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RESEARCH AND ANALYSIS

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Update to limits to growth

Comparing the World3 model with empirical data

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Abstract

In the 1972 bestseller *Limits to Growth* (LtG), the authors concluded that, if global society kept pursuing economic growth, it would experience a decline in food production, industrial output, and ultimately population, within this century. The LtG authors used a system dynamics model to study interactions between global variables, varying model assumptions to generate different scenarios. Previous empirical-data comparisons since then by Turner showed closest alignment with a scenario that ended in collapse. This research constitutes a data update to LtG, by examining to what extent empirical data aligned with four LtG scenarios spanning a range of technological, resource, and societal assumptions. The research benefited from improved data availability since the previous updates and included a scenario and two variables that had not been part of previous comparisons. The two scenarios aligning most closely with observed data indicate a halt in welfare, food, and industrial production over the next decade or so, which puts into question the suitability of continuous economic growth as humanity's goal in the twenty-first century. Both scenarios also indicate subsequent declines in these variables, but only one—where declines are caused by pollution—depicts a collapse. The scenario that aligned most closely in earlier comparisons was not amongst the two closest aligning scenarios in this research. The scenario with the smallest declines aligned least with empirical data; however, absolute differences were often not yet large. The four scenarios diverge significantly more after 2020, suggesting that the window to align with this last scenario is closing.

KEYWORDS
collapse, industrial ecology, limits to growth, system dynamics modeling, systems thinking, World3

1 | INTRODUCTION

1.1 | Limits to growth

In the 1972 bestseller *Limits to Growth* (LtG), 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 the twenty-first 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 (Turner), 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 the present day and a sharp decline starting around 2030.

This article describes the research into whether humanity was still following BAU and whether there seemed opportunity left to change course to become more aligned with another LtG scenario, perhaps one in which collapse is avoided. World3 scenarios were quantitatively compared with empirical data. The research thus constitutes an update to previous comparisons but also adds to them in several ways. Earlier data comparisons used scenarios from the 1972 LtG book. The scenarios in this research were created with the latest, revised and recalibrated, World3 version. This data comparison also included a scenario and two variables that had not been part of such research before, and benefited from better empirical proxies thanks to improved data availability.

1.2 | Limits to growth message

The LtG message was that continuous growth in industrial output cannot be sustained indefinitely (Meadows, Meadows, Randers, & Behrens, 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 & Meadows, 2007; Meadows, Meadows, & Randers, 2004). 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 then becomes the binding constraint to growth (Meadows & Meadows, 2007). To illustrate this point, the LtG authors 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.

1.3 | LtG publications

The first book (Meadows et al., 1972) was commissioned by the Club of Rome and introduced World3 together with 12 scenarios. The most widely discussed scenario has been the BAU. It maintained parameters at historic levels from the latter part of the twentieth 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 toward 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).

There were 11 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 onward (Meadows et al., 1972). A change in values and policies translates 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, Meadows, & Randers). 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 20 years after the first LtG book, society had now reached overshoot (i.e., exceeds the earth's carrying capacity).

The third and last book, *Limits to Growth: The 30-Year Update*, dates from 2004 (Meadows et al.). It described 10 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 (EF) 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.

1.4 | Criticism

The LtG books and World3 received much criticism at the time (e.g., Bardi, 2011; Norgard, Peet, & Ragnarsdóttir, 2010). Much of this was focused on the economic and technological assumptions underlying the World3 model. Additionally, there was technical criticism of World3 and the new modeling technique (system dynamics) itself. There were also misconceptions about the scenarios and LtG message, some of which have proven persistent and influential in the public debate. An example is the claim that the first book predicted resource depletion by 1990 (Passell, Roberts, & Ross, 1972). This misconception spread to the point of being repeated by organizations like the United Nations Environment Programme (2002). It was actively revived by analysts ("Plenty of Gloom", 1997; Bailey, 1989; Lomborg & Olivier, 2009), who subsequently dismissed LtG because depletion and collapse had not taken place. Reversal points lie beyond 2000 in all the scenario graphs in the LtG books, however.

