrowth

Lyneis, J. M. (2000). System dynamics for market forecasting and structural analysis. *System Dynamics Review, 16*, 3-25.

Maddison, A. (2006). *The world economy: Volume 1: A millennial perspective and Volume 2: Historical statistics* (Development Centre Studies). Paris: OECD Publishing.

Meadows, D. H. (2012). *Thinking in systems*. White River Junction, VT: Chelsea Green Publishing.

Meadows, D. L. (1974). *Dynamics of growth in a finite world*. Cambridge, MA: Wright-Allen Press.

Meadows, D. H., Meadows, D. L. (2007). The history and conclusions of The Limits to Growth. *System Dynamics Review, 23*, 191–197. doi: 10.1002/sdr.371

Meadows, D. H., Meadows, D. L., & Randers, J. (n.d.). A Synopsis: Limits to Growth: The 30-Year Update. Retrieved from http://donellameadows.org/archives/a-synopsis-limits-to-growth-the-30-year-update/

Meadows, D. H., Meadows, D. L., & Randers, J. (1992). *Beyond the limits: Confronting global collapse, envisioning a sustainable future*. White River Junction VT: Chelsea Green Publishing Co.

Meadows, D. H., Meadows, D. L., & Randers, J. (2004). *The limits to growth: The 30-year update*. White River Junction VT: Chelsea Green Publishing Co.

Meadows, D. H., Meadows, D. L., Randers, J., & Behrens, W. W. (1972). *The limits to growth: A report for the Club of Rome's project on the predicament of mankind*. New York: Universe Books

MetaSD. (2019). world3-03. Retrieved from https://metasd.com/tag/world3/

Moles, P., & Terry, N. (1997). *The handbook of international financial terms*. Oxford, United Kingdom: Oxford University Press.

National Oceanic & Atmospheric Administration (NOAA). (2019). *NOAA/ESRL calculation of global means*. Retrieved from https://www.esrl.noaa.gov/gmd/ccgg/about/global_means.html

Nizzetto, L., Langaas, S., & Futter, M. (2016). Pollution: Do microplastics spill on to farm soils? *Nature, 537*. doi: 10.1038/537488b

Nordhaus, W. (1973). World dynamics: Measurement without data. *The Economic Journal, 83*, 1156-1183. doi: 10.2307/2230846

Nordhaus, W. (1992). Lethal model 2: Limits to growth revisited. *Brookings Papers on Economic Activity.* Retrieved from https://www.brookings.edu/bpea-articles/lethal-model-2-the-limits-to-growth-revisited/

Norgard, J., Peet, J., & Ragnarsdottir, K. (2010). The history of limits to growth. *Solutions, 1*, 59-63. Retrieved from http://www.thesolutionsjournal.com/node/569

Organisation for Economic Co-operation and Development. (2017). *Environmental Fiscal Reform: Progress, prospects, and pitfalls*. Retrieved from http://www.oecd.org/tax/tax-policy/environmental-fiscal-reform-progress-prospects-and-pitfalls.htm

Organisation for Economic Co-operation and Development. (2018). *Effective carbon rates 2018: Pricing carbon emissions through taxes and emissions trading.* OECD Publishing: Paris. doi:10.1787/9789264305304-en.

Passell, P., Roberts, M., Ross, L. (1972). The Limits to Growth. *The New York Times*. Retrieved from https://www.nytimes.com/1972/04/02/archives/the-limits-to-growth-a-report-for-the-club-of-romes-project-on-the.html

Pasqualino, R., Jones, A., Monasterolo, I., & Phillips, A. (2015). Understanding global systems today—A calibration of the World3-03 model between 1995 and 2012. *Sustainability,* 7, 9864-9889. doi: 10.3390/su7089864.

Piketty, T. (2014). *Capital in the twenty-first century*. Cambridge, MA: Harvard University Press.

Qui, S., & Yao, K. (2019). China's slowdown deepens; industrial output growth falls to 17-1/2 year low. *Reuters*. Retrieved from https://www.reuters.com/article/us-china-economy-activity-idUSKBN1W102H

Randers, J. (2000). From limits to growth to sustainable development or SD (sustainable development) in a SD (system dynamics) perspective. *System Dynamics Review*, *16,* 213–224.

Randers, J. (2012). *2052: A global forecast for the next forty years*. White River Junction VT: Chelsea Green Publishing Co.

Sabin, P. (2013). Betting on the apocalypse. *The New York times*. Retrieved from https://www.nytimes.com/2013/09/08/opinion/sunday/betting-on-the-apocalypse.html

Saeed, K. (2014). *Policy space and system dynamics modeling of environmental agendas*. Unpublished manuscript. Retrieved from: http://digitalcommons.wpi.edu/ssps-papers/4

Senge, P. (1994). *The fifth discipline: The art and practice of the learning organization*. New York: Currency Doubleday.

