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

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Abstract

I conducted a data update to *Limits to Growth* (LtG), best known from the 1972 bestseller that forecasted a scenario of global societal collapse occurring around the present time if humanity did not alter its priorities. Empirical data comparisons since then indicated that the world was still heading for collapse. My objectives were to examine whether this was still the case based on the most recent data, and whether there was opportunity left to change that trajectory. My research benefited from improved data availability, and included a scenario and two variables that had not been part of previous comparisons. I collected data from academia, (non-)government agencies, United Nations entities, and the World Bank. This was plotted along four LtG scenarios spanning a range of technological, resource, and societal assumptions. From these graphs and two quantitative accuracy measures, I found that the scenarios aligned closely with observed global data, which is a testament to the LtG work done decades ago. The two scenarios aligning most closely indicate a halt in growth over the next decade or so, which puts into question the usability of continuous growth as humanity's goal in the 21st century. Both scenarios also indicate subsequent declines, but only one—the scenario in which declines are caused by pollution, including greenhouse gas pollution—depicts a collapse pattern. The scenario with the smallest declines aligned least with empirical data, however, absolute differences were rarely big and sometimes insignificant. This suggests that it's almost, but not yet, too late for society to change course.

1. INTRODUCTION

1.1. Limits to Growth

In the 1972 bestseller Limits to Growth (LtG), the authors (Meadows et al.) 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 21st 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 the present day, and a sharp decline starting around 2030.

I considered whether humanity was still following BAU, and whether there was opportunity left to change course and become more aligned with another LtG scenario, perhaps one in which collapse was avoided. This article describes the research to answer that question. I quantitatively compared World3 scenarios with empirical data. My 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. I used the latest, revised and recalibrated, World3 version. My comparison also included a scenario and two variables that had not before been part of such research, 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 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 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 twelve scenarios. The most widely discussed scenario has been the BAU. It maintained parameters at historic levels from the latter part of the 20^{th} 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).

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 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 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, society had now reached overshoot (i.e., transgression above 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 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 (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 (e.g., Norgard et al., 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 et al., 1972). This misconception promulgated to the point of being repeated even by organizations like the United Nations Environment Programme (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 would halt before 2100. It is clear from the scenario graphs that reversal points lie beyond 2000.

Modeling 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 (including with those who 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). Nobel prize winning economist Solow (1973), for example, 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 (OECD, 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 et al., 2017), totaling 6.5% of global gross domestic product (GDP).

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). 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 amount of non-renewable resources. I 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 et al.). 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.

1.6. My research: a data comparison to LtG

I examined whether comparing 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 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 scenarios of World3-03 (henceforth called "World3"). I compiled data from various official databases, as 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. I 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.