Criticism on World3's underlying assumptions focused mostly on those concerning technological progress and market correction. Some 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). Economist Solow (1973), for example, argued that increased scarcity would drive up prices of non-renewable resources, and also that pollution externalities would drive more regulation and higher taxes. Research by the Organisation for Economic Co-operation and Development (OECD, 2017, 2018), amongst others, suggests; however, that the social costs of pollution and natural resource depletion are currently not fully reflected in taxes. Fossil fuels alone still carry large indirect after-tax government subsidies (Coady, Parry, Le, & Shang, 2019), totaling 6.4% of global gross domestic product (GDP). Others argued in a reaction to the first LtG book that World3 did not give enough credence to humanity's ability to invent technological solutions to environmental challenges (Cole, Freeman, Jahoda, & Pavitt, 1973; Kaysen, 1972). The LtG authors have since pointed out (Meadows et al., 2004; Meadows et al., 1992) that their books contained several scenarios other than the BAU, which were based on assumptions about technological innovation and adoption that are significantly higher than historic averages. These optimistic assumptions on humankind's ingenuity and willingness to share technological solutions do not prevent declines in an LtG scenario, unless it is paired with societal value and policy changes (as in SW).

Technical criticism included the claim that 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). Recreation of runs with the same parameter changes as in these critical studies confirmed that finding, although it also showed that the parameter changes did not avoid an overshoot and collapse pattern (Turner, 2013). A 1973 review of World3 by Cole, Freeman, Jahoda, & Pavitt, concluded that the model was inadequate from the perspective of linear modeling. Sterman (2000) has since pointed out that adequacy as a linear model is not the right criterion for a system dynamics model.

1.5 | 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). Around 1990, it became clear that non-renewable resources, particularly fossil fuels, had turned out to be more plentiful than assumed in the 1972 BAU scenario. Randers 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 amount of non-renewable resources. This scenario is referred to as BAU2, and received more focus than the BAU scenario in the second and third LtG books. More natural resources do not avoid collapse in World3; the cause changes from resource depletion to a pollution crisis.

BAU2 was quantitatively assessed in a 2015 recalibration study of World3-03 (Pasqualino, Jones, Monasterolo, & Phillips, 2015). 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. Thus, their findings could not be taken as an indication that humanity had done enough to avoid declines, as the authors themselves made sure to point out.

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 3 of the 12 scenarios from the first book: BAU, CT, and SW. Turner concluded that world data compared favorably to key features of BAU, and much more so than for the other two scenarios.

1.6 | This research: A data comparison to LtG

In this research, data available in 2019 was compared with the recalibrated World3-03 to examine whether this 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 EF. Another open question therefore was to what extent these variables aligned with their real-world counterparts. Lastly, given the attention that BAU2 had received 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.

The research goal was to determine to what extent empirical data aligned with selected scenarios of World3-03 (henceforth called "World3"). Data was compiled from various official databases, as indicators for what the following 10 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