Simmons, M. R. (2000). Revisiting the Limits to Growth: Could the Club of Rome have been correct, after all?. *Mud City Press*. Retrieved from http://www.mudcitypress.com/PDF/clubofrome.pdf

Smillie, S. (2017). From sea to plate: how plastic got into our fish. *The Guardian*. Retrieved from https://www.theguardian.com/lifeandstyle/2017/feb/14/sea-to-plate-plastic-got-into-fish

Solow, R. M. (1973). Is the end of the world at hand?. *Challenge*, *16*, 39–50. doi: 10.1080/05775132.1973.11469961.

Sterman, J. (1994). Learning in and about complex systems. *System Dynamics Review, 10*, 291-330. doi:10.1002/sdr.4260100214

Sterman, J. (2000). *Business dynamics: Systems thinking and modeling for a complex world*. Boston: Irwin/McGraw-Hill.

Schmitz, O. (2007). *Ecology and Ecosystem Conservation*. Washington: Island Press.

Sverdrup, H., & Ragnarsdóttir, K. (2014). Natural resources in a planetary perspective. *Geochemical Perspectives*, *3*, 129-341. doi: 7185/geochempersp.3.2.

Sverdrup, H., Koca, D., & Ragnarsdóttir, K. (2015) *40 years after Limits to Growth: The World3 system dynamics model and its impacts*. [PowerPoint slides] Retrieved from http://www.wrforum.org/wp-content/uploads/2015/09/Limits-to-growth.pdf

Tans, P., & Keeling, R. (2019). *Globally averaged marine surface annual mean data*. [Data file]. Retrieved from https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html

"Plenty of gloom". (1997, December 18). Retrieved from https://www.economist.com/christmas-specials/1997/12/18/plenty-of-gloom

The University of Texas at Austin. (2019). New Oil and Gas Production Technologies. Robert Strauss Center. Retrieved from https://www.strausscenter.org/energy-and-security/new-oil-and-gas-production-technologies.html

Thwink.org. (n.d.). Retrieved from http://www.thwink.org/sustain/glossary/FeedbackLoop.htm

Turner, G. M. (2008). A comparison of the Limits to Growth with 30 years of reality. *Global Environmental Change*, *18*, 397-411.

Turner, G. M. (2012). On the cusp of global collapse? Updated comparison of the Limits to Growth with historical data. *GAIA, 21*(2), 116 – 124. Retrieved from https://www.ethz.ch/content/dam/ethz/special-interest/usys/ites/ecosystem-management-dam/documents/EducationDOC/Readings_DOC/Turner_2012_GAIA_LimitsToGrowth.pdf

Turner, G. (2013). The limits to growth model is more than a mathematical exercise: Reaction to R. Castro. 2012. Arguments on the imminence of global collapse are premature when based on simulation models. GAIA, 21/4: 271-274. *GAIA, 22*, 18-19.

Turner, G. (2014). *Is global collapse imminent?* Melbourne Sustainable Society Institute, The University of Melbourne. Retrieved from http://sustainable.unimelb.edu.au/sites/default/files/docs/MSSI-ResearchPaper-4_Turner_2014.pdf

United Nations Department of Economic & Social Affairs, Population Division (UN DESA PD). (2019). *Total population - Both sexes* [Datafile]. Retrieved from https://population.un.org/wpp/DVD/Files/1_Indicators%20(Standard)/EXCEL_FILES/1_Population/WPP2017_POP_F01_1_TOTAL_POPULATION_BOTH_SEXES.xlsx

United Nations Department of Economic & Social Affairs, Statistical Division (UN DESA Statistical Division). (2019). System of National Accounts 1993 - 1993 SNA. Retrieved from https://unstats.un.org/unsd/nationalaccount/sna1993.asp

United Nations Development Programme (UN DP). (2019a). Human Development Data (1990-2017). Retrieved from http://hdr.undp.org/en/data

United Nations Development Programme (UN DP). (2019b). Education index (1990-2017). Retrieved from http://hdr.undp.org/en/content/education-index

United Nations Development Programme (UN DP). (2019c). Technical Notes. (Human development indices and indicators: 2018 statistical update). Retrieved from http://hdr.undp.org/sites/default/files/hdr2018_technical_notes.pdf

United Nations Development Programme (UN DP). (2019d). Frequently Asked Questions - Human Development Index (HDI). Retrieved from http://hdr.undp.org/en/faq-page/human-development-index-hdi#t292n2872