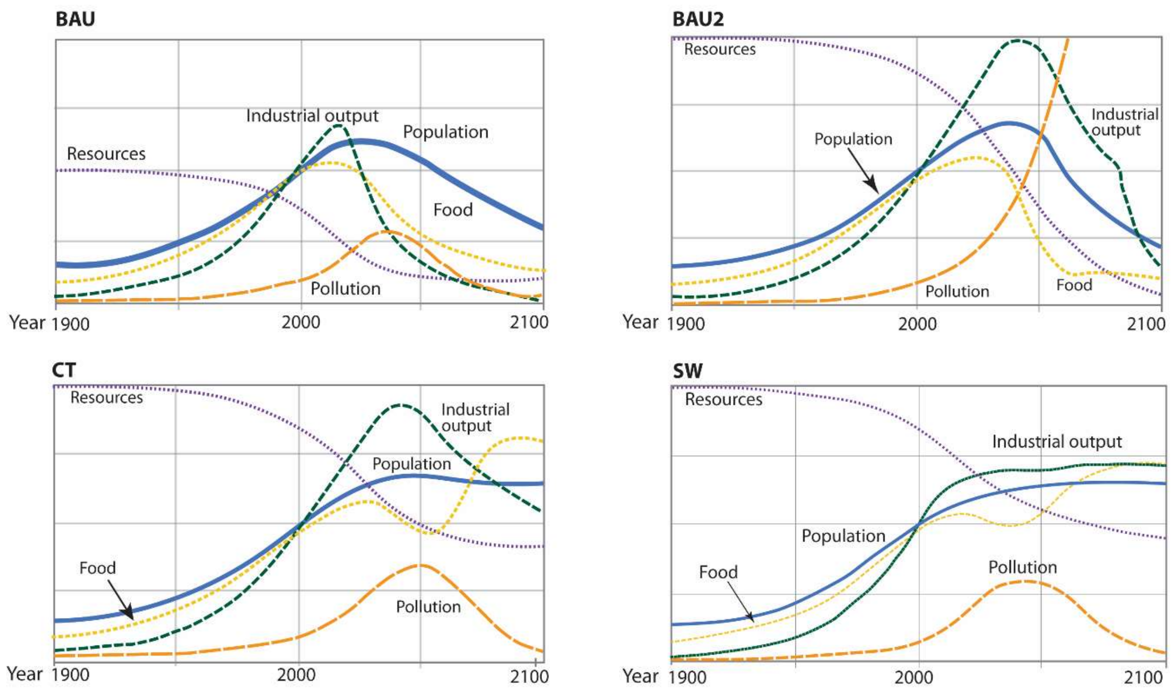

Figure 1. The BAU, BAU2, CT, and SW scenarios. Adapted by from *Limits to Growth: The 30-Year Update* (p. 169, 173, 219, p.245), by Meadows, D. H., Meadows, D. L., & Randers, J., 2004, Chelsea Green Publishing Co. Copyright 2004 by Dennis Meadows. Adapted with permission.

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).

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 21st century, as does human welfare on a high level.

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, I assumed policy changes starting in 2002. To create the scenarios, I used the original CD-ROM that came with the 2004 book. (I obtained a mint condition copy with the CD-ROM still attached.) 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 (2019) and it can be run on free software from Vensim (2019).

2.2. Determination of accuracy

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

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. They are, when combined with visual inspection and given World3's global scope and aggregation, appropriate measures for the scenarios' accuracy. 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'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. In the equations below, I assume the final year to be 2015 for ease of interpretation. It is straightforward to adjust the formulas 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 I assume the start of the calculation to be 1990. This is what I 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.

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

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. I 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. I do not suggest interpreting 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. Data Sources

Below I list for each variable the source of empirical data that was used for the comparison. Its reliability is briefly discussed in the supporting information (SI).

Some variables required proxies because the variable in World3 is not directly observable or quantifiable in the real world. I often used the same data sources as Turner, however, in several cases I was 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, I normalized them to the 1990 scenario value, because that is the year that World3 was recalibrated to last (Meadows et al., 1992).

2.3.1. *Population*. I 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 I 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.

2.3.2. *Fertility and mortality (two variables).* I used the data series from the WB Open Data site (2019b; 2019c) for both of these variables. The WB mentions as its sources the same organizations and publications as for its population series.

2.3.3. *Food per capita*. I 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 (2019), the database of the Food and Agriculture Organization of the UN.

2.3.4. *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). I used the index of industrial production (IIP) and gross fixed capital formation (GFCF) as proxies. I divided both proxy series 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 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 I created one with a weighted average of country IIPs. As weights I 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.

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

The EI is constructed by the UN Development Programme (UNDP, 2019a). It's 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). UNDP does not provide a global EI, so I created one by weighing each country's EI by its population fraction.

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 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 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" (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.

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

Atmospheric CO_2 data (Tans & Keeling, 2019) were obtained from the National Oceanic & Atmospheric Administration. I 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 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 is accurate time series data.

Global plastic production data was sourced from Geyer et al. (2017). I 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, I 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 et al., 2017), from agricultural land (Nizzetto et al., 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).

2.3.7. *Non-renewable resources*. I used two fossil fuel proxies and one metal proxy. I assumed full substitution between energy or metal resources, which is conservative given the current state of technology (Brathwaite et al., 2010; Driessen et al., 2016; Graedel et al., 2015). The proxy data series that I 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. I 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 (2019g).

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 I 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.

2.3.8. *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, I scaled the current HDI data with a factor 1.106 to line up with the World3 scenarios value as at 2000.

2.3.9. *Human ecological footprint*. The Global Footprint Network (GFN, 2019a) publishes the EF on its website. I scaled the EF series 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 the SI. Table 2 shows the results for accuracy measure 1, the graph in Figure 3 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 3 and marked by a dashed green line for ease.

Table 2. Accuracy measure 1: value difference and rate of change difference (in %).