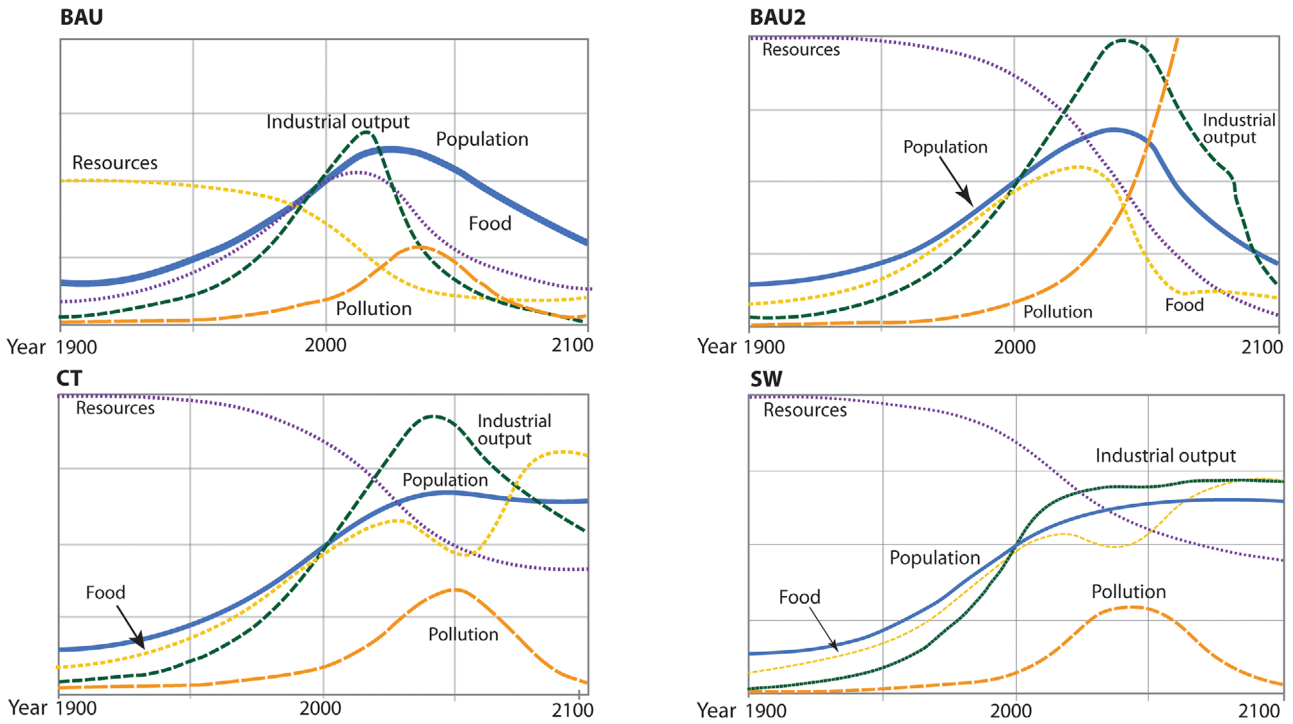

FIGURE 1 The BAU, BAU2, CT, and SW scenarios. Adapted from *Limits to Growth: The 30-Year Update* (p. 169, 173, 219, 245), by Meadows, D. H., Meadows, D. L., and Randers, J., 2004, Chelsea Green Publishing Co. Copyright 2004 by Dennis Meadows. Adapted with permission

TABLE 1 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 twenty-first century, as does human welfare on a high level.

ecological footprint (EF). This data was plotted 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 1 shows how some of the LtG variables behave in each of these four scenarios. It should be noted that the numerical scales of the World3 output differ widely between variables. They are scaled in Figure 1 (as in the LtG books) to fit in one plot. This means that relative positions to each other on the *y*-axis have no meaning whatsoever. What is relevant is the movement of the variables over time in each of the four scenarios. These movements together depict the storyline of that scenario, which unfolds based on the specific scenario assumptions.

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 1).

2 | METHODS

2.1 | Scenario data

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, policy changes are assumed to start in 2002. To create the scenarios, the original CD-ROM that came with the 2004 book was used. The CD-ROM contains simulations of the scenarios and numerical output of the variables. A zip file of World3-03 is also available from MetaSD (2020) and it can be run on free software from Vensim (2020).

2.2 | Determination of accuracy

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

1. the combination of
   a. the value difference (between the model output and empirical data), and
   b. the difference (between the model output and empirical data) in rate of change (ROC)

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

2 the normalized root mean square difference (NRMSD).

These two measures do not provide the level of precision of some statistical tests, which is not possible given World3's global scope and aggregation. Rather, the measures are meant to be combined with visual inspection to gauge the scenarios' accuracy. In other words, the accuracy measures are meant to determine World3's merit, not for point predictions, but as an analysis tool for general global dynamics.

2.2.1 | Formulas

The calculations of the two measures are done for 5-year intervals ending in the final year of the data series. The 5-year interval aligns with the LtG team's practice in the plots in their books. World3 provides output in half-year increments, but the LtG team did not consider changes over smaller periods significant (Meadows et al., 1972). In the equations below, the final year is assumed to be 2015 for ease of interpretation. The final year varied per data source, from 2015 to 2020 (see Supporting Information S2). It is straightforward to adjust the formulas for data series ending in another year.