United Nations Environment Programme (UN EP). (2002). *Global Environment Outlook 3*. Retrieved from https://www.unenvironment.org/resources/global-environment-outlook-3

United Nations Industrial Development Organization (UNIDO). (2019a). Selected Database: INDSTAT 2 2019, ISIC Revision 3:. Retrievable from https://stat.unido.org/database/INDSTAT%202%202019,%20ISIC%20Revision%203

United Nations Industrial Development Organization (UNIDO). (2019b). Selected Database: MVA 2019, Manufacturing:. Retrieved from https://stat.unido.org/database/MVA%202019,%20Manufacturing

United Nations Industrial Development Organization (UNIDO). (2019c). UNIDO in brief. Retrieved from https://www.unido.org/who-we-are/unido-brief

United Nations Industrial Development Organization (UNIDO). (2019d). Statistical Databases. Retrieved from https://www.unido.org/researchers/statistical-databases

United Nations Population Fund (UN Population Fund). (2018). *One vision, three zeros*: *UNFPA annual report 2018*. Retrieved from https://www.unfpa.org/annual-report

United States Geological Survey (USGS). (2019). Historical statistics for mineral and material commodities in the United States. Retrieved from https://www.usgs.gov/centers/nmic/historical-statistics-mineral-and-material-commodities-united-states

van Sebille, E., Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B. D., van Franeker, J. A., …Law, K. L. (2015). A global inventory of small floating plastic debris. *Environmental Research Letters, 10*(12).

Vargish, T. (1980). Why the person sitting next to you hates limits to growth. *Technological Forecasting & Social Change, 16*(3), 179-189.

Vensim. (2019). Free downloads. Retrieved from: https://vensim.com/free-download/

Vermeulen, P. J., & de Jongh, D.C.J. (1976). 'Dynamics of growth in a finite world' – comprehensive sensitivity analysis. *IFAC Proceedings Volumes, 9*, 133-145. Retrieved from https://www.sciencedirect.com/science/article/pii/S1474667017673336

Woody, T. (2013, August). New drilling technologies could give us so much oil, the climate won't stand a chance. *Quartz*. Retrieved from https://qz.com/117504/new-drilling-technologies-could-give-us-so-much-oil-the-climate-wont-stand-a-chance/

World Bank (WB). (2019a). Population, total. Retrieved from https://data.worldbank.org/indicator/SP.POP.TOTL

World Bank (WB). (2019b). Fertility rate, total (births per woman). Retrieved from https://data.worldbank.org/indicator/SP.DYN.TFRT.IN

World Bank (WB). (2019c). Death rate, crude (per 1,000 people). Retrieved from https://data.worldbank.org/indicator/SP.DYN.CDRT.IN

World Bank (WB). (2019d). Gross fixed capital formation (constant 2010 US$). Retrieved from https://data.worldbank.org/indicator/NE.GDI.FTOT.KD

World Bank (WB). (2019e). Who we are. Retrieved from https://www.worldbank.org/en/who-we-are

World Bank (WB). (2019f). Gross capital formation (constant 2010 US$). Retrieved from https://data.worldbank.org/indicator/NE.GDI.TOTL.KD

World Bank (WB). (2019g). Government expenditure on education, total (% of GDP). Retrieved from https://data.worldbank.org/indicator/SE.XPD.TOTL.GD.ZS

World Bank (WB). (2019h). Government expenditure on health, total (% of GDP). Retrieved from https://data.worldbank.org/indicator/SH.XPD.CHEX.GD.ZS

World Bank (WB). (2019i). [Data files]. Unpublished Excel files. Retrievable from World Bank at request.

World Health Organization (WHO). (2019). Global health expenditure database. Retrieved from http://apps.who.int/nha/database

World Inequality Database. (2018). *World inequality report 2018*. Retrieved from https://wir2018.wid.world/part-2.html

Worstall, T. (2013). But why did Julian Simon win the Paul Ehrlich bet? *Forbes*. Retrieved from https://www.forbes.com/sites/timworstall/2013/01/13/but-why-did-julian-simon-win-the-paul-ehrlich-bet/#6f3ef9fa1b03

Wright, S. L., Kelly, F. J. (2017a). Plastic and human health: a micro issue? *Environmental Science & Technology, 51*. doi:10.1021/acs.est.7b00423pmid:28531345

Wright, S. L., Kelly, F. J. (2017b). Threat to human health from environmental plastics. *BMJ, 358*(4334). doi: https://doi-org.ezp-prod1.hul.harvard.edu/10.1136/bmj.j4334