Scenario		Population	Fertility	Mortality	Food p.c.	Industrial output p.c.	Services p.c.	Pollution	Natural cap.p.c.	Welfare	EF
BAU	Δ value	-6	-18	12	-15	1; 1; 7	-1; -11	-20; 59	-15; -11; -8; -2; 15	-4	15
	ΔROC	-42	118	-109	-342	1; 12; 76	-123; -90	-14; 169	12; 43; 55; 121; 179	-152	593
BAU2	Δ value	-5	-12	5	-14	3; 4; 9	-7; 9	-20; 59	-15; -11; -8; -2; 15	-2	19
	ΔROC	-28	41	-105	-279	53; 70; 140	-64; 240	-14; 173	12; 43; 55; 121; 179	-62	940
CT	Δ value	-5	-12	3	-12	3; 5; 9	-6; 9	-20; 59	-15; -11; -8; -2; 16	-1	18
	ΔROC	-25	43	-104	-194	53; 71; 140	-62; 250	-14; 170	7; 41; 50; 113; 166	-40	841
SW	Δ value	-11	-24	9	-10	12; 13; 19	-9; -2	-19; 62	-15; -11; -8; -2; 16	-1	13
	ΔROC	-52	-50	-107	-275	33; 49; 134	-127; -95	-8; 190	-3; 36; 39; 97; 143	-67	247