Measure 1: value change and rate of change

$$\Delta\text{Value} = \frac{\text{Variable}_{2015} - \text{Observed Data}_{2015}}{\text{Observed Data}_{2015}}$$

$$\Delta\text{Rate of Change} = \frac{(\text{Variable}_{2015} - \text{Variable}_{2010}) - (\text{Observed Data}_{2015} - \text{Observed Data}_{2010})}{\text{Observed Data}_{2015} - \text{Observed Data}_{2010}}$$

Measure 2: NRMSD

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

$$\text{NRMSD}_{2015} = \frac{\sqrt{\frac{\sum_{t=0}^{5}(\text{Variable}_{1990+5t} - \text{Observed Data}_{1990+5t})^2}{6}}}{\left(\frac{\sum_{t=0}^{5}\text{Observed Data}_{1990+5t}}{6}\right)}$$

2.2.2 | Uncertainty ranges

It was necessary to establish suitable uncertainty ranges for each of these measures, given World3's low precision and the error margins one can expect in the empirical data. The same uncertainty ranges as suggested in Turner's comparisons were used, that is, 20%, 50%, and 20% for the value difference, ROC and NRMSD, respectively. This recognizes that global data are unlikely to have a very high 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. It is not suggested to interpret the 20% and 50% as strictly as, say, one would use α as a cut-off point in statistical analysis. As mentioned, the accuracy measures and uncertainty ranges complement a visual inspection of the graphs by quantifying the alignment error.

2.3 | Closest fit count

Apart from a measure of absolute fit, the above-mentioned uncertainty range, it was also necessary to distinguish amongst the four scenarios in terms of relative fit. This can be done with a simple tally over the variables for each scenario. A scenario was counted as a closest fit when it aligned more closely than other scenarios and at least one of that variable's proxies was within the uncertainty bounds for both accuracy measures. Another option would have been to count a scenario as a closest fit if either measure 1 or measure 2 was within the uncertainty range for at least one proxy. The choice to only count a scenario when both accuracy measures were within range was made because it's more conservative. When all scenarios were outside of uncertainty bounds for at least one measure, they were counted as inconclusive. For cases where two or more scenarios aligned to the same extent, they were all counted.

2.4 | Data sources

Below follows a list of the source(s) of empirical data used for each variable in this comparison. Reliability of each source is briefly discussed in Supporting Information S1.

Some variables required proxies because the variable in World3 is not directly observable or quantifiable in the real world. The same data sources as Turner were often chosen; however, in several cases it was possible to improve on previous proxies thanks to new or recently enhanced indices and databases. When empirical data was expressed in different units than the LtG scenarios, they were normalized to the 1990 scenario value, because that is the year that World3 was recalibrated to last (Meadows et al., 1992).

2.4.1 | Population

Figures from the Population Division of the United Nations Department of Economic & Social Affairs (UN DESA PD, 2019) were used for this variable. Their population series includes estimates for 2020, which were compared 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.

2.4.2 | Fertility and mortality (two variables)

The data series from the WB Open Data site (2019b, 2019c) were used for both of these variables. The WB mentions as its sources the same organizations and publications as for its population series.

2.4.3 | Food per capita

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

2.4.4 | Industrial output per capita

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). The index of industrial production (IIP) and gross fixed capital formation (GFCF) were used as proxies. Both proxy series were divided by population to arrive at per capita numbers.

IIP is a standardized macroeconomic indicator of an economy's real output in manufacturing, mining, and energy (e.g., Moles & Terry, 1997). Unlike GDP, IIP excludes retail and professional services, making it a useful 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 one was created with a weighted average of country IIPs. National manufacturing value added, also sourced from UNIDO (2019b), was used for weighting.

The WB (2019d) provides a global GFCF series. GFCF includes land improvements (e.g., fences and drains), infrastructure (e.g., roads), buildings and construction (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.

2.4.5 | Services per capita

In World3, services p.c. represents education and health services (Meadows et al., 2004). The Education Index (EI), spending on health, and spending on education were used as proxies.

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

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

2.4.6 | Pollution

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

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

Global plastic production data was sourced from Geyer, Jambeck, and Law (2017). The data was adjusted downwards to 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, plastic's persistence and ubiquity in today's society, and documented impacts on human health, aligns with World3's assumptions on the pollution variable. Various kinds of plastics can be found throughout the entire consumer product and food supply chain, from oceans and marine wildlife (Smillie, 2017; van Sebille et al., 2015) to tap water (Kosuth, Wattenberg, Mason, Tyree, & Morrison, 2017), from agricultural land (Nizzetto, Langaas, & Futter, 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).

2.4.7 | Non-renewable resources

Two proxies were used for this variable, both based on different expert estimates of fossil fuel resources. Full substitution between energy resources is assumed, 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 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. Turner's series were updated 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 proxy was constructed using the same method, but with fossil energy resource estimates from a Geochemical Perspective (GP) publication (Sverdrup & Ragnarsdóttir, 2014), and production data from the World Bank (WB) (2019g). For that reason, this proxy is indicated with "WB" at the end in the results.

TABLE 2 Accuracy measure 1: Value difference and rate of change (ROC) difference (both in %) for each scenario and variable

Scenario		Population	Fertility	Mortality	Food p.c.	Industrial output p.c.	Services p.c.	Pollution	Natural cap	Welfare	EF
BAU	Δ value	−6	−17	15	−15	−11; 3	5; 8; 9	−20; 64	−15; −11; −2; 15	−4	15
	ΔROC	−42	55	−12	−342	−107; −90	−7; −5; 33	−14; 68	12; 55; 121; 179	−152	593
BAU2	Δ value	−5	−10	8	−14	−7; 13	10; 11; 13	−20; 65	−15; −11; −2; 15	−2	19
	ΔROC	−28	−4	−6	−279	−64; 5	57; 85; 97	−14; 73	12; 55; 121; 179	−62	940
CT	Δ value	−5	−10	6	−12	−6; 13	10; 11; 13	−20; 64	−15; −11; −2; 16	−1	18
	ΔROC	−25	−3	−7	−193	−62; 8	57; 86; 97	−14; 69	7; 50; 113; 166	−40	841
SW	Δ value	−11	−22	11	−10	−9; 2	18; 20; 22	−19; 68	−15; −11; −2; 16	−1	13
	ΔROC	−52	−61	−9	−275	−108; −95	22; 32; 68	−8; 78	−3; 39; 97; 143	−67	247

2.4.8 | Human welfare

The HDI data series can be found on the website of UNDP (2019a). The HDI has undergone methodological changes over the years (UNDP, 2019d), which have led to significant retroactive adjustment to the series. The 2004 LtG book (Meadows et al.) notes that the World3 welfare variable was very close to the UNDP value as at 1999, but this was no longer the case for the latest version of the HDI data series. The UNDP (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". UNDP (2019d) therefore advises not to source HDI numbers from Reports, but to use the "data series available in the on-line database". Therefore, the current HDI data were scaled with a factor 1.106 to line up with the World3 scenarios value as at 2000.

2.4.9 | Human ecological footprint

The LtG team created this variable after Wackernagels' Ecological Footprint (Meadows et al., 2004). The Global Footprint Network (GFN, 2019a) publishes the EF on its website. The EF series were scaled to scenario values between 1990 and 2000 (with a factor of 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), similar to the HDI.

3 | RESULTS

3.1 | Overview for each accuracy measure

The table and graph below provide an overview of the two accuracy measures for each variable and scenario. Graphs for each variable plotted with the scenarios are provided in Supporting Information S1. Table 2 shows the results for accuracy measure 1, the graph in Figure 2 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 2 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 2 and marked by a dashed green line.

3.2 | Closest fit counts per scenario

Table 3 contains a count per scenario for each time it was the closest fit. As mentioned in Section 2, for variables where two or more scenarios aligned to the same extent, each scenario was counted. This is why Table 3 shows 22 total counts over 10 variables. The use of more than one proxy for some variables did not lead to contradictory counts; although different proxies for the same variable sometimes had different numerical results, they led to the same outcomes in terms of alignment (or not) to a certain scenario.