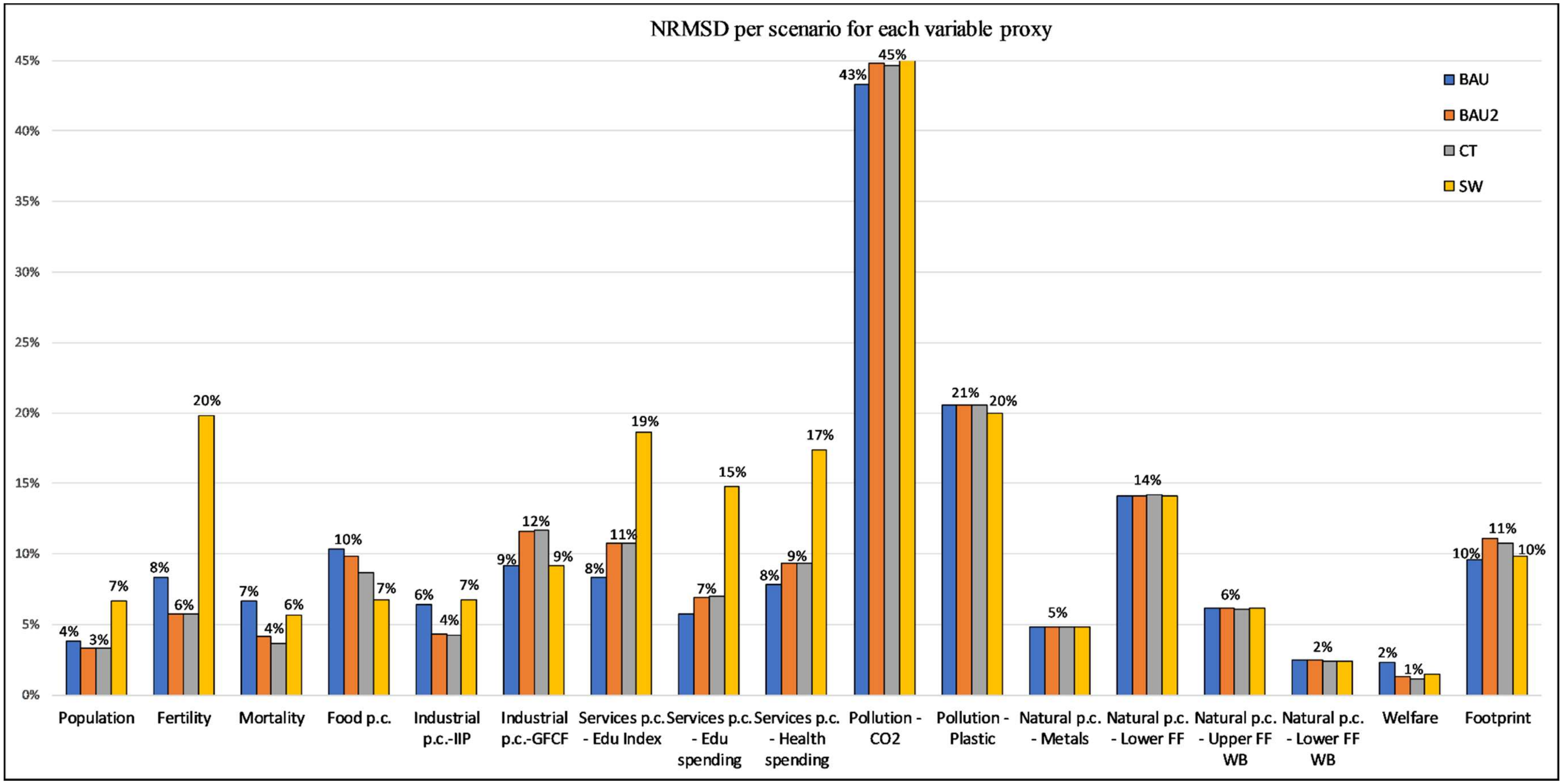

Figure 2. Accuracy measure 2: NRMSD. Plotted for each scenario and variable proxy. Data visualization was aided by Daniel's XL Toolbox addin for Excel, version 7.3.4, by Daniel Kraus, Würzburg, Germany (www.xltoolbox.net).

3.2. Closest fit counts per scenario

Table 3 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 criterion is stringent; I could also have used the requirement of only one accuracy measure being within uncertainty bounds. (As is clear from Figure 3, accuracy measure 2 is within bounds for at least one proxy for every variable.) I chose both measures instead of either one, because scenarios show a reversal around the 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., I decided to balance the ROC's 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 3). For cases where two or more scenarios aligned to the same extent, they were all counted. This is why Table 3 shows 22 total counts 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 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 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 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 3), except for pollution. Table 2 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. The overall close alignment in value between the LtG scenarios and empirical data is a testament to the work of the LtG team, as well as to the potential of dynamic systems modeling for strategic planning and policy evaluations in general.

4.2. The end of growth

Despite all scenarios showing a relatively close track, there were differences between scenarios for some variables. Unlike previous comparisons, this research did not reveal the BAU scenario aligning with empirical data more closely than the others. 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. 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, i.e., pursuing continuous growth, is not possible. Even when paired with unprecedented technological development and adoption, business as usual would inevitably lead to declines in industrial capital, agricultural output, and welfare levels within this century. These forecasts put the recent relatively 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) in perspective.

4.3. Collapse?

My findings are inconclusive as to whether subsequent declines can be expected to be so steep as to constitute 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 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 et al., 2016; Lenton et al., 2019; Pearce, 2019; Intergovernmental Panel on Climate Change, 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 (Meadows et al., 2004). 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, my findings 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 change course and significantly alter the trajectory of future data points. If we are to bet our future on the possibility of tipping points, rather than the technological ones, we should 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.

4.5. Conclusion

I compared empirical world data 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 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 aligned closest with empirical data were BAU2 and CT. This constitutes a break from previous comparisons that used the earlier World3 version, which indicated BAU as the most closely followed. The BAU not being the closest fit scenario does not imply that societal collapse is ruled out based on World3. The scenario that depicts the smallest declines, SW, is also the one that aligned least closely with observed data. Furthermore, one of the closest aligning scenarios, BAU2, shows a collapse pattern. The other scenario however, CT, shows only a moderate decline. At this point therefore, results indicate a slowdown and eventual halt in growth within the next decade or so but leave open whether the subsequent decline will constitute a collapse. Global society does not have to settle for CT as a best-case scenario, however. Although SW tracks least closely, a deliberate trajectory change brought about by society turning towards another goal than growth is still possible. That window of opportunity is closing fast.

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7. 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*. Chelsea Green Publishing Co.

Branderhorst, G. (2018, June 20–22). *Mapping the mess: Planning for the unprecedented in a complex, dynamic, and interconnected world*. [Paper presentation] United Nations Department of Economic and Social Affairs Public Service Forum 2018, Marrakech, Morocco.

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

Cai, Y., Lenton, T. M., & Lontzek, T. S. (2016). Risk of multiple interacting tipping points should encourage rapid CO_2 emission reduction. *Nature Climate Change, 6*(5), 520–525.

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.* Universe Publishing.

David Tàbara, J., Frantzeskaki, N., Hölscher, K., Pedde, S., Kok, K., Lamperti, F., . . . Berry, P. (2018). Positive tipping points in a rapidly warming world. *Current Opinion in Environmental Sustainability, 31*(C), 120–129.

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 CO_2 over the last 1000 years from air in Antarctic ice and firn. *Journal of Geophysical Research, 101*.

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

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

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

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).

Intergovernmental Panel on Climate Change. (2019). *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Retrieved from https://www.ipcc.ch/srocc/

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

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

Lenton, T., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., & Schellnhuber, H. (2019). Climate tipping points – too risky to bet against. *Nature, 575*(7784), 592–595.

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

Meadows, D. H. (2012). *Thinking in systems*. Chelsea Green Publishing.

Meadows, D. L. (1974). *Dynamics of growth in a finite world*. 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. (1992). *Beyond the limits: Confronting global collapse, envisioning a sustainable future*. Chelsea Green Publishing Co.

Meadows, D. H., Meadows, D. L., & Randers, J. (2004). *The limits to growth: The 30-year update*. 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*. 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 University Press.

Montresor, F. (2014, August 14). 14 tech predictions for our world in 2020. https://www.weforum.org/agenda/2014/08/14-technology-predictions-2020/

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

Norgard, J., Peet, J., & Ragnarsdóttir, K. (2010). The history of limits to growth. *Solutions, 1*(2), 59–63. https://www.thesolutionsjournal.com/article/the-history-of-the-limits-to-growth/

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

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

Organisation for Economic Co-operation and Development (OECD). (2020). *OECD Economic Outlook, Interim Report March 2020.* https://www.oecd-ilibrary.org/economics/oecd-economic-outlook/volume-2019/issue-2_7969896b-en

Otto, I., Donges, J., Cremades, R., Bhowmik, A., Hewitt, R., Lucht, W., . . . Schellnhuber, H. (2020). Social tipping dynamics for stabilizing Earth's climate by 2050. *Proceedings of the National Academy of Sciences of the United States of America, 117*(5), 2354–2365.

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.

Pearce, F. (2019). As Climate Change Worsens, A Cascade of Tipping Points Looms. https://e360.yale.edu/features/as-climate-changes-worsens-a-cascade-of-tipping-points-looms

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*. Chelsea Green Publishing Co.

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

Smillie, S. (2017). From sea to plate: how plastic got into our fish. *The Guardian*. 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

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

Tans, P., & Keeling, R. (2019). *Globally averaged marine surface annual mean data*. [Data file]. 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

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. 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. (2014). *Is global collapse imminent?* Melbourne Sustainable Society Institute, The University of Melbourne. 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]. https://population.un.org/wpp/Download/Files/1_Indicators%20(Standard)/EXCEL_FILES/1_Population/WPP2019_POP_F01_1_TOTAL_POPULATION_BOTH_SEXES.xlsx

United Nations Development Programme (UNDP). (2019a). Human Development Data (1990–2017). http://hdr.undp.org/en/data

United Nations Development Programme (UNDP). (2019b). Education index (1990–2017). http://hdr.undp.org/en/content/education-index

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

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

United Nations Environment Programme. (2002). *Global Environment Outlook 3*. 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. https://stat.unido.org/database/MVA%202019,%20Manufacturing

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).

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

Westley, F., Olsson, P., Folke, C., Homer-Dixon, T., Vredenburg, H., Loorbach, D., . . . Leeuw, S. (2011). Tipping Toward Sustainability: Emerging Pathways of Transformation. *AMBIO, 40*(7), 762–780.

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

World Bank (WB). (2019b). Birth rate, crude (per 1,000 people). https://data.worldbank.org/indicator/SP.DYN.CBRT.IN

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

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

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

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

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

World Bank (WB). (2019h). Global Economic Prospects: Slow Growth, Policy Challenges. https://www.worldbank.org/en/publication/global-economic-prospects#overview

World Economic Forum. (2015). *Deep Shift: Technology Tipping Points and Societal Impact.* http://www3.weforum.org/docs/WEF_GAC15_Technological_Tipping_Points_report_2015.pdf

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

8. SUPPORTING INFORMATION

There are two SI files for this article, one Word and one Excel document. These can be found on the published article's page of the *Journal of Industrial Ecology* at https://doi.org/10.1111/jiec.13084.

The Word SI provides the graphs of each of the ten variables against the four scenarios, and discusses reliability of data sources. The Excel SI contains the data tables for Figure 2 in the main text and in the Word SI.

9. Figure Legends