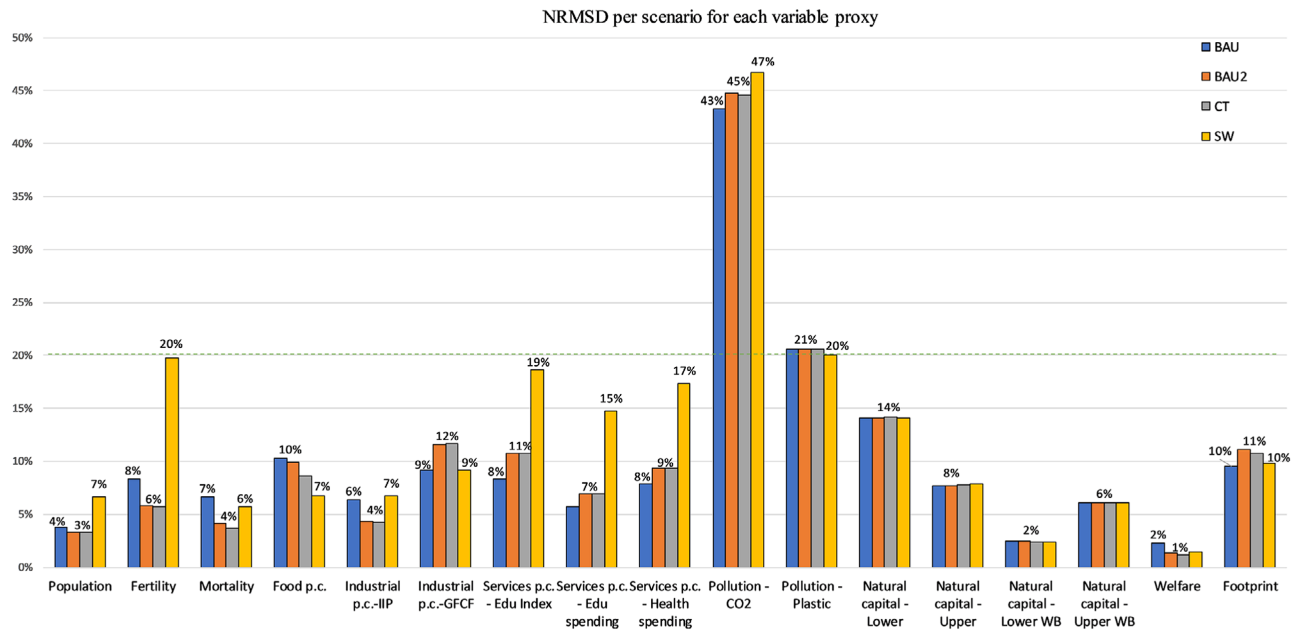

FIGURE 2 Accuracy measure 2: NRMSD. Plotted for each scenario and variable proxy. Underlying data used to create this figure can be found in Supporting Information S2. Data visualization was aided by Daniel's XL Toolbox addin for Excel, version 7.3.4, by Daniel Kraus, Würzburg, Germany (www.xltoolbox.net)

TABLE 3 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

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 is because scenarios start to deviate later in World3-03 than was the case in the 1972 version of World3. Such was the case with non-renewable resources, for example, and with the plastics proxy for the pollution variable. In particular, the BAU2 and the CT scenarios do not 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 next years' datapoints will cause their rates of change (now 62% and 67%) to dip below 50%. This should be kept in mind with Table 3.

4 | DISCUSSION

4.1 | Close alignment

When it comes to value, both measures indicate an overall close alignment between the LtG scenarios and empirical data. Measure 2 (the NRMSD) was not greater than 20% for all variables (Figure 2), except for pollution. Table 2 shows that most differences in value were also within the 20% range, except for pollution and for fertility (i.e., birth rate) in SW.

The ROC showed more and larger deviations between scenarios and empirical data. Sometimes this was due to little movement in the variable itself, leading to a low difference between observed datapoints. This low difference meant that the numerator (see Section 2.2.1) would get inflated, even though value differences were not large. This was the case for the EF and welfare variables, and to a lesser extent for services p.c., food p.c., and natural capital.

4.2 | The end of growth

Despite all scenarios showing a relatively close track in value, there were differences between them for some variables. Unlike previous comparisons, this research did not reveal the BAU scenario aligning with empirical data more closely than the others. Like in Turner's work, however, the lowest count for closest fit was for SW, the scenario that the LtG work models as eventually following a sustainable path. When it was possible to distinguish between scenarios, the CT and BAU2 aligned closest most often. BAU2 and CT scenarios show a halt in growth within a decade or so from now. Both scenarios thus indicate that continuing business as usual, that is, pursuing continuous growth, is not possible. Even when paired with unprecedented technological development and adoption, business as usual as modeled by LtG would inevitably lead to declines in industrial capital, agricultural output, and welfare levels within this century. These forecasts put in perspective the recent low economic predictions (e.g., OECD, 2020; WB, 2019h), and talks from organizations like the IMF about a "synchronized slowdown" of global growth (Lawder, 2019) and "uncertain recovery" from the COVID-19 pandemic (IMF, 2020).

4.3 | Collapse?

The CT and BAU2 scenarios show distinctly different decline patterns, and one cannot simply "take the midway" between two scenarios produced by a complex, non-linear model like World3. Although the steepness of a scenario's decline cannot be used for predictive purposes (Meadows et al., 2004), it can be said that BAU2 shows a clear collapse pattern, whereas CT suggests the possibility of future declines being relatively soft landings, at least for humanity in general. The moderate declines in CT would align with a global forecast made in 2012 by LtG author Randers. Randers' forecast (2012) was made with a different model than World3 and so it cannot be compared with CT in most ways. However, the overall developments are not dissimilar, as the forecast includes consumption and GDP stagnation around the middle of the century followed by declines but not a collapse pattern.

4.4 | About tipping points

The BAU2 and CT scenarios seem to align quite closely not just with observed data, but also with contemporary debate. On one hand, the BAU2 scenario resonates with messages from climate scientists that we currently might be at the "climate tipping point" (Cai, Lenton, & Lontzek, 2016; Intergovernmental Panel on Climate Change, 2019; Lenton et al., 2019; Pearce, 2019). On the other hand, CT is the scenario of those who believe in humanity's ingenuity to innovate ourselves out of any limit. The assumptions underlying CT 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. Given the rising trend in global CO_2 emissions so far, halving these within the next 20 years seems unrealistic. However, the technologist could argue that history is full of "technological tipping points" (Montresor, 2014; World Economic Forum, 2015), where innovations disrupted trends and revolutionized society beyond what conventional wisdom deemed possible.

Detailing this discussion goes beyond the scope of this article. More important, the findings and LtG work indicate an altogether different question to ask than whether society could be following the CT. Two best fit scenarios that marginally align closer than the other two, point to the fact that it's not yet too late for humankind to purposefully change course to significantly alter the trajectory of future data points. The fact that the SW scenario shows the smallest declines, suggests that if we are to bet our future on the possibility of tipping points, rather than just the technological ones, we should also aim for the "social tipping points" (David Tàbara et al., 2018; Otto et al., 2020; Westley et al., 2011): A transformation of societal priorities which, together with technological innovations specifically aimed at furthering these new priorities, can bring humanity back on the path of the SW scenario.

5 | CONCLUSION

Empirical world data was compared against scenarios from the last LtG book, created by the World3 model. The data comparison, which used 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 do nott significantly diverge until 2020. When scenarios had started to diverge, the ones that aligned closest with empirical data most often were BAU2 and CT. This result is different to previous comparisons that used the earlier World3 version, and which indicated BAU as the most closely followed scenario. The scenario that depicts the smallest declines in economic output, SW, is also the one that aligned least closely with observed data. Furthermore, the two closest aligning scenarios BAU2 and CT, respectively, predict a collapse pattern and moderate decline in output. At this point therefore, the data most aligns with the CT and BAU2 scenarios which indicate a slowdown and eventual halt in growth within the next decade or so, but World3 leaves open whether the subsequent decline will constitute a collapse. World3 also indicates the possibility, for now, of limiting declines to less than in the CT. Although SW tracks least closely, a deliberate trajectory change brought about by society turning toward another goal than growth is still possible. The LtG work implies that this window of opportunity is closing fast.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